

# THE 1993 ATOMIC MASS EVALUATION

## (I). Atomic mass table

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**Abstract.** This paper is the first of a series of four. In it, a table is given to replace the 1983 atomic mass table. The differences with the earlier table are briefly discussed and information is given of interest for the users of this table. Part II of this series gives values for several derived quantities (decay-, separation- and reaction energies), part III shows graphs of several of those quantities, and part IV gives a list of input data and full information on the used input data and on the procedures used in deriving the tables in the preceding parts.

## 1. Introduction

As in our previous work [ 1, 2], the tables presented in this work give atomic masses and derived quantities. With very few exceptions, data on masses of nuclei refer to “*atomic*” masses or to masses of singly ionized atoms. In this last case the ionization energy is generally (much) smaller than the error on the mass, and, for the small number of very precise mass measurements, corrections for the first -and second- ionization potentials could be applied without much loss of accuracy. This

fact is the reason for the decision to present, in our evaluations, atomic rather than nuclear masses.

Nuclear masses can be calculated from atomic ones by using the formula:

$$M_N(A, Z) = M_A(A, Z) - Z \times M_e + B_e(Z) \quad (1)$$

For the electron mass  $M_e$ , see table A; the total atomic binding energy  $B_e(Z)$  of all electrons can be found in ref. [ 3]. Unfortunately, the precision of the values  $B_e(Z)$  is not clear; this quantity (values going up to 760 keV for  ${}_{92}\text{U}$ ) cannot be measured easily. Very probably, its precision for  ${}_{92}\text{U}$  is rather less than the 2 keV accuracy with which the mass of, e.g.,  ${}^{238}\text{U}$  is known.

The atomic masses are given in mass units and the derived quantities in energy units. The atomic mass unit is 1/12 of the mass of a  ${}^{12}\text{C}$  atom in its atomic and nuclear ground states. The energy unit is the electron-volt; to be exact: using the volt as *maintained* in standard laboratories (by using a standard value for the ratio of frequency and voltage in the Josephson effect).

## 2. New features

Recently [ 4], the choice of the conventional Josephson constant used in the definition of the energy unit was changed by 7 ppm. We have taken care that the input precision reaction and decay energies are recalibrated to the new unit (see ref. [ 5] and table A).

Of the other new features (for references see part IV) the most essentially new is the development by groups at Princeton, Seattle, Mainz, Tallinn, Moscow and very recently at MIT, Ohio and Stockholm of the measurement of cyclotron resonance frequency ratios of ions in a magnetic field (as done earlier by Lincoln Smith) but now using Penning traps. This way, extremely precise measurements could be made of some fundamental masses. As a result of this development, but also of the drastic improvement of (p, $\gamma$ ) and (n, $\gamma$ ) reaction energies, the atomic masses of atoms near the line of  $\beta$ -stability, for mass numbers up to 40, are in an extremely satisfactory shape (see figs. 2a-2b).

Far from stability, very important developments have occurred since our last evaluation. Following the pioneering work, in the 70's, of Klapisch and Thibault [ 8] on direct mass-measurements of radioactive species, several projects have given important results on nuclear masses for exotic species, extending thus significantly our knowledge of the mass-surface. Among these new projects, the Chalk-River on-line isotope separator and the on-line St Petersburg prism mass spectrometer exploit further the well-established technique, in mass-spectrometry, of voltage measurements, whereas in the others there is a striking evolution towards time and frequency

**Table A.** Constants used in this work or resulting from the present evaluation.

$1 \text{ u} = M_u$	=	$M(^{12}\text{C})/12$	=	atomic mass unit <sup>a)</sup>
$1 \text{ u}$	=	$1660540.2 \pm 1.0$	$\times 10^{-33}$	kg
$1 \text{ u}$	=	$931494.32 \pm 0.28$		keV
$1 \text{ u}$	=	$931493.86 \pm 0.07$		keV* <sup>b)</sup>
$1 \text{ MeV}^*$	=	$1073544.38 \pm 0.08$		nu
$M_e$	=	$548579.903 \pm 0.013$		nu
	=	$510999.06 \pm 0.15$		eV
$M_p$	=	$1007276466.6 \pm 0.6$		nu
$M_\alpha$	=	$4001506174.7 \pm 1.5$		nu
n-H	=	$839891.7 \pm 2.4$		nu
	=	$782353.9 \pm 2.3$		eV*
$^{35}\text{Cl}-^{37}\text{Cl}+2\text{u}$	=	$2950110 \pm 65$		nu
$S_{2n}(^{37}\text{Cl})$	=	$18890655 \pm 60$		eV*

- <sup>a)</sup> Due to the unfortunate acceptance of the mole as a unit rather than as a number, the dimension of the atomic mass unit is kg/mole.
- <sup>b)</sup> The ‘*maintained*’ volt, as defined by accepting the exact value 483597.9, given in the 1990 standard [ 6], for the constant ( $2e/h$ ) in the Josephson effect.

The symbols  $^{35}\text{Cl}$  and  $^{37}\text{Cl}$  in the last line but one of the table stand for their masses. The first seven items are derived from the work of Cohen and Taylor [ 7], except those which refer to eV\* energy units.

measurements. Time-of-flight experiments are characterized by exploration in extended regions far from  $\beta$ -stability, even for very short-lived species ( $1\mu s$ ), with fair to medium accuracies ( $3 \times 10^{-6}$  to  $5 \times 10^{-5}$ ). In a Penning trap on-line at ISOLDE, the cyclotron frequency of a radioactive ion is directly compared to that of a stable nucleus, and leads, as above for stable species, to a drastic improvement in accuracy (better than  $10^{-7}$ ) for not too short-lived radioactive nuclei (1 or 2 seconds were needed for interaction in the trap) up till quite far from the line of  $\beta$ -stability.

A considerable number of new  $\alpha$ - and  $\beta$ -decay energies of nuclides far from stability have also been measured and quite interestingly also several proton-decay energies. Unfortunately, the precision of the  $\beta$ -decay energies is often not as high as one should wish. Moreover, though  $\alpha$ -particle energies are quite satisfactory, the level fed in the final nuclide is most often not known; thus here some uncertainties remain. We have used study of systematic trends in mass values and derived quantities for finding out where such uncertainties were unacceptable. And in the case of the nuclei beyond  $A = 225$ , we have used the Nilsson model to get estimates for the energies of the final levels; which we think has caused a definite improvement in the estimates of the most heavy masses. A similar treatment for the region  $A = 146$ –190 has not yet been tried in view of the required vast investment in time.

Electron capture decay-energies are often most difficult to determine for proton-rich nuclides. Therefore some new reaction energies of the type of, e.g.,  $^{204}\text{Pb}(\alpha, ^8\text{He})^{200}\text{Pb}$  have been very welcome. Near the line of  $\beta$ -stability, it is worth mentioning the increasing number of measurements of reaction energy differences, which can often be determined with much higher precision than absolute reaction energies.

One new feature in the present evaluation is the calculation and use of the *flow-of-information* matrix defined recently by one of us and which is of general use in the least-squares method. This method was incomplete as used until then, in the sense that it didn't allow to *see*, except in simple cases, how information could flow from the experimental data (inputs) into the adjusted masses (outputs). In ref. [ 9] the "*influence*" of each piece of data on each of the adjusted masses, and also the total influence, or "*significance*", of one datum are defined and it is shown that the elements of the flow-of-information matrix are the above *influences* and that the sum of all elements in a line are the *significances*. Implemented in the calculation for the evaluation of masses, this matrix happens to be very useful. Therefore, as an additional help for the reader, we add now also, in part IV, a table of the most important data (and their relative *influence*) in the determination of the mass of each primary nucleus. The table of adjusted input data in part IV (table II) has also been extended to indicate for each datum its *significance* and the nucleus to which this piece of data contributes the most (main *influence*).

In previous tables, we gave estimates of extra unknown masses with the help of the property of regularity of the mass surface, but only as far as necessary to avoid blank spaces in tables like those in parts I and II of the present work, and the resulting missing points in the graphs of part III. On request from various sides, we

now estimate rather more values, particularly for several far from stability nuclei which have been identified in recent experiments. Also, a special effort was made in a far extrapolation to get an as good as possible estimate of the masses of neutron-rich nuclei up to  ${}^{78}\text{Ni}$ , in view of the large interest of projected experiments in this region, and also of theoretical astrophysical calculations [10]. For the latter, use was made of other works in progress [11] in which the concept of regularity is extended to define an *idealized* surface of masses (or “*mass-geoid*”).

Finally, element symbols Ns (Nielsbohrium), Hs (Hassium) and Mt (Meitnerium) have been proposed for elements 107, 108 and 109. We will use them here, though they have not yet been officially accepted. The same is true for the element symbols Rf and Ha for elements 104 and 105. For element 106 no name has yet been proposed; we will continue use of the provisional symbol Nh used already in our previous tables.

### 3. Use of input data

We retained the distinction between primary and secondary masses and input data [ 1]. Secondary masses are, essentially, determined by one type of input data as mentioned in Column 5 of the *Atomic mass table*. Thus, if new material is becoming available, such mass values can easily be updated. This is more complicated for primary data. (Originally, the difference was made in order to save computer time; this is now slightly less important.)

Penning trap measurements, just as earlier mass spectrometric ones, often give either data on essentially one nuclide (absolute mass doublets), or on the difference in mass of two nuclides with no or only slightly different mass number (relative mass doublets). All nuclear decay data and almost all nuclear reaction energy measurements are also relative measurements. Reaction energy differences are in principle represented by a combination of four masses. For completeness we mention that early mass spectrometric measurements on unstable nuclides can best be represented as linear combinations of masses of three isotopes, with non-integer coefficients [12]. The new Penning trap measurements are in most cases best represented as similar combinations of two masses.

As in our earlier work, we want to represent the input data in a graphical way (fig. 1). This is straightforward for the absolute mass-doublets and for the difference-for-two-nuclide data; but not for spectrometric triplets and for differences in reaction energies. The latter are in general more important for one of the two reaction energies than for the other one; in the graphs we therefore represent them simply by the former. (These data are primary even though the diagrams then show only one connection.)

## 4. Regularity of the mass-surface and use of systematic trends

A striking feature in the observation of the mass surface is its regularity, at least at first and all second orders derivatives, in all places where no physical effects are known to exist. Any deviation from this regularity could then be considered as a warning that either some new physical property is being discovered or that there might be some undetected systematic contribution to the reported result of an experiment. In cases where some experimental data on the mass of a particular nuclide disagree among each other, and no particular reason for rejecting one or some of them could be found from studying the involved papers, the measure of agreement with the just mentioned regularity has been used for selecting what we think to be the most dependable result, thus following the same policy as used in our earlier work.

However, a new policy has been adopted for those locally irregular masses which are derived from one, two or (in one case) three measurements of the same physical quantity, all diverging from the mentioned regularity and which were not confirmed by a different method. These data were in previous edition of the Mass-Tables replaced by ‘*values derived from trends in systematics*’. In order to achieve higher transparency in the evaluation of experimental masses, all experimental data for such cases, published in regular refereed journals, are used in the present compilation and evaluation (with only one exception). Consequently, the values, given here and in part II, do no more represent the “*best recommended values*” for the masses of these few nuclei (and for the differences in masses), but rather the values as derived from “*all experimental data*”.

Table B gives the 56 such cases involving 67 data and the values we recommend, based on the regularity of the mass surface. These cases are mentioned in part IV, in remarks added to the proper data, as being *suggested by systematical trends*. Changes in these data imply several more changes in the masses, due to connecting chains (see fig. 1). They are obtained by repeating our calculations with a data set modified according to table B. Table C lists the 99 nuclei (plus 14 isomeric states) involved and gives the experimentally determined masses (from calculation 1) together with the values we recommend (from calculation 2). To help the reader a flag is set in the atomic mass table for these nuclei. The plots displaying the surface of mass in part III of the present evaluation are drawn with both sets of values and allow the reader to check our judgment. As far as the errors on the estimates are concerned, we did not try everywhere to get an independent estimate for them.

Not all irregularities of the type above have been smoothened with *systematics*, but only some of the most striking ones, and those necessary to avoid, as much as possible, confusions in the plots in part III.

The lists in tables B and C as well as the other local irregularities that can be observed in the figures in part III could be considered as incentive to remeasure the masses of the involved nuclei, preferably by different methods, in order to remove any doubt and possibly point out true irregularities due to physical properties.

To summarize, in our new procedure, two series of tables are produced: the series of **“tables derived from all experimental data”** for masses (main table in this part) and for nuclear-reaction and separation energies (part II); and the series of **“tables of best recommended values”** that results from the data used for the preceding ones combined with table B. The latter series is not given in full here, it is used to derive the differences with the first one in table C (for the masses) and the plots in part III (for the separation and decay energies).

## 5. Overview of the results

Fig. 2 shows the difference between the absolute mass values in the 1983 and 1993 evaluations. The situation for the lightest nuclides ( $A < 17$ ) is amazingly satisfactory. The errors have been reduced by more than an order of magnitude; and the differences with the 1983 results are well within the then reported errors. The region  $A = 19$ –40 also shows a nice improvement: the errors have been reduced, in general, by about a factor 3, and with the exception of the  $A = 20$ –22 Ne isotopes and  $^{23}\text{Na}$  the differences with 1983 agree satisfactory with the reported errors. The Ne and Na differences are caused by the fact that the 1983 values for the neutron binding energy in  $^{22}\text{Ne}$  and the proton one in  $^{24}\text{Mg}$  were both 2 keV lower than the values measured, with high precision, in newer experiments; the new values yield quite satisfactory agreement with the new Penning trap measurement of  $^{20}\text{Ne}$ . In view of this situation, one must expect indeed that the *real* value of the atomic mass of the stable Si isotopes, of possible importance for the future definition of the mass unit, the kg, will certainly be to the  $3\sigma$  confidence level (99.7%) within  $0.6\mu\text{u}$  of the value reported here.

The precision of the mass values along the line of  $\beta$ -stability for  $A > 40$  did not improve drastically, as shown in fig. 2c. This observation hides the fact that differences in those mass values, especially neutron binding energies, are much more accurate than before. As apparent in fig. 2c, a progressive difference develops nearing mass number 200. It is caused by an 18 keV shift in the mass difference between  $^{228}\text{Th}$  and  $^{230}\text{Th}$  discovered recently. The resulting somewhat complex differences between 1983 and 1993 mass values for  $A > 200$  are discussed in part IV (see fig. 1 there). Beyond mass number  $A = 230$ , the mass differences along the line of  $\beta$ -stability are again only small. The change removes about one third of the difference with mass values for stable Hg isotopes as measured by an able and respected group of mass spectrometrists. They report a precision of about 1 keV, but the difference with the present mass values, with a reported precision of about 3 keV, is some 20

**Table D.** The most precise masses.

	Mass excess (keV)		Atomic mass ( $\mu$ u)	
<sup>1</sup> n	8071.3231	0.0022	1008664.9236	0.0023
<sup>1</sup> H	7288.96917	0.00077	1007825.03190	0.00057
<sup>2</sup> H	13135.7196	0.0011	2014101.77795	0.00062
<sup>3</sup> H	14949.7943	0.0017	3016049.2677	0.0014
<sup>3</sup> He	14931.2033	0.0016	3016029.3094	0.0012
<sup>4</sup> He	2424.9111	0.0014	4002603.2497	0.0015
<sup>13</sup> C	3125.0113	0.0046	13003354.8383	0.0049
<sup>14</sup> C	3019.8943	0.0040	14003241.9906	0.0042
<sup>14</sup> N	2863.4190	0.0017	14003074.0074	0.0018
<sup>16</sup> O	-4736.9981	0.0024	15994914.6223	0.0025
<sup>20</sup> Ne	-7041.9293	0.0028	19992440.1764	0.0030
<sup>40</sup> Ar	-35039.8895	0.0054	39962383.1235	0.0050

keV. It goes without saying that we have good reasons to trust the present mass values better than the mass spectrometric Hg values, as discussed in part IV. And fortunately, almost all differences in mass values of importance calculated from our work can be expected to be affected only little by this uncertainty. Yet, we consider solution of this problem the single most desired improvement for the future.

Fig. 2c shows that another curious difference is present between mass numbers 130 and 138. It is caused by the fact that the Penning trap measurements on the unstable Cs isotopes showed that the earlier accepted  $\beta$ -decay energies of <sup>130</sup>Cs and <sup>135</sup>Cs were rather less accurate than earlier assumed. This shows the great importance of this new type of measurements.

Due to the drastic increase in the precision of the mass values of the very light nuclei (fig. 2a), the printing format of the mass table was no more adequate. Table D gives, for the most precise among them, values of mass excesses and atomic masses. Conversion of the errors from  $\mu$ u to keV were obtained by:

$$\sigma_{M_{keV}}^2 = (\sigma_{M_u} \times u)^2 + (M_u \times \sigma_u)^2 \quad (2)$$

where  $M_u$  is the mass excess in  $\mu$ u.

## 6. General informations and acknowledgements

As in our previous evaluations, all the uncertainties in the present tables are one-standard deviation ( $1 \sigma$ ) errors.

The cut-off date of the data from literature used in the present tables is February 28, 1993. A few preprints and private communications received by the authors up



to March 31, 1993 have also been included. Final calculation was performed on June 30, 1993.

The table of masses (part I) and the table of nuclear reaction and separation energies (part II) are being made available electronically [13] at the nuclear data centers. A total of six files can be obtained. The first file with name **mass\_exp.mas93** contains the table of masses, as printed here. The next two files correspond to the table of reaction and separation energies in two parts of 6 entries each, as in part II: **rct1\_exp.mas93** for  $S_{2n}$ ,  $S_{2p}$ ,  $Q_\alpha$ ,  $Q_{2\beta}$ ,  $Q_{\epsilon p}$  and  $Q_{\beta n}$ , and **rct2\_exp.mas93** for  $S_n$ ,  $S_p$ ,  $Q_{4\beta}$ ,  $Q_{d,\alpha}$ ,  $Q_{p,\alpha}$  and  $Q_{n,\alpha}$ . The three last files with names **mass\_rmd.mas93**, **rct1\_rmd.mas93** and **rct2\_rmd.mas93** are identical to the first three ones except for the values resulting from the few experimental data, listed in table B, for which we recommend better values that we estimate from systematic trends.

Calculations are performed on the IBM 9021-820 computer of the Centre de Calcul de l'In2p3 (Lyon) to which we wish to express our gratitude, more particularly for their help in *vectorizing* our calculations (see part IV).

The help of the NNDC at Brookhaven laboratories, and more particularly of J.K. Tuli and M. Bhat, in trying to be complete in updating our files of input data and of references is highly appreciated. We are grateful to D. Polizzi for the high quality in the drawings of the connection diagrams, to M. Dziri for preparing the lay-out of the tables and to B. Wage at Elsevier for setting them up nicely. One of us (AHW) expresses his gratitude to the NIKHEF-K laboratory for the permission to use their facilities.

## References

- [ 1] A.H. Wapstra and G. Audi, Nucl. Phys. **A432** (1985) 1
- [ 2] A.H. Wapstra, G. Audi and R. Hoekstra, Nucl. Phys. **A432** (1985) 185
- [ 3] K.-N. Huang, M. Aoyagi, M.H. Chen, B. Crasemann and H. Mark, At. Nucl. Data Tables **18** (1976) 243
- [ 4] T.J. Quin, Metrologia **26** (1989) 69,  
B.N. Taylor and T.J. Witt, Metrologia **26** (1989) 47
- [ 5] A.H. Wapstra, Nucl. Instrum. Methods **A292** (1990) 671
- [ 6] B.N. Taylor and E.R. Cohen, J. Res. Natl. Inst. Stand. Technol. **95** (1990) 497
- [ 7] E.R. Cohen and B.N. Taylor, CODATA Bull. **63** (1986), Rev. Mod. Phys. **59** (1987) 1121
- [ 8] R. Klapisch, R. Prieels, C. Thibault, A.M. Poskanzer, C. Rigaud and E. Roeckl, Phys. Rev. Lett. **31** (1973) 118

- [ 9] G. Audi, W.G. Davies and G.E. Lee-Whiting, Nucl. Instrum. Methods **A249** (1986) 443
- [10] P. Haensel and B. Pichon, Astron. Astrophys. , accepted for publication
- [11] C. Borcea, G. Audi and J. Duflo, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues 1992, Inst. Phys. Conf. Series 132(1993)59;  
C. Borcea and G. Audi, Rev. Roum. Phys. **38** (1993) #45, to appear November 1993; CSNSM-9238 report, Orsay 1992.
- [12] G. Audi, M. Epherre, C. Thibault, A.H. Wapstra and K. Bos Nucl. Phys. **A378** (1982) 443
- [13] Description of the procedures for retrieving the 6 files can be obtained:  
for Western Europe and Japan, from NEA-DB, internet nea@nea.fr;  
for USA and Canada, from NNDC, internet nndc@bnlnd2.dne.bnl.gov;  
for other countries, from IAEA, Vienna; bitnet rnds@iaea1;  
or from internet audi@frcpn11.in2p3.fr

**Table B.** Experimental data that we recommend to replace by values following from the regular trends of the atomic masses.

Item	Reference <sup>a)</sup>	Experimental value		Recommended value	
<sup>35</sup> Mg-C <sub>2.917</sub>	91Or01	18669	1721	17490	470
<sup>53</sup> Sc-C <sub>4.417</sub>	90Tu01	-41440	260	-40760	320
	93Se.A	-41830	280		
<sup>55</sup> Sc-C <sub>4.583</sub>	90Tu01	-30600	1100	-32530	1100
<sup>57</sup> Ti-C <sub>4.75</sub>	90Tu01	-35700	1000	-36550	1000
<sup>66</sup> As( $\beta^+$ ) <sup>66</sup> Ge	79Da.A	9550	50	9800	200
<sup>70</sup> Br( $\beta^+$ ) <sup>70</sup> Se	79Da.A	9970	170	10350	300
<sup>71</sup> Se( $\beta^+$ ) <sup>71</sup> As	73Sc17	4428	125	4800	200
<sup>79</sup> Zn( $\beta^-$ ) <sup>79</sup> Ga	86Ek01	8550	240	9090	240
<sup>80</sup> Y( $\beta^+$ ) <sup>80</sup> Sr	81Li12	6952	152	9140	400
	82De36	6934	242		
<sup>88</sup> Nb( $\beta^+$ ) <sup>88</sup> Zr	84Ox01	7550	100	7200	200
<sup>90</sup> Tc( $\beta^+$ ) <sup>90</sup> Mo	74Ia01	8900	400	9140	300
	81Ox01	8870	300		
<sup>108</sup> Mo( $\beta^-$ ) <sup>108</sup> Tc	92Gr.A	5135	60	4635	60
<sup>109</sup> Tc( $\beta^-$ ) <sup>109</sup> Ru	89Gr23	6315	70	5985	70
<sup>110</sup> Sb( $\beta^+$ ) <sup>110</sup> Sn	72Mi26	8750	200	8300	200
	72Si28	9085	100		
<sup>111</sup> Sb( $\beta^+$ ) <sup>111</sup> Sn	72Si28	4470	50	5100	200
<sup>112</sup> Ru( $\beta^-$ ) <sup>112</sup> Rh	91Jo11	4520	80	3670	80
<sup>112</sup> Rh( $\beta^-$ ) <sup>112</sup> Pd	88Ay02	6200	500	6800	500
<sup>113</sup> Te( $\beta^+$ ) <sup>113</sup> Sb	74Bu21	5520	300	6100	200
	74Ch17	5720	200		
<sup>114</sup> Cs( $\epsilon$ p) <sup>113</sup> I	82Pl05	8730	150	9270	300
<sup>114</sup> Ru( $\beta^-$ ) <sup>114</sup> Rh	92Jo05	6100	200	4800	200
<sup>114</sup> Rh( $\beta^-$ ) <sup>114</sup> Pd	88Ay02	6500	500	7900	300
<sup>116</sup> Cs <sup>m</sup> ( $\epsilon$ p) <sup>115</sup> I	78Da07	6450	300	7180	300
<sup>116</sup> Rh( $\beta^-$ ) <sup>116</sup> Pd	88Ay02	8000	500	8900	500
<sup>116</sup> Xe( $\beta^+$ ) <sup>116</sup> I	76Go02	4340	200	4660	200
<sup>117</sup> Ba( $\epsilon$ p) <sup>116</sup> Xe	78Bo20	7900	300	8660	600
<sup>118</sup> Cs( $\epsilon\alpha$ ) <sup>114</sup> Te	76Jo.A	11100	500	11080	200
	77Bo28	10600	200		
<sup>129</sup> Ce( $\beta^+$ ) <sup>129</sup> La	93Al03	5600	200	5050	200
<sup>140</sup> Sm( $\epsilon$ ) <sup>140</sup> Pm	87De04	3400	300	3020	200
<sup>140</sup> Gd( $\beta^+$ ) <sup>140</sup> Eu	91Fi03	4800	400	5460	400
<sup>140</sup> Tb( $\beta^+$ ) <sup>140</sup> Gd	91Fi03	11300	800	10800	800
<sup>142</sup> Gd( $\beta^+$ ) <sup>142</sup> Eu	91Fi03	4200	300	4500	300
<sup>142</sup> Tb( $\beta^+$ ) <sup>142</sup> Gd	91Fi03	10400	700	10060	700
<sup>142</sup> Dy( $\beta^+$ ) <sup>142</sup> Tb	91Fi03	7100	200	6900	200
<sup>144</sup> Gd( $\beta^+$ ) <sup>144</sup> Eu	70Ar04	4300	400	3740	200
<sup>145</sup> Dy( $\beta^+$ ) <sup>145</sup> Tb	93Al03	7300	200	7720	200
<sup>149</sup> Er( $\epsilon$ p) <sup>148</sup> Dy	89Fi01	7080	470	6680	470
<sup>150</sup> Ho( $\beta^+$ ) <sup>150</sup> Dy	93Al03	6560	100	7240	100
<sup>156</sup> Ho( $\beta^+$ ) <sup>156</sup> Dy	76Gr20	4400	400	5060	200
<sup>156</sup> Er( $\beta^+$ ) <sup>156</sup> Ho	82Vy06	1670	70	1370	150

Item	Reference <sup>a)</sup>	Experimental value		Recommended value	
<sup>158</sup> Er( $\beta^+$ ) <sup>158</sup> Ho	61Bo24	1940	80	900	100
	68Ab18	1860	60		
	82Vy06	1710	40		
<sup>160</sup> Eu( $\beta^-$ ) <sup>160</sup> Gd	73Da05	3900	300	4580	200
	73Mo18	4200	200		
<sup>160</sup> Lu( $\beta^+$ ) <sup>160</sup> Yb	83Ge08	7210	240	7880	100
	93Al03	7300	100		
<sup>161</sup> Yb( $\beta^+$ ) <sup>161</sup> Tm	81Ad02	3850	250	4150	200
<sup>162</sup> Lu( $\beta^+$ ) <sup>162</sup> Yb	83Ge08	6740	270	7220	100
	93Al03	6960	100		
<sup>167</sup> W( $\beta^+$ ) <sup>167</sup> Ta	89Me02	5620	270	6240	300
<sup>173</sup> Ta( $\beta^+$ ) <sup>173</sup> Hf	73Re03	3670	200	2790	200
<sup>176</sup> Tm( $\beta^-$ ) <sup>176</sup> Yb	67Gu11	4200	200	3880	200
<sup>182</sup> Au( $\beta^+$ ) <sup>182</sup> Pt	72We.A	6850	200	7780	300
<sup>182</sup> Hg( $\beta^+$ ) <sup>182</sup> Au	72We.A	4950	200	4780	300
<sup>189</sup> Au( $\beta^+$ ) <sup>189</sup> Pt	75Un.A	3160	300	2850	200
<sup>189</sup> Hg( $\beta^+$ ) <sup>189</sup> Au	75Un.A	4200	200	3950	200
<sup>191</sup> Tl <sup>m</sup> ( $\beta^+$ ) <sup>191</sup> Hg	75Un.A	5140	200	4790	200
<sup>192</sup> Tl( $\beta^+$ ) <sup>192</sup> Hg	75Un.A	6380	200	6120	200
<sup>195</sup> Bi( $\beta^+$ ) <sup>195</sup> Pb	91Gr12	4850	550	5850	350
<sup>204</sup> Au( $\beta^-$ ) <sup>204</sup> Hg	67Wa23	4500	300	3800	200
<sup>224</sup> Fr <sup>x</sup> - <sup>228</sup> Fr. <sub>491</sub> <sup>220</sup> Fr. <sub>509</sub>	82Au01	-540	320	-970	200

<sup>a)</sup> References are listed in part IV.

**Table C.** Nuclides for which values derived from systematic trends are judged better than the experimental ones given in the mass table and derived from the experimental data in table B.

Nucleus	Mass excess		Recommended	
	from exp. data		Mass Excess	
<sup>35</sup> Mg	17390	1600	16290#	440
<sup>53</sup> Sc	-38770	180	-37970#	300
<sup>55</sup> Sc	-28500	1020	-30300#	1020
<sup>57</sup> Ti	-33250	930	-34050#	930
<sup>66</sup> As	-52070	60	-51820#	200
<sup>70</sup> Br	-51970#	270	-51590#	360
<sup>71</sup> Se	-63460	130	-63090#	200
<sup>79</sup> Zn	-53940	270	-53400#	270
<sup>80</sup> Y	-63360	130	-61160#	400
<sup>88</sup> Nb	-76080	100	-76420#	200
<sup>90</sup> Tc	-71290	240	-71030#	300
<sup>106</sup> Sb	-66890	170	-66350#	310
<sup>108</sup> Mo	-70800	140	-71300#	140
<sup>109</sup> Tc	-74540	100	-74870#	100
<sup>110</sup> Sb	-76820	90	-77530#	200
<sup>110</sup> I	-60890	170	-60350#	310
<sup>111</sup> Sb	-81470	50	-80840#	200
<sup>112</sup> Ru	-75620	510	-75870#	510
<sup>112</sup> Rh	-80140	500	-79540#	500
<sup>113</sup> Te	-78770	170	-78320#	200
<sup>114</sup> Ru	-70890	540	-70790#	360
<sup>114</sup> Rh	-76990	500	-75590#	300
<sup>114</sup> Te	-81520	190	-81930#	200
<sup>114</sup> Cs	-55110	160	-54560#	310
<sup>115</sup> I	-75670	500	-76400#	500
<sup>115</sup> Xe	-68030	230	-68440#	240
<sup>116</sup> Rh	-71950	500	-71050#	500
<sup>116</sup> Xe	-73230	250	-72910#	250
<sup>117</sup> Ba	-58040	390	-56960#	650
<sup>129</sup> Ce	-75750	210	-76300#	210
<sup>140</sup> Sm	-74990	300	-75370#	200
<sup>140</sup> Eu	-66590	500	-66970#	450
<sup>140</sup> Gd	-61790	640	-61510#	600
<sup>140</sup> Tb	-50490	1030	-50710#	1000
<sup>142</sup> Gd	-67430	320	-67130#	310
<sup>142</sup> Tb	-57030	770	-57070#	770
<sup>142</sup> Dy	-49930	790	-50170#	790
<sup>144</sup> Gd	-71350	400	-71910#	200

Nucleus	Mass excess		Recommended	
	from exp. data		Mass Excess	
<sup>145</sup> Dy	-59140	240	-58720#	240
<sup>149</sup> Er	-53540	470	-53940#	470
<sup>149</sup> Er <sup>m</sup>	-52800	470	-53200#	470
<sup>150</sup> Ho	-62760	100	-62080#	100
<sup>150</sup> Er	-58650	100	-57970#	100
<sup>151</sup> Yb	-42360	320	-41680#	320
<sup>154</sup> Tm	-55240	110	-54560#	110
<sup>154</sup> Yb	-50750	100	-50070#	100
<sup>156</sup> Ho	-66130	400	-65470#	200
<sup>156</sup> Er	-64460	410	-64100#	250
<sup>158</sup> Er	-64400	40	-65280#	100
<sup>158</sup> Tm	-57870	110	-58750#	140
<sup>158</sup> Lu	-48030	120	-47350#	120
<sup>158</sup> Hf	-42930	100	-42250#	100
<sup>160</sup> Eu	-63840	170	-63370#	200
<sup>160</sup> Lu	-50880#	230	-50280#	230
<sup>161</sup> Yb	-58190	270	-57890#	220
<sup>161</sup> Lu	-52890	280	-52590#	240
<sup>162</sup> Lu	-52920#	230	-52630#	230
<sup>162</sup> Ta	-40600	130	-39920#	130
<sup>162</sup> W	-34830	100	-34150#	100
<sup>166</sup> Re	-32530	140	-31850#	140
<sup>166</sup> Os	-26270	100	-25590#	100
<sup>167</sup> Ta	-47840#	420	-48460#	430
<sup>170</sup> W	-48000	350	-47240#	470
<sup>170</sup> Ir	-23940	150	-23260#	150
<sup>170</sup> Pt	-17140	100	-16460#	100
<sup>173</sup> Ta	-51610#	230	-52490#	220
<sup>173</sup> W	-47610#	380	-48490#	370
<sup>174</sup> Re	-44610#	350	-43680#	410
<sup>174</sup> Os	-40700	350	-39940#	470
<sup>174</sup> Au	-14730	150	-14050#	150
<sup>174</sup> Hg	-7500#	140	-6820#	140
<sup>176</sup> Tm	-49300	200	-49620#	200
<sup>178</sup> Ir	-37180	280	-36250#	360
<sup>178</sup> Pt	-32700	350	-31940#	470
<sup>178</sup> Tl	-5120#	210	-4440#	210
<sup>178</sup> Pb	2770#	210	3450#	210

Nucleus	Mass excess from exp. data		Recommended Mass Excess	
<sup>182</sup> Au	-29230	280	-28300#	360
<sup>182</sup> Hg	-24280	350	-23520#	470
<sup>186</sup> Tl	-20910	290	-19980#	360
<sup>186</sup> Tl <sup>m</sup>	-20810#	290	-19880#	370
<sup>186</sup> Tl <sup>n</sup>	-20440#	290	-19510#	370
<sup>186</sup> Pb	-15380	350	-14620#	470
<sup>189</sup> Au	-33330	300	-33630#	200
<sup>189</sup> Hg	-29130	360	-29680#	280
<sup>189</sup> Tl	-23950	410	-24510#	350
<sup>189</sup> Tl <sup>m</sup>	-23660	410	-24220#	350
<sup>190</sup> Bi	-11630	290	-10690#	360
<sup>190</sup> Bi <sup>m</sup>	-11420#	290	-10490#	370
<sup>190</sup> Po	-5320	350	-4560#	470
<sup>191</sup> Tl	-25840	220	-26190#	220
<sup>191</sup> Tl <sup>m</sup>	-25540	220	-25890#	220
<sup>192</sup> Hg	-32330#	720	-32070#	720
<sup>193</sup> Bi	-15220	410	-15780#	350
<sup>193</sup> Bi <sup>m</sup>	-14910	410	-15470#	350
<sup>194</sup> At	-1700#	350	-770#	420
<sup>194</sup> At <sup>m</sup>	-1640#	300	-710#	370
<sup>195</sup> Pb	-22430	590	-23780#	410
<sup>195</sup> Pb <sup>m</sup>	-22230	590	-23580#	410
<sup>195</sup> Bi	-17580	220	-17930#	220
<sup>195</sup> Bi <sup>m</sup>	-17180	220	-17530#	220
<sup>197</sup> At	-5690	420	-6250#	350
<sup>197</sup> At <sup>m</sup>	-5640	420	-6200#	350
<sup>199</sup> Po	-13930	590	-15280#	410
<sup>199</sup> Po <sup>m</sup>	-13620	590	-14970#	410
<sup>199</sup> At	-8380	220	-8730#	220
<sup>201</sup> Fr	4270	420	3710#	350
<sup>203</sup> Rn	-4880	590	-6230#	410
<sup>203</sup> Rn <sup>m</sup>	-4510	590	-5860#	410
<sup>203</sup> Fr	1330	230	980#	230
<sup>204</sup> Au	-20210	300	-20910#	200
<sup>207</sup> Ra	4820	590	3470#	410
<sup>207</sup> Ra <sup>m</sup>	5370	590	4020#	410
<sup>228</sup> Fr	32400	980	33270	420

**Figs. 1a–1h.** Diagram of connections for input data.

For *primary data* (those checked by other data, see part IV, sect. 3.2):

square	absolute mass-doublet nuclide (i.e. connected to $^{12}\text{C}$ , $^{35}\text{Cl}$ or $^{37}\text{Cl}$ ) or nuclide connected by a relative mass-doublet connection to a remote reference nuclide;
○	other primary nuclide;
dotted square, ⊙	primary nuclide with relevant isomer;
//	mass-spectrometric connection;
——	other primary reaction connection.

Primary connections are drawn with two different thicknesses. Thicker lines represent data of the highest precision in the given mass region (limits: 1 keV for  $A < 36$ , 2 keV for  $A = 36$  to 165 and 3 keV for  $A > 165$ )

For *secondary data* (cases where masses are known from one type of data and are therefore not checked by a different connection):

•	secondary nuclide determined from only experimental data;
*	secondary nuclide involving only experimental data and levels from Nilsson systematics;
○	nuclide for which mass is estimated from systematical trends;
-----	connection to a secondary nuclide. Note that an experimental connection may exist between two systematic nuclides when none of them is connected to the network of primaries.

**Fig. 2.** Differences between the mass values obtained in the 1993 and 1983 adjustments, for nuclides along the line of  $\beta$ -stability. The errors found in the 1983 evaluation are given by the lines symmetric around  $\delta = 0$ , the error bars refer to the 1993 adjustment.

2a. The fundamental nuclides with  $A < 17$ , differences in  $\mu\text{u}$ ;

2b. The region  $A = 19\text{--}40$ , differences in  $\mu\text{u}$ ;

2c. The region  $A = 40\text{--}200$  (odd mass number nuclides only), differences in keV; (for the region  $A > 200$  see part IV).



## Atomic mass table

### EXPLANATION OF TABLE

$N$	Number of neutrons.
$Z$	Number of protons.
$A$	Mass number $A = N + Z$ .
Elt.	Element symbol (for $Z > 103$ see sect. 2).
Orig.	Origin of values for secondary nuclides.
	$zpn$ : mass of ${}^A Z$ derived from mass of ${}^{A+Z+z}(Z+z)$ .

#### Special notations:

IT	when $z = 0, n = 0$ ;
+	when $z = +1, n = -1$ ;
-	when $z = -1, n = +1$ ;
++	when $z = +2, n = -2$ ;
ep	when $z = -2, n = +1$ ;
+ $\alpha$	when $z = +2, n = +2$ ;
x	for distant connection.

$S$	Flag (diamond) for nuclei for which masses estimated from systematical trends are thought better than the experimental masses.
Mass excess	<p>Mass excess <math>[M(\text{in u}) - A]</math>, in keV, and its one standard deviation error. In cases where the furthest-left significant digit in the error was larger than 3, values and errors were rounded off, but not to more than tens of keV. (Examples: <math>2345.67 \pm 2.78 \rightarrow 2345.7 \pm 2.8</math>, <math>2345.67 \pm 4.68 \rightarrow 2346 \pm 5</math>, but <math>2346.7 \pm 468.2 \rightarrow 2350 \pm 470</math>).</p> <p># in place of decimal point: values and errors estimated from systematic trends.</p> <p>* in place of decimal point: values and errors estimated with help of Nilsson model, for nuclei beyond <math>A = 235</math> (see sect. 2).</p>
Binding energy	<p>Total binding energy <math>[ZM({}^1\text{H}) + NM({}^1\text{n}) - m(A, Z)]</math> in keV and its one standard deviation error.</p> <p># or * in place of decimal point: see above.</p>
Beta-decay energy	<p>Direction of decay, value and standard error in keV:</p> <p style="padding-left: 2em;">for <math>\beta^-</math>, <math>Q^- = M(A, Z) - M(A, Z + 1)</math>;</p> <p style="padding-left: 2em;">for <math>\beta^+</math>, <math>Q^+ = M(A, Z) - M(A, Z - 1)</math>.</p> <p>For a few odd-odd nuclides near maximum <math>\beta</math>-stability decaying both <math>\beta^-</math> and <math>\beta^+</math>, the <math>Q^+</math> values are given as negative <math>Q^-</math> values for the preceding even-even isobar.</p>

\* in place of value: not calculable.  
# or \* in place of decimal point: see above.

Atomic mass

Atomic mass  $M$  and its one standard deviation error in  $\mu\text{u}$ .  
# or \* in place of decimal point: see above.

# THE 1993 ATOMIC MASS EVALUATION

## (II). Nuclear-reaction and separation energies

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**Abstract.** The present table gives values and their estimated precision for the separation energies and reaction energies for twelve carefully selected combinations of nuclides. This selection, together with the  $\beta$ -decay energies given in part I, yields all differences in masses between any pair of nuclei differing at most by 2 units in  $Z$  and  $N$ . These data are derived from a least-squares evaluation of all available experimental data. A method is indicated in which many more reaction energy values can be derived from the present table.

## Introduction

A least-squares adjustment of experimental data (reaction and decay energies and mass-spectrometric data) determining atomic masses of nuclides, as described in part IV of this series of papers, is not represented completely by the adjusted values of the input data given there and the resulting values of the atomic masses given in part I. A complete representation would require reproduction of a matrix of correlation coefficients. Since this matrix contains  $\frac{1}{2}N(N+1)$  elements in which  $N = 812$ , this is not very attractive.

**Table A.** Correlation matrix for the most precise very light nuclei (in squared nano atomic mass units).

n	H	D	<sup>3</sup> H	<sup>3</sup> He	<sup>4</sup> He
5.228697					
-0.225234	0.329531				
0.278575	0.103769	0.382684			
0.073315	0.003832	0.077134	1.862938		
0.046648	0.012823	0.059596	1.158685	1.519977	
-0.000091	0.000010	-0.000008	-0.000002	-0.000002	2.249887

The main use of the correlation matrix is in obtaining errors in linear combinations of atomic masses. In practice, the correlations are important only for combinations involving two neighbouring nuclides with small differences in mass number and particles such as n, p, d, t, <sup>3</sup>He and  $\alpha$ . Such combinations, consisting of various kinds of decay and binding energies of particles or groups of particles, are important for systematic studies of the nuclear energy surface and for Q-values of frequently studied reactions. As before [1], we present here a table of values for 12 such combinations and their standard errors.  $\beta$ -decay energies are given in part I.

With the help of the instructions given in the ‘Explanation of Table’, values for 28 additional reactions and their standard errors can be derived. The derived values will be correct, but in a few cases (of reactions on very light nuclei measured with extreme precision) the errors will be slightly larger than would follow from a calculation including correlations.

The precision (standard error) in the value of any combination of the most precise mass values, for very light nuclei, can be obtained with the help of the correlation coefficients given in table A. When doing this, one should calculate the values to which these errors belong from the mass values (in  $\mu$ u), and not from the mass-excesses (in keV), in the mass table of part I.

## References

- [1] A.H. Wapstra and G. Audi, Nucl. Phys. **A432** (1985) 55

## Table of nuclear-reaction and separation energies

### EXPLANATION OF TABLE

We present, for all nuclei for which such data can be derived, separation energies of particles or groups of particles and nuclear-reaction energies obtained as the following combinations of atomic masses (see accompanying diagram):

$Q(\beta^-)$	=	$M(A, Z) - M(A, Z + 1)$ (in part I)	(a)
$Q(2\beta^-)$	=	$M(A, Z) - M(A, Z + 2)$	(b)
$Q(4\beta^-)$	=	$M(A, Z) - M(A, Z + 4)$	(c)
$Q(\beta^-n)$	=	$M(A, Z) - M(A - 1, Z + 1) - n$	(d)
$S(n)$	=	- $M(A, Z) + M(A - 1, Z) + n$	(e)
$S(p)$	=	- $M(A, Z) + M(A - 1, Z - 1) + {}^1\text{H}$	(f)
$Q(\epsilon p)$	=	$M(A, Z) - M(A - 1, Z - 2) - {}^1\text{H}$	(g)
$S(2n)$	=	- $M(A, Z) + M(A - 2, Z) + 2n$	(h)
$Q(d, \alpha)$	=	$M(A, Z) - M(A - 2, Z - 1) - {}^2\text{H} - {}^4\text{He}$	(i)
$S(2p)$	=	- $M(A, Z) + M(A - 2, Z - 2) + 2{}^1\text{H}$	(j)
$Q(p, \alpha)$	=	$M(A, Z) - M(A - 3, Z - 1) - {}^4\text{He} + p$	(k)
$Q(n, \alpha)$	=	$M(A, Z) - M(A - 3, Z - 2) - {}^4\text{He} + n$	(l)
$Q(\alpha)$	=	$M(A, Z) - M(A - 4, Z - 2) - {}^4\text{He}$	(m)

$A$  Mass number.

Elt. Element symbol (for  $Z > 103$  see part I, sect. 2).

$Z$  Atomic number.

2224.57 0.04 2224.57  $\pm$  0.04 keV. The errors are derived from the adjusted masses and the correlation matrix. For the most precise very light nuclides the precisions are often better than 5 eV and could not be given conveniently in this table. In table A the correlation matrix for these nuclides allows easy derivation.

- \* in place of value: not calculable from the present input data.
- # in place of decimal point: values and errors estimated from systematic trends.
- \* in place of decimal point: values and errors estimated with help of Nilsson model, for nuclei beyond  $A = 235$  (see part I, sect. 2).

Other reaction energies can be derived from the given data with the help of the following relations:

$$\begin{aligned}
Q(\gamma, p) &= - S(p) \\
Q(\gamma, n) &= - S(n) \\
Q(\gamma, 2p) &= - S(2p) \\
Q(\gamma, pn) &= Q(d, \alpha) - 26071.1007 \pm 0.0033 \\
Q(\gamma, d) &= Q(d, \alpha) - 23846.5280 \pm 0.0025 \\
Q(\gamma, 2n) &= - S(2n) \\
Q(\gamma, t) &= Q(p, \alpha) - 19813.8523 \pm 0.0025 \\
Q(\gamma, {}^3\text{He}) &= Q(n, \alpha) - 20577.6153 \pm 0.0032 \\
Q(\gamma, \alpha) &= Q(\alpha)
\end{aligned}$$

$$\begin{aligned}
Q(p, n) &= Q(\beta) - 782.3539 \pm 0.0023 \\
Q(p, 2p) &= - S(p) \\
Q(p, pn) &= - S(n) \\
Q(p, d) &= - S(n) + 2224.5727 \pm 0.0020 \\
Q(p, 2n) &= Q(\beta^- n) - 782.3539 \pm 0.0023 \\
Q(p, t) &= - S(2n) + 8481.8211 \pm 0.0044 \\
Q(p, {}^3\text{He}) &= Q(d, \alpha) - 18353.0426 \pm 0.0024
\end{aligned}$$

$$\begin{aligned}
Q(n, 2p) &= Q(\epsilon p) + 782.3539 \pm 0.0023 \\
Q(n, np) &= - S(p) \\
Q(n, d) &= - S(p) + 2224.5727 \pm 0.0020 \\
Q(n, 2n) &= - S(n) \\
Q(n, t) &= Q(d, \alpha) - 17589.2796 \pm 0.0031 \\
Q(n, {}^3\text{He}) &= - S(2p) + 7718.0581 \pm 0.0025
\end{aligned}$$

$$\begin{aligned}
Q(d, pn) &= 0 - 2224.5727 \pm 0.0020 \\
Q(d, t) &= - S(n) + 6257.2484 \pm 0.0026 \\
Q(d, {}^3\text{He}) &= - S(p) + 5493.4854 \pm 0.0015
\end{aligned}$$

$$\begin{aligned}
Q({}^3\text{He}, t) &= Q(\beta^-) - 18.5910 \pm 0.0010 \\
Q({}^3\text{He}, \alpha) &= - S(n) + 20577.6153 \pm 0.0032
\end{aligned}$$

$$Q(t, \alpha) = - S(p) + 19813.8523 \pm 0.0025$$

# THE 1993 ATOMIC MASS EVALUATION

## (III). Separation and decay energies. Graphs of systematic trends

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**Abstract.** This third paper in a series of four presents graphs of: two neutron separation energies and  $\alpha$ -decay energies as a function of neutron number, two proton separation energies as a function of proton number and double  $\beta$ -decay energies as a function of mass number which are considered as the most illustrative ones for the systematic trends.

## Introduction

All the informations contained in the mass table (part I) and in the nuclear reaction and separation energy table (part II) can in principle be displayed in a plot of the binding energy or the mass versus  $Z$  and  $N$ . Such a plot, in which the binding energies vary rapidly, is complicated by the fact that there are four sheets, corresponding to the four possible combinations of parity for  $Z$  and  $N$ . These sheets are nearly parallel almost everywhere in this three dimensional space and

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have remarkably regular trends, as one may convince oneself by making various cuts (e.g.  $Z$  or  $N$  or  $A$  constant). Any derivative of the binding energies also define four sheets. In the present context, *derivative* means a specified difference between the masses of two nearby nuclei. They are also smooth and have the advantage of displaying much smaller variations. For a derivative specified in such a way that differences are between nuclides in the same mass sheet, the nearly parallelism of these leads to an (almost) unique surface for the derivative, allowing thus a single display. Therefore, in order to illustrate the systematic trends of the masses, four derivatives of this last type were chosen:

1. the two neutron separation energies versus  $N$ , with lines connecting the isotopes of a given element (figs. 1–8);
2. the two proton separation energies versus  $Z$ , with lines connecting the isotones (the same number of neutrons) (figs. 9–15);
3. the  $\alpha$ -decay energies versus  $N$ , with lines connecting the isotopes of a given element (figs. 16–23);
4. the double  $\beta$ -decay energies versus  $A$ , with lines connecting the isotopes and the isotones (figs. 24–32).

These graphs of systematic trends supersede earlier graphs [1].

Other various representations are possible (e.g. separately for odd and even nuclei: one neutron separation energies versus  $N$ , one proton separation energy versus  $Z$ ,  $\beta$ -decay energy versus  $A$ , etc...); they can all be built starting from the values in papers I and II of the present series.

Clearly showing the systematic trends, these graphs can be quite useful for checking the quality of any interpolation or extrapolation (if not too far) and generally is an excellent testground for theoretical mass models. When some masses in a defined region deviate from the systematic trends, almost always there is a serious physical cause behind, like a shell or subshell closure or onset of deformation. But, if only one mass presents a *pathologic* situation, violating the systematic trends, then one may seriously question the correctness of the related data. As already mentioned in the preceding two papers, the new policy regarding the so called *systematics* is that those locally *irregular* masses which are derived from one, two or (in one case) three measurements of the same physical quantity are preserved in the tables as such. There are 56 such physical quantities that were selected partly in order to avoid too strongly oscillating plots. Taking into account the connections (see part I, figs. 1a–1h) has the consequence that 99 ground-state masses are concerned (and twice as many values in each type of plot). The recommended values for these masses are given in an additional table (table C in part I). It should be stressed that these are only the most striking cases and that not all irregularities have been removed here. In particular, as happened previously, the plots of  $\alpha$ -decay energies of light



nuclei exhibit many overlaps and crossings that obscure the drawings; no attempt was made to locate possible origins of such irregularities. Work is in progress [2] for constructing an *idealized* surface of masses from the point of view of its regular character. Such a surface can be useful in order to single out the regions presenting an *anomaly*, in other words, a specific local physical effect. It can be very useful also for making extrapolations and it can help improving the existing models since the experimental *noise* will be much reduced.

In cases where the experimental mass values were replaced, the graphs connect with dashed lines the values of decay and separation energies given in part II. With solid lines are connected the *regularized* values and unreplaced ones.

The replaced values for data, masses and reaction and separation energies have been derived by observing the continuity property not only in the four representations given here but also several other possible representations, using a special graphic program [2] that takes also into account the consequences of a mass change due to its decay chains and also consulting the predictions of all existing models. Therefore they are the best estimates such a procedure can yield.

## References

- [1] K. Bos, G. Audi and A.H. Wapstra, Nucl. Phys. **A432** (1985) 140
- [2] C. Borcea, G. Audi and J. Duflo, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues 1992, Inst. Phys. Conf. Series 132(1993)59;  
C. Borcea and G. Audi, Rev. Roum. Phys. **38** (1993) #45, to appear November 1993; CSNSM-9238 report, Orsay 1992.

## Figures

Figs. 1–8.  $2n$  separation energies.

Figs. 9–15.  $2p$  separation energies.

Figs. 16–23.  $\alpha$ -decay energies.

Figs. 24–32.  $\beta\beta$ -decay energies.

Mass numbers and element symbol are indicated only along the borders of the graphs; those for the intermediate points must be derived by enumeration. Open circles represent values estimated from systematic trends; points, experimental values. Lines connect points for isotopes ( $S_{2n}, Q_\alpha, Q_{\beta\beta}$ ) or isotones ( $S_{2p}, Q_{\beta\beta}$ ). Nuclides, for which the recommended value is different from the experimental one (see part I, sect. 4 and tables B and C there), are represented twice: with solid line and without symbol for the recommended value; with dotted line and with appropriate symbol for the experimental one. Where relevant, nuclidic name is given only besides the solid line. Other nuclides are connected with solid lines. In fig. 1, the  $S_{2n}({}^5\text{He})$  point has been omitted for drawing purposes.

# THE 1993 ATOMIC MASS EVALUATION

## (IV). Evaluation of input data, adjustment procedures

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**Abstract.** This last paper in a series of four describes the philosophy and procedures in selecting nuclear-reaction and decay data and mass spectrometric results as input values in a least-squares evaluation of best values for atomic masses. All accepted data, and rejected ones with a reported precision still of interest, are presented in a table and compared there with the adjusted values. Significances and influences of all primary data are also given.

## 1. Introduction

Since the calculation end 1983 of our earlier table of atomic masses [ 1, 2], an uncommonly large number of quite important new data has become available. In fact, as much as 28% of the data used in the present calculation were not used in the previous one.

Only one group [ 3] is still making measurements of stable nuclei with a conventional mass spectrometer. But the new technique of measuring cyclotron resonances of

ions captured in Penning traps [ 4] has resulted, in the first place, in extremely precise measurements of fundamental atoms like the  $A = 1-3$  hydrogen isotopes, the  $A = 3$  and 4 helium ones, and those of  $^{13}\text{C}$ ,  $^{14}\text{N}$ ,  $^{16}\text{O}$ ,  $^{20}\text{Ne}$  and  $^{40}\text{Ar}$ .

A large number of neutron capture  $\gamma$ -ray energies, and therefore neutron separation energies are now known with high precision, strengthening thus the backbone [ 5]. For comparison the number of couple of nuclides connected by  $(n,\gamma)$  reactions with an accuracy of 0.5 keV or better is 198 against 143 in the 1983 evaluation and 60 in the 1977 one. The number of cases known to better than 0.1 keV is presently 62 against 34 in 1983. Also, several reaction energies of  $(p,\gamma)$  reactions are known about as precisely (26 and 8 cases with accuracies better than 0.5 keV and 0.1 keV respectively). In fact, the precision is so high that we were forced to correct for the recent 7 ppm change in the definition of the energy unit and to harmonize the calibrations (see sect. 2). Several  $\alpha$ -particle energies are also known with comparable precision; and here too it was found necessary to harmonize the calibrations.

Another feature near the line of stability is the increased number of measurements of reaction energy differences, which can often be measured with rather higher precision than the absolute reaction energies. In view of this fact, our computer program has been modified to accept this kind of inputs; they are therefore now given as such in the present table of input data (table II). This new feature might be another incentive for giving *primary* results in publications: in later evaluations the results will be corrected automatically if calibration values change, due to new work.

A considerable extension of our knowledge of light ( $A < 70$ ) very neutron-rich nuclides was obtained by the new method of measuring masses of undecelerated products of reactions in thin bombarded targets by a combination of magnetic deflection and time of flight measurements.

Another extremely important development further away from the line of  $\beta$ -stability concerns a version of the Penning trap technique to even rather short-lived (few seconds) isotopes of some alkali and nearby elements [ 6]. It is to be hoped that this technique will be used in future for many more elements. A different approach has been made recently [92Ge08] in storing, cooling and measuring the frequency of a circulating beam of unstable species in a storage ring (ESR at GSI), but the precision in this first experiment is not yet sufficient for our evaluation. For the near future it worth mentioning the efforts being put for direct mass measurements of unstable nuclei in new technical developments, like time-of-flight measurements in the ESR at GSI or in the second cyclotron CSS2 at GANIL, and frequency measurements with the Smith's type mass spectrometer [ 7] that was built in Orsay.

Also, a great number of  $\beta$ - and  $\alpha$ -decay energies was measured, further away from stability. We have checked them by comparison with systematic trends, using both a new technique of studying the systematics of the mass differences between actually known masses and a suitably chosen mass formula [ 8], and a computerized

version [ 9] allowing simultaneous consideration of, e.g.  $\alpha$ - and  $\beta\beta$ -decay energies, 2-neutron separation energies and a difference between experimental masses and any of 16 mass-model calculations.

One of us [10] has investigated the possibility of using data on isobaric analogues of nuclear ground-states in order to find mass values for nuclides for which direct data were unprecise, or unavailable. For reasons discussed below, no such results have been included here.

Two possibly promising new developments may be mentioned here. Reaction energies have been measured of single proton and  $\alpha$ -decay following fusion of the heavy nuclei  $^{90}\text{Zr}$  and  $^{89}\text{Y}$  [91Br17], yielding information on the rather proton-rich nuclides  $^{178}\text{Pt}$  and  $^{175}\text{Ir}$ . The results are given in table II; but their precision is not yet interesting for our purpose. And some nuclides have been found to decay by cluster radioactivity, that is emission of nuclei such as  $^{13}\text{C}$  [11]. But the measurement on these weak processes, requiring thick sources and therefore hindered by absorption, are rather less accurate than already available information.

Another interesting feature is the very precise value for the electron capture decay energy of  $^{163}\text{Ho}$  calculated from the decay rate of the inverse desintegration. Fully ionized  $^{163}\text{Dy}^{66+}$  ions (*bare nuclei*) are capable of decaying into  $^{163}\text{Ho}^{66+}$  ions with one electron in the *K*- or (rarely) the *L*-shell. By collecting such nuclei in a storage ring and removing the Ho ones, after some time, by ionizing them further (see [92Ju01]), the decay rate can be determined. The possible number of applications of this method is evidently limited. Another example might be  $^{205}\text{Pb}(\epsilon)^{205}\text{Tl}$ , which is of possible use for measuring the intensity of long term (millions of years) neutrino irradiation of Tl ores by the sun or possibly other astronomical objects. It may be mentioned that this was the reason for measuring a number of accurate reaction energies in this region (see [90Li40]).

The development of cryogenic calorimeters opened the way for measuring low energy electrons or gamma rays with high resolution and accuracy. The method is, probably, of limited use for our purpose. Yet, it allowed a precise determination of the very low  $\beta$ -decay energy of  $^{187}\text{Re}$  [92Co23].

As in the preceding evaluation, we include reaction data on isomers. We exclude those cases where only  $\gamma$ -ray energy measurements are available. Excitation energies from such  $\gamma$ -ray measurements (normally far more precise than the reaction energy measurements), where important for use in connection with the reaction data, are taken from Nuclear Data Sheet except in cases where newer, important values are available. Table III lists the isomers used in the present evaluation, with proper identification from half-lives, spins and parity, and gives the excitation energies as used in, or resulting from the present adjustment.

**Table A.** Definition of used Volt units, and resulting mass-energy conversion constants.

$2e/h$		u	
1983	483594.21(1.34)	GHz/V	931501.2 (2.6) keV
1983	483594 (exact)	GHz/V <sup>®</sup>	931501.6 (0.3) keV <sup>®</sup>
1986	483597.67(0.14)	GHz/V	931494.32 (0.28) keV
1990	483597.9 (exact)	GHz/V*	931493.86 (0.07) keV*

## 2. Units; recalibration of $\alpha$ - and $\gamma$ -ray energies

Two units are used in the present work. The mass unit is defined by  $1u = M(^{12}\text{C})/12$ ,  $M$  being the mass of one free atom in its atomic and nuclear ground states. The energy unit is the electronvolt. The choice of the volt in this unit is not evident. One might expect use of the *international* volt V, but one can also choose the volt V<sup>®</sup> (our notation) as *maintained* in standard laboratories and defined by adopting a value for the constant ( $2e/h$ ) in the relation between frequency and voltage in the Josephson effect. An analysis by Cohen and Wapstra [12] shows that all precision measurements of reaction and decay energies are calibrated in such a way that they can be more accurately expressed in the second type of volt. Also, the precision of the conversion factor between mass units and *maintained* volts is more accurate than that between it and *international* volts (see table A). Thus, already in our previous mass evaluation we decided to use a *maintained* volt.

The new evaluation of Taylor and Cohen [13] showed that the empirical ratio between the two types of volts, which had of course been selected to be nearly equal to 1, had changed by as much as 7 ppm. For this reason, in 1990 a new value was chosen [14] to define the *maintained* volt (which we here indicate V\*). The defining value, and the resulting mass-energy conversion factor are given in table A; the conversion coefficient we actually use in this evaluation is V\*, the *maintained* 1990 one.

The difference between the *maintained* eV\* and the *international* eV (0.5 ppm) is almost negligible for the measured reaction energies (the accuracy of the most precise among them is a few ppm, with as only exception the 1 ppm precision  $^1\text{H}(n,\gamma)^2\text{H}$  reaction). In fact, the difference is less than shown here, since new measurements indicated that the 1986 value for the conversion constant to *international* eV was a little high [15] and resulted in a slightly lower value for the 1990 definition.

As said, the earlier precision reaction energy measurements were essentially expressed in keV<sup>®</sup> rather than in keV. The precision of some of them is not much worse than the 7 ppm change. Also, we must take into account that the use of the voltage definition causes a systematic error, as is most clear from the occurrence of chains of  $\alpha$ -decays. We were therefore obliged to have the precision data adjusted

to the new keV\* standard. For  $\alpha$ -particle energies, Rytz [16] has taken this change into account in updating his earlier evaluation of  $\alpha$ -particle energies. We have used his values in our input data table (table II) and indicated this by adding in the reference-field the symbol “Z”.

Then, also a considerable number of (n, $\gamma$ ) and (p, $\gamma$ ) reactions has a precision not much worse than the 7ppm mentioned. One of us [17] has discussed the necessary recalibration for several  $\gamma$ -rays often used for calibration. In the input data table we present many reaction energies for (n, $\gamma$ ) reactions that have been revised with help of these results. As in the case of Rytz’ recalibrations, they are marked by “Z” behind the reference key-number; or, if this was made impossible since this position was used to indicate that a remark was added, by the same symbol added to the error value mentioned in the remark.

For proton resonance energy measurements in (p, $\gamma$ ) reactions, the main calibration item is the 992 keV resonance in the  $^{27}\text{Al}+\text{p}$  reaction. The value most used in earlier work is 991.88(.04) keV of Roush *et al.* [18]. Endt *et al.* [19] recently averaged it with a later result by Stoker *et al.* [20] to get a slightly modified value 991.858(0.025) keV. In doing this, the changes in the values of natural constants used in the derivation of these values was not taken into account. Correcting for this omission, and critically evaluating earlier data, one of us [21] derived a value 991.843(.033) keV for this standard. The proton resonance energies reported in precision (p, $\gamma$ ) reactions have been recalibrated, where necessary, using this standard. In the accompanying tables, the resulting excitation energies of these resonances have been mentioned only in exceptional cases, e.g. for the  $^{28}\text{Si}^r$  resonance following from the above mentioned calibration item.

For each of the data mentioned, the changes are relatively minor. We judge it necessary to make them, however, since otherwise they add up to systematic errors that are non-negligible.

### 3. Calculation Procedures

We refer to sections 2 and 3 of our preceding publication [ 2] for further details and reasons, but mention here some policies and procedures that may be of interest for use of the present tables.

#### 3.1. Used policies in treating data

In averaging  $\beta$ - (or  $\alpha$ -) decay energies derived from branches, found in the same experiment, to or from different levels in the decay of a given nuclide, the error we use for the average is not the one resulting from the least-squares, but the smallest

occurring one.

Some quantities have been reported more than once by the same group. If the results are obtained by the same method and all published in regular refereed journals, only the most recent one is used in the calculation, unless explicitly mentioned otherwise. The reason is that one is inclined to expect that authors who believe their two results are of the same quality would have averaged them in their latest publication. Our policy is different if the newer result is not published in a regular refereed paper (abstract, preprint, private communication, conference, thesis or annual report), then the older one is used in the calculation, except if the newer is an update of the values in the other. In the later case the original reference in our list mentions the unrefereed paper.

In two cases,  $^{100}\text{Sn}$  and  $^{146}\text{Tb}^m$ , we accepted, and treated as systematics, estimates made by other authors for the  $\beta$ -decay energy of the first one and the internal transition energy of the second. They are labelled S in table II.

The important interdependence of most data, as illustrated by the connection diagrams (see part I figs. 1a–1h) allows local and general consistency tests. These can indicate that something may be wrong with input values. We follow the policy of checking all significant data differing by more than two (sometimes 1.5) standard deviations from the adjusted values. Fairly often, study of the experimental paper shows that a correction is necessary. Possible reasons are that a transition has been assigned to a wrong final level or that a reported decay energy belongs to an isomer rather than to a ground state or even that the mass number assigned to a decay has been shown to be incorrect. In such cases, the values are corrected and remarks are added below the corresponding data in table II to explain the reasons for the corrections.

It can also happen, though, that study of the paper leads to serious doubts about the validity of the results within the reported error, but could not permit making a specific correction. In that case, the result is labelled F and not used in the adjustment. It is however given in table II and compared to the adjusted value. The reader might observe that, in several cases, the difference between the experimental value and the adjusted one is small compared to the experimental error: this does not disprove the correctness of the label F assignment.

Cases where reading the paper does not lead to correction or rejection, but yet the result is not trusted within the given error, are labelled B, if published in a regular refereed journal or C otherwise.

In some cases thorough analysis of strongly conflicting data could not lead to reasons to think that one of them is more dependable than the others or could not lead to the rejection of a particular piece of data. Also, bad agreement with other data is not the only reason for doubt in the correctness of reported data. As in previous work, we made use of the property of regularity of the surface of masses for helping making



a choice and also for making further checks on the other data. For this purpose, graphs like those in part III of the present series of papers are used. But they give only differences for one of the four sheets of the mass surface (e-e, e-o, o-e and e-e; in a plot of mass against  $N$ ,  $Z$  or  $A$ ; e-o standing for even  $Z$  and odd  $N$ ). This may lead to a divergence between these sheets. One of us [ 8] therefore introduced the possibility of scrutinizing the differences of the masses with a suitably chosen mass formula, in which for pairing energies the values suggested by Jensen *et al.* [22] were used (it is recognized that this pairing formula is probably not generally valid; in fact a recent investigation [ 8, 23] suggests that the  $I = (N - Z)$  dependence may be exaggerated in it). Extending this possibility a program [ 9] was developed allowing simultaneous observation of four graphs of any of the quantities above, plus the one-neutron and one-proton separation and single- $\beta$  decay energies, allowing thus to connect the four sheets, and also of the difference between experimental masses and the result of any of some 16 nuclear mass-models, as a function of any of the variables  $N$ ,  $Z$ ,  $A$ ,  $N - Z$  or  $2Z - N$ . This program allows to test any modification of value in any of the four graph plots and to observe the corresponding changes in the other three, plus all the consequences due to connections to masses in the same chain. With this graphical tool, the results of such analysis are felt safer; and also the estimation of unknown masses are felt more reliable (see also part I sect. 4, and part III).

The above analysis could again lead to F, B or C assignments. Data with these labels are not used in the calculation. But, otherwise than in our earlier work, we have not assigned such labels if, as a result, no experimental value published in a regular refereed journal could be given for one or more resulting masses. In the present evaluation 56 such data occur, all of them of course resulting in secondary mass values. They are indicated in table II in remarks giving the changes “*suggested by systematical trends*”. They are also listed in table B of part I. However, even here, we did not accept experimental results if informations on other quantities (e.g. half-lives), derived in the same experiment and for the same nuclide, were in strong contradiction with well established values. This happens for example for the  $\beta$ -decay of  $^{70}\text{Se}$ , for which a half-life of  $20 \pm 2$  min is reported, whereas a value of  $41.1 \pm 0.3$  min is evaluated in Nuclear Data Sheets. This piece of data is labelled F and the mass of  $^{70}\text{Se}$  is estimated from the systematical trends.

One consequence of this new policy is that label D (see [ 2], sect. 3) is no more used in the present evaluation.

### 3.2. Compacting the set of data

The equations representing the input data can be separated in primary and secondary ones. For primary ones the least-squares calculation gives an improved output. Secondary ones remain unchanged; they do not contribute to  $\chi^2$ . This also means that they can easily be replaced by new information becoming available

(but one has to watch that the replacement can change other secondary masses; this can be seen from the diagrams fig. 1 in part I). Degree of secondary masses or secondary data reflect their distances along the chains connecting them to the network of primaries, they range from 2 to 13. Degree 1 is for primary masses and data. In the main table in part I, each secondary nuclide is marked with a label indicating from which other nuclide its mass value is calculated. In table II, the degree of data is indicated in column ‘Dg’.

Reaction data occur that give essentially values for the mass difference between the same two nuclides, except in the rare cases where the precision is comparable to the precision in the masses of the reaction particles. Example:  $G(n,\gamma)H$ ,  $H(d,t)G$ ,  $G(d,p)H$ ,  $H(^3\text{He},\alpha)G$ . Such data are represented together, in the main least-squares calculation, by an average value for one of them (pre-averaging). If the consistency factor (or Birge ratio)  $B = \sqrt{\chi^2/(N - n)}$  resulting in the calculation of this average is greater than 2.5, the (internal) error  $R_i$  in the average is multiplied with the Birge ratio ( $R_e = R_i \times B$ ). However, this treatment is not used in cases where the errors in the values to be averaged differ too much from one another. In such cases, considering policies from the Particle Data Group [24] and some possibilities reviewed by Rajput and MacMahon [25], we adopted an arithmetic average and the dispersion of values as error (three  $\beta$ -decays are concerned, those of:  $^{35}\text{S}$ ,  $^{91}\text{Sr}$  and  $^{184}\text{Ir}$  and also the non-used electron capture decay of  $^{207}\text{Bi}$ ). High values of  $B$  occur only in 14 out of the 929 pre-averaged cases (table B). As much as 28% of the 929 cases had a Birge ratio beyond unity, 4.5% beyond two, 0.7% beyond 3 and only one case beyond 4, giving an overall very satisfactory distribution for our treatment. As a matter of fact, in a complex system like the one here, many values of  $B$  beyond 1 or 2 are expected to exist, and if errors were multiplied by  $B$  in all these cases, the  $\chi^2$ -test on the total adjustment would have been invalidated. This explains the choice we made here of a rather high threshold ( $B = 2.5$ ), compared e.g. to  $B = 2$  recommended by Woods and Munster [26] or  $B = 1$  used in a different context by the Particle Data Group [24], for departing from the rule of internal error of the weighted average (see also [27]).

Large contributions to  $\chi^2$  have been known to be caused by a nuclide  $G$  connected to two other ones  $H$  and  $K$  by reaction links with errors large compared to the error in the mass difference of  $H$  and  $K$ , in cases where the two disagreed. Evidently, contributions to  $\chi^2$  of such local discrepancies suggest a not realistic too large value of the overall consistency parameter. This is avoided by a replacement procedure: one of the two links is replaced by an equivalent value for the other. The pre-averaging procedure then takes care both of giving the most reasonable mass value for  $G$ , and of not causing undesirably large contributions to  $\chi^2$ .

Similar replacements are made in several cases where reactions to isomers would otherwise make upper isomers (not mentioned in the main table of part I) primary and the corresponding ground states secondary. It must be mentioned that in a few cases this was found impractical, as can be seen in the table of isomers (table III).

**Table B.** Worst pre-averagings.  $n$  is the number of data in the pre-average.

Reaction or Decay	$n$	Birge Ratio	Accuracy
$^{113}\text{Cs}(p)^{112}\text{Xe}$	2	4.22	14
$^{115}\text{Cd}(\beta^-)^{115}\text{In}$	3	3.61	6.5
$^{99}\text{Ru}(n,\gamma)^{100}\text{Ru}$	2	3.58	0.15
$^{149}\text{Pm}(\beta^-)^{149}\text{Sm}$	2	3.54	5.4
$^{35}\text{S}(\beta^-)^{35}\text{Cl}$	*	3.45	0.12
$^{176}\text{Lu}(n,\gamma)^{177}\text{Lu}$	2	3.20	0.8
$^{99}\text{Sr}(\beta^-)^{99}\text{Y}$	2	3.01	177
$^{91}\text{Sr}(\beta^-)^{91}\text{Y}$	*	2.95	7.7
$^{85}\text{Y}(\beta^+)^{85}\text{Sr}$	2	2.82	27
$^{30}\text{Si}(t,p)^{32}\text{Si}$	2	2.82	2.3
$^{114}\text{Sb}(\beta^+)^{114}\text{Sn}$	2	2.78	216
$^{242}\text{Am}(\alpha)^{238}\text{Np}$	2	2.76	1.3
$^{68}\text{Cu}(\beta^-)^{68}\text{Zn}$	3	2.57	49
$^{76}\text{Ge}(^{14}\text{C}, ^{16}\text{O})^{74}\text{Zn}$	2	2.55	51

\* arithmetic average and dispersion of values are being used in the adjustment.

Another feature to increase the meaning of the final  $\chi^2$  is, that data with weights at least a factor 10 less than other data, or than combinations of other data giving the same result, have not been included, generally speaking, in the calculation. They are given in the list of input data (except for older data of this type that already appeared in our previous tables), but labelled U; comparison with the output values allows to check our judgment. We introduced a slight change of policy in this respect. Earlier, data were labelled U if their weight was 10 times less than that of a *simple* combination of other data. In the present evaluation, this concept is being extended to data that weigh 10 times less than the combination of *all* other accepted data. This new procedure although largely used here is not yet completely generalized.

### 3.3. Least-squares method: recall and notations

Each piece of data has a value  $l_i \pm dl_i$  with the accuracy  $dl_i$  (one standard deviation) and makes a relation between 2, 3 or 4 masses with unknown values  $m_\lambda$ . An overdetermined system of  $M$  data to  $N$  masses ( $M > N$ ) can be represented by a system of  $M$  linear equations with  $N$  parameters:

$$\sum_{\lambda} k_i^{\lambda} m_{\lambda} = l_i \pm dl_i \quad (3)$$

or, in matrix notation,  $\mathbf{K}$  being the matrix of coefficients:  $\mathbf{K}|m\rangle = |l\rangle$ . A diagonal weight matrix  $\mathbf{W}$  can be defined by its elements  $w_{ii} = 1/(dl_i dl_i)$ . The solution of

the least-squares method leads to a very simple construction:

$${}^t\mathbf{KWK}|m \rangle = {}^t\mathbf{KW}|l \rangle \quad (4)$$

the normal matrix  $\mathbf{A} = {}^t\mathbf{KWK}$  is a square matrix of order  $N$ , positive-definite, symmetric and regular and hence invertible [28]. Thus:

$$|m \rangle = \mathbf{A}^{-1} {}^t\mathbf{KW}|l \rangle \quad \text{or} \quad |m \rangle = \mathbf{R}|l \rangle \quad (5)$$

The rectangular  $(N, M)$  matrix  $\mathbf{R}$  is called the ‘response’ matrix.

### 3.4. The computer program in the evaluation of masses

Our computer program in 4 phases has to do the following tasks: **i)** decode and check the data file; **ii)** build up a representation of the connections between masses, allowing thus to separate primary masses and data from secondary ones and then to reduce drastically the size of the system of equations to be solved (see sect. 3.2), without any loss of information; **iii)** perform the least-squares matrix calculations (see above) and **iv)** deduce the atomic masses (part I), the nuclear reaction and separation energies (part II), the adjusted values for the input data (table II), the *influences* of data on the primary masses described in next section and given in tables I and II, and display information on the inversion errors, the correlations coefficients (see e.g. part II, table A), the values of the  $\chi^2$ s and the distribution of the  $v/s$  (see below), etc...

An important new feature in the calculation itself worth to be mentioned, the conversion of large parts of the programs of the evaluation for parallel processing. This, together with built-in modules for matrix operations, resulted in much faster (12 times faster) calculation, allowing thus more frequent full calculations, which is highly appreciated in the evaluation.

### 3.5. Results of the calculation

In this evaluation we have 5220 experimental data of which 660 are labelled U (see above) and 186 are not accepted and labelled B, C or F (respectively 101, 27 and 58 items). In the calculation we have thus 4374 valid input data, compressed to 3051 in the pre-averaging procedure. To these are added 601 data estimated from systematic trends, some of which are essential for linking unconnected experimental data to the network of experimentally known masses (see figs. 1a–1h, in part I). The total number of evaluated masses (including 368 mass values for isomeric states) is 3018, giving thus a system of 3652 equations with 3017 parameters ( $^{12}\text{C}$  not included). Separating data and masses in primary and secondary as described above, reduces the system to 1447 primary equations with 812 parameters, and leaves 2205 secondary equations to determine the 2205 secondary masses. In total we evaluate

the masses of 1920 ground state masses and estimate those of 730 other nuclei. The total  $\chi^2$  is 878 compared to an expectation value  $635 \pm 36$ ; this means that, in the average, the errors in the input values have been underestimated by 18%, a rather acceptable result. The distribution of the  $v/s$  (the individual contributions to  $\chi^2$ , see table II) is also quite acceptable, with 17% of the cases beyond unity, 2.6% beyond two, 0.4% beyond 3 and only one case (.07%) beyond 4.

As in the preceding work [ 2], we have tried to estimate the average accuracy of groups of data by calculating partial consistency factors. We [27] have concluded that the definition in our previous work was incorrect (see also Cohen [29]), but the exact definition, which has not yet been implemented in our computer program, is not expected to result in dramatic changes in the assigned consistency factors.

## 4. Influences and significances of data

This section is devoted to describe how a method that allows to trace back, in the least-squares method, the contribution of each individual piece of data to each of the parameters (here the atomic masses) has been used in the evaluation of masses.

### 4.1. Construction of the flow-of-information matrix

The flow-of-information matrix  $\mathbf{F}$  is defined as follows:  $\mathbf{K}$ , the matrix of coefficients, is a rectangular  $(M, N)$  matrix, the transpose of the response matrix  ${}^t\mathbf{R}$  is also a  $(M, N)$  rectangular one. The  $(i, \lambda)$  element of  $\mathbf{F}$  is defined as the product of the corresponding elements of  ${}^t\mathbf{R}$  and of  $\mathbf{K}$ . In reference [30] it is demonstrated that such element represents the “*influence*” of datum  $i$  on parameter (mass)  $m_\lambda$ . A column of  $\mathbf{F}$  thus represents all the contributions brought by all data to a given mass  $m_\lambda$ , and a line of  $\mathbf{F}$  represents all the influences given by a single piece of data. The sum of influences along a line is the “*significance*” of that datum. It has also been proven [30] that the influences and significances have all the expected properties, namely that the sum of all the influences on a given mass (along a column) is unity, that the significance of a datum is always less than unity and that it always decreases when new data are added. As a further proof, the significances defined here are exactly the quantities obtained by squaring the ratio of the adjusted over the input uncertainties. The flow-of-information matrix  $\mathbf{F}$ , provides thus insight on how the information from datum  $i$  flows into each of the masses  $m_\lambda$ .

A simple interpretation of influences and significances can be obtained in calculating, from the adjusted masses and Eq.(1), the adjusted data:  $|\bar{l}\rangle = \mathbf{KR}|l\rangle$ . The  $i^{th}$  diagonal element of  $\mathbf{KR}$  represents then the contribution of datum  $i$  to the determination of  $\bar{l}_i$  (same datum): this quantity is exactly what is called above the *significance* of datum  $i$ . This  $i^{th}$  diagonal element of  $\mathbf{KR}$  is the sum of the products

of line  $i$  of  $\mathbf{K}$  and column  $i$  of  $\mathbf{R}$ . The individual terms in this sum are then nothing else than the *influences* defined above.

## 4.2. The flow-of-information matrix in the evaluation of masses

The flow-of-information matrix cannot be given in full in a table. It can be observed along lines, displaying then for each datum which are the nuclei influenced by this datum and the values of these *influences*. It can be observed also along columns to display for each primary mass all contributing data with their *influence* on that mass.

The first display is partly obtained by adding in the table of input data (table II) a column for the *significance* of primary data and the largest *influence*. Since in the large majority of cases only two nuclei are concerned in each piece of data, the second largest *influence* could easily be deduced. It is therefore not felt necessary to give a table of all *influences* for each primary datum.

The second display is given in table I for the up to three most important data with their *influence* in the determination of each primary mass.

## 5. Mass spectrometric results

### 5.1. Masses of stable nuclei

Rather few new measurements of stable species with a classical mass spectrometer have become available; all of them of the Winnipeg group (see the items marked H38-H47 in the 'Lab' column of table II). For the newer measurements, made with a somewhat revised instrumentation [ 3], the consistency with other data was found decidedly improved. We therefore reduced for them the consistency factor [ 2] to 1.5.

A very important group of new data is obtained by precision measurements of ratios of cyclotron frequencies of ions in Penning traps. Similarly to the classical measurements of ratios of voltages or resistances, we found that they can be converted to linear combinations in  $\mu u$  of masses of electrically neutral atoms, without any loss of accuracy. In such cases, we added a remark, to the equation used in the table of input data (table II), to describe the original data. Other groups give their results directly as masses, a not recommended practice for high precision measurements. In order to test the validity of the reported errors, we made a separate least-squares evaluation, following the policy accepted already in 1962 [31]. Involved were results on  $^1,2,3\text{H}$ ,  $^3,4\text{He}$ ,  $^{14}\text{N}$ ,  $^{16}\text{O}$ ,  $^{20}\text{Ne}$  and  $^{40}\text{Ar}$ . The consistency was first not perfect; the consistency factor came out to be  $R_e/R_i = 1.5$ . We used this factor as a correc-

tion factor  $CF$  to the errors reported by the authors. In a private communication received after the deadline for accepting data, a change was reported [93Va.B] for an earlier value of the mass of  $^2\text{H}$ . Then, the consistency factor came out to be 1.07. In view of the great importance for the fundamental masses we decided yet to accept the new mass value, but to retain the above value of  $CF$ . The improvement in the masses of light nuclides (up to  $^{40}\text{Ar}$ ) due to this work is demonstrated in fig. 2a and 2b of part I.

Quite interesting is that application of commercial Penning trap instruments yielded masses for a number of stable Xe isotopes [90Me08] that are not much worse (precisions of the order of 5 keV) than the values derived in this work, but were systematically lower by some ten keV. Such results may be useful in future. Interesting also is the use of Fourier-transform cyclotron resonances for comparing the masses of tritium and  $^3\text{He}$ . Nikolaev *et al.* [84Ni16] and Lipmaa *et al.* [85Li02] reported values with a precision of a few eV, but unfortunately their difference is almost an order of magnitude larger.

## 5.2. Masses of unstable nuclei

Far from stability there has been a wealth of new projects. The Chalk-River on-line isotope separator [89Sh10] and the St Petersburg on-line prism mass spectrometer [89Al33] continue the classical technique, in mass-spectrometry, of voltage measurements, whereas in the other projects, the measured quantities are times [32, 33] and frequencies [6].

A few mass ratios for unstable isotopes have been measured with mass separators. These ratios too could be expressed as linear combination of masses (see e.g.  $^{117,118,119}\text{I}$  in [92Sh.A]). By detecting radiations of the ions that arrived at the focal plane, confusion of isomers, or isobars, could be avoided.

A new approach of time-of-flight mass spectrometry was made by SPEG at GANIL [32] and TOFI at Los Alamos [33]. Masses of almost undecelerated fragment products, coming from thin targets bombarded with heavy ions [32] or high energy protons [33] are measured from a combination of magnetic deflection and time of flight determination. Nuclei in an extended region in  $A/Z$  and  $Z$  are analyzed simultaneously. Each individual ion, even if very short-lived ( $1\mu\text{s}$ ), is identified and has its mass measured at the same time. In this way, mass values with accuracies of ( $3 \times 10^{-6}$  to  $5 \times 10^{-5}$ ) are obtained for a large number of neutron-rich nuclides of light elements, up to  $A = 70$ . A disadvantage is that the obtained value applies to an isomeric mixture where an isomer exists with a half-life of the order of, or longer than the time of flight (about  $1\mu\text{s}$ ). Also, the resolving power is around  $10^4$  and cross-contaminations can cause significant shifts in masses. Finally, calibration is obtained from an empirically determined function, which, in several cases, had to be extrapolated rather far from the calibration masses. For the latter case, it is

hoped that in the future a few mass-measurements far from stability may provide better calibration points and allow a re-analysis of the concerned data, on a firmer basis.

With the Penning trap on-line with ISOLDE [6], the cyclotron frequency of a radioactive ion captured in the trap is directly compared to that of a well known nucleus. Methods which are relying on cyclotron frequency measurements have the advantage that, roughly speaking, only one parameter has to be measured, namely a frequency, that is the physical quantity that can be measured the best with high accuracy. Very high resolving power ( $10^8/A$ ) and accuracies (better than  $10^{-7}$ ) are achieved for radioactive isotopes of not too short half-lives (few seconds) of Rb, Sr, Cs, Ba and Fr up till quite far from the line of  $\beta$ -stability. Such high resolving power made it possible, for the first time in the history of mass-spectrometry, to resolve a nuclear isomer ( $^{84}\text{Rb}^m$ ) from its ground state. The results of these experiments have allowed to check several data close to stability and to re-assess the mass of  $^{130}\text{Cs}$  and  $^{135}\text{Cs}$  (see part I, sect. 5 and fig. 2c). Far from stability, the mass-triplet measurements, in which undetectable systematic effects could build-up in large deviations when the procedure is iterated [86Au02], could be calibrated for the first time for the low  $N$  branch of Cesium isotopes. Quite interesting is to note that a very far doublet ( $^{226}\text{Ra}$ – $^{133}\text{Cs}$ ) has been measured with fair precision. Such far doublets, with carbon clusters, may lead to important connections across the chart of nuclides. The method however is only applicable for certain elements, but developments underway might provide wider applicability in a near future.

## 6. Decay energies from capture ratios and relative positron feedings

For allowed transitions, the ratio of electron capture in different shells is proportional to the ratio of the squares of the energies of the emitted neutrinos, with a proportionality constant dependent on  $Z$  and quite well known [34]. For (non-unique) first forbidden transitions, the ratio is not notably different; with few exceptions. The neutrino energy mentioned is the difference of the transition energy with the electron binding energy in the pertinent shell. Especially if the transition energy is not too much larger than the binding energy in, say, the  $K$  shell, it can be determined rather well from a measurement of the ratio of capture in the  $K$  and  $L$  shells. The non-linear character of the relation between  $Q$  and the ratio introduces two problems. In the first place, a symmetrical error for the ratio is generally transformed in an asymmetrical one for the transition energy. Since our least-squares program cannot handle them, we have roughly symmetrized the probability distribution of the result in energy by taking as central value the mid-value between the upper and lower  $1\sigma$ -equivalent limits, and as error, the average of the two errors. More strictly, one should have considered the first and second momenta of the real probability distribution; nevertheless, our approximation is quite accept-



able for not too strongly asymmetric distributions. The other problem is related to averaging of several values that are reported for the same ratio. Otherwise than in earlier evaluations, we now average the capture ratios, and calculate the decay energy following from that average. In this procedure we used the best values [34] of the proportionality constant. We also recalculated older reported decay energies originally calculated using now obsolete values for this constant.

The ratio of positron emission and electron capture in the transition to the same final level also depends on the transition energy in a known way (anyhow for allowed and not much delayed first forbidden transitions). Thus, the transition energy can be derived from a measurement of the relative positron feeding of the level, which is often easier than a measurement of the positron spectrum end-point. For several cases we made here the same kind of combinations and corrections as mentioned for capture ratios. But in this case, a special difficulty must be mentioned.

Positron decay can only occur when the transition energy exceeds  $2m_e c^2 = 1022$  keV. Thus, more often than not, a level fed by positrons is also fed by  $\gamma$ -rays coming from higher levels fed by electron capture. Determination of the intensity of this *side* feeding is often difficult. Cases exist where such feeding occurs by a great number of weak  $\gamma$ -rays easily overlooked (the *pandemonium* effect [35]). Then, the reported decay energy may be much lower than the real value. In judging the validity of experimental data, we kept this possibility in our mind.

## 7. Changes in the classical radioactive series and the Hg problem

A measurement of the (p,t) reactions on Th isotopes [91Gr13] showed, that the mass difference between  $^{230}\text{Th}$  and  $^{228}\text{Th}$  is almost 18 keV different from the earlier value. The latter, for which a 5 keV error had been found, was due to a combination of rather many, each not so very accurate, reaction bridges. The difference has a bearing on the following problem. Absolute mass-doublets of Hg isotopes ( $^{199-202,204}\text{Hg}$ ) are reported [80Ko25] with a precision of about 1 keV. Hg mass values can also be obtained, with a precision of about 3 keV, from a reaction bridge to mass spectrometric data on lighter elements and another one to Th and U isotopes, as discussed in our earlier evaluation (ref. [2] sect. 4) and as illustrated by the connection diagrams (figs. 1f–1h of part I). These reaction data suggest some 20 keV more stability than deduced from the direct measurements. The new  $^{230}\text{Th}(p,t)$  result has the right sign for substantially reducing this discrepancy. We show this in a calculation in which the other bridge was broken; actually by not using the  $^{194}\text{Pt}(n,\gamma)^{195}\text{Pt}$  reaction. In fig. 1 we show the mass differences between this calculation and the 1983 one. We do this separately for the three naturally radioactive series and the later discovered  $^{233}\text{U}$ - $^{237}\text{Np}$  one, since at least the  $\alpha$ -decay energies in each of them are known quite accurately. Thus, the differences must

occur at the places where  $\beta$ -decay bridges occur, which is at different mass numbers in these series.

**Fig. 1.** Differences with the 1983 mass excesses (error band around zero) of mass values obtained in a special calculation excluding  $^{194}\text{Pt}(n,\gamma)$  (error bars) and of the final 1993 calculation (broken line). Errors in the latter values (not drawn) differ only slightly from those in the special calculation.

One observes that the lighter isotopes in all series in the trial calculation come out 16 keV less stable than in the 1983 one, which would remove about half the difference with the mass spectrometric result. A complete removal is not expected since differences between the latter and our evaluations show a 6 keV even-odd staggering which could be understood as a dirt effect (see [ 2]). In fact, this was the reason for not fully trusting these mass spectrometric results.

In view of this new result, we have diligently searched for a possible similar error in one or more of the reaction bridges to lower mass elements. Almost all of them are checked by parallel data. Not all these checks are completely satisfactory; but the differences are not of a magnitude to explain the discrepancy. Only the bridge  $^{194}\text{Pt}(n,\gamma)^{195}\text{Pt}$  is not checked by another datum. An error of 20 keV in it must be considered very unlikely. We therefore cannot offer a solution, and conclude that still the Hg doublets are the least improbable source for the discrepancy. Thus, the 1993 mass adjustment removes only about 1/3 of the discrepancy. We do not feel happy about this situation and think that a remeasurement of the Hg masses, if possible combined with that of lighter elements ( $Z = 73-77$ ) is the single most desirable experiment concerning masses near the line of  $\beta$ -stability. A new mass determination in the U–Th region, though certainly desirable, is not so urgent for the present problem.

## 8. Data from the Isobaric Multiplet Mass Equation

The masses of a set of isobaric analogue levels are predicted to follow a quadratic equation of the charge number  $Z$  (or of the third components of the isospin,  $T_3 = \frac{1}{2}(N - Z)$ ). In cases where the relation can be tested, it has been found to agree approximately within the errors reported for these masses, with as sole serious exception the isobaric analogues of the  $^9\text{Li}$  and  $^9\text{C}$  ground-states. This relation has therefore been used in our previous work, and also by Endt [36] in his recent compilation of nuclear data for  $A = 21-44$ , for deriving mass values for nuclides for which no, or poor information was available.

In a recent study [10], one of the present authors argued that this method could be extended. The validity of the method, however, is made uncertain by possible effects spoiling the relation. In the first place, the strength of some isobaric analogues at high excitation energies is known to be distributed over several levels with the same

spin and parity. Even in cases where this is not known to happen, the possibility of its occurrence introduces an uncertainty in the level energy to be used for this purpose. In the second place, as argued by Thomas [37] and Ehrman [38], particle-unstable levels must be expected to be shifted somewhat.

For these reasons, we decided not to present any IMME-derived mass values in the present evaluation. The study of this possibility, though, will continue.

Recently, mass values have been reported in several cases where masses of  $T_3 = -T + 1$  analogues could be derived from their proton emission, following electron capture decay of their  $T_3 = -T$  parents. The mass of the latter parents was then derived by assuming that their decay energy to the isobaric analogue had a value that followed from the formula for Coulomb shifts derived by Antony *et al.* [39]. Though we accepted some of these values, we have treated them as all values derived from systematic trends, with errors as following from the latter.

## 9. Nuclides just above $^{146}\text{Gd}$

In our preceding work [ 2] we discussed the possibility [40] to get information in this region from a discussion of known ground state masses and known excitation energies of high spin states with a simple shell model structure. A new analysis along the same lines has recently been published by Keller *et al.* [41].

Before we start discussion of their results we must point out that our previous value of the mass of  $^{147}\text{Gd}$  had to be revised to make it 140 keV less stable. The earlier value was based on choosing, of the two discrepant available values for the  $\beta^+$  decay energy of  $^{147}\text{Gd}$ , the one that agreed with the measured reaction energy of  $^{144}\text{Sm}(^{12}\text{C}, ^9\text{Be})^{147}\text{Gd}$  (see table II). Several later precision energy measurements showed this to be the wrong choice. As a result, the masses of its two known  $\alpha$ -decay precursors, and of its  $\beta$ -decay parent  $^{147}\text{Tb}^m$ , changed by the same amount.

Also, the masses of  $^{147}\text{Tb}$  and of its many  $\alpha$ -decay ancestors changed; these changes were, however, also influenced by the following circumstances. The excitation energy of  $^{147}\text{Tb}^m$  was newly measured to be 50.6 keV rather than the value  $106 \pm 29$  keV derived before. (The mass of the  $^{147}\text{Tb}$  gs, following from this item, is confirmed by the measurement of the proton binding energy of this isotope in the  $^{147}\text{Dy}(\text{ep})^{146}\text{Gd}$  decay.) But also, the assignment of the  $^{151}\text{Ho}$   $\alpha$ -particle emitting isomers had to be changed: the earlier  $^{151}\text{Ho}^m(\alpha)^{147}\text{Tb}^m$  decay is now assigned  $^{151}\text{Ho}(\alpha)^{147}\text{Tb}^m$ . As a result,  $^{151}\text{Ho}$  and its  $\alpha$  ancestors are 170 keV less stable than estimated in our 1983 table. The latter change has little to do with the  $^{146}\text{Gd}$  problem but is mentioned as example for several changes made since our last mass evaluation.

A real problem occurs, however, with the determination of the mass of  $^{148}\text{Tb}$ , and

**Table C.** Experimental decay energies in keV, and resulting values for that of  $^{148}\text{Tb}^m$ , their errors, and the measuring method (TAG = total absorption  $\gamma$ -ray method). Label B in column 2 is for data not used in the present evaluation.

Reference <sup>a)</sup>	Decay	$Q_\beta$	$Q_\beta(^{148}\text{Tb}^m)$	Method	
76Cr.B	$^{148}\text{Tb}(\beta^+)^{148}\text{Gd}$	5630	5720	80	$E^+$
83Ve06		5580	5670	60	$E^+$
85Ti01	B	5390	5480	100	$p^+$
93Al01		5700	5790	80	TAG
83Ve06	$^{148}\text{Tb}^m(\beta^+)^{148}\text{Gd}$		5925	70	$E^+$
85Sc09			5800	100	$p^+$
93Al01			5910	80	TAG
93Al01	$^{152}\text{Ho}(\beta^+)^{152}\text{Dy}$	6270	5580	90	TAG
84Al36	B $^{152}\text{Ho}^m(\beta^+)^{152}\text{Dy}$	6850	6000	100	$E^+$
90Sa32		6430	5580	140	$p^+$
93Al01	B	6330	5480	100	TAG
$^{146}\text{Gd}$ analysis			5823	16	
Present compromise			5780	30	

<sup>a)</sup> References are under “References to table II”.

therefore of its ( $\beta^+$ ) parent  $^{148}\text{Dy}$  and, most important, of its  $\alpha$ -decay ancestors, the extremely proton-rich nuclides  $^{176}\text{Hg}$  and  $^{180}\text{Pb}$  which, although not known experimentally, could be estimated with great confidence (as explained in sect. 11.5). Measurements have been made of the  $\beta$ -decay energies of both isomers in both  $^{148}\text{Tb}$  and its  $\alpha$ -decay ancestor  $^{152}\text{Ho}$ . They are connected by reportedly quite accurate values for the excitation energies of  $^{148}\text{Tb}^m$  and  $^{152}\text{Ho}^m$ , and  $\alpha$ -decay energies of the latter two and of their  $\beta$ -decay daughter  $^{152}\text{Dy}$  (see table of input data). In table C we present their reported  $\beta$ -decay energies, and the resulting values for the decay energy of  $^{148}\text{Tb}^m$ .

One sees that, even compared with the rather large errors, there is some spread in the values. A quite remarkable observation is that, whereas the average of the values derived for the isomers 5862(44) keV agrees quite well with the value obtained in the  $^{146}\text{Gd}$  analysis of Keller *et al.*, the one derived from the ground states, 5692(37) keV does not. From these two set of data one could deduce an excitation energy of 260(57) keV for  $^{148}\text{Tb}^m$ . The direct experimental value 90.1(.3) keV [87St.A] has been derived from an analysis of level energies in  $\text{Tb}^m$  from  $\gamma$ -rays measured in the  $^{144}\text{Sm}(^6\text{Li},2n)^{148}\text{Tb}$  reaction, in which all levels of the  $\pi h_{11/2}\nu f_{7/2}$  multiplet, of which  $^{148}\text{Tb}^m$  is the highest spin member, were observed; this beautiful result is very difficult to doubt.

We also considered the experimental methods used in the determination of the above values (last column in table C). Strikingly, the results of positron end-point measurements ( $E^+$ ) belong to the highest values; those from positron intensities

**Table D.** Comparison, for nuclides with non measured masses, of the results of the  $^{146}\text{Gd}$  analysis with the mass values we estimate from trends in systematics.

Nucleus	our value	$^{146}\text{Gd}$ analysis
$^{150}\text{Er}$ <sup>a)</sup>	-57970# 100#	-57890 51
$^{151}\text{Er}$	-58410# 300#	-58299 41
$^{151}\text{Tm}$	-50880# 360#	-50898 129

<sup>a)</sup> see part I, table C.

( $p^+$ ) to the lower ones (even though some values have been corrected upwards to take care of the side feeding intensities reported as possible by the authors). This suggests that this side feeding may have been underestimated in some cases. Quite remarkable is that the values obtained by the relatively new method of total  $\gamma$ -ray absorption [42] for the two isomers agree, separately, for  $A = 148$  and for  $A = 152$ ; but that the values at  $A = 152$ , combined with the  $\alpha$ -ray data, result in very low values for  $^{148}\text{Tb}^m$ . This method depends on the reduced half-lives of transitions to the many highly excited levels in the daughter nuclide being not too much different; possibly this supposition does not hold at rather high decay energies.

Our final value is a compromise, with an error following from the replacement and averaging procedures, which certainly appears somewhat optimistic; but since it does not disagree badly with the result of the  $^{146}\text{Gd}$  analysis, we accept it.

The possibility that the excitation energies are underestimated, even if remote, is disturbing. Fortunately, there is a reason to believe that this may not be the case. The recent accurate value for the  $^{148}\text{Dy}(\beta^+)^{148}\text{Tb}$  energy, combined with the derived mass of  $^{148}\text{Tb}$ , yields a mass excess value  $-67908 \pm 32$  keV for  $^{148}\text{Dy}$  which agrees nicely with the value  $-67872 \pm 13$  keV derived from the  $^{146}\text{Gd}$  analysis. Thus, we feel that the mass values of the  $\alpha$ -radioactive sequence starting with  $^{180}\text{Pb}$  (see sect. 11.5) are probably rather good, even though the errors reported here are probably somewhat optimistic.

The remaining new values from the  $^{146}\text{Gd}$  analysis are compared in table D with the values that we derived from consideration of systematic trends. It can be seen that this analysis agrees reasonably well, not only with the experimental values, but also with our estimates.

## 10. Alpha decay to Nilsson levels with unknown excitation energies

$\alpha$ -particle energies are usually determined with quite satisfactory precision. Except for even-even nuclides, however, the transition to the ground state in the daughter is

in general not the most intense one. Thus, if only one, or a few  $\alpha$  branches have been measured, one must assume that even the highest one does not necessarily feed the ground state, and that therefore the decay energy derived from it underestimates the real decay energy.

In our previous work [ 5] we have made a study of the systematic trends of the  $\alpha$ -decay energies calculated by assuming feeding of the ground states. Comparison with the energies of even-even nuclei showed that for the majority of these cases the deviations were less than 50 keV. For cases where the deviations were decidedly larger, we replaced the experimental decay energies by values derived from systematics. For the other cases, we accepted the result, but added (quadratically) an extra error of 50 keV to the result.

For regions of nuclear deformation, the *favoured*  $\alpha$ -transition is known to feed, in the daughter nucleus, the level with the same Nilsson level assignment as the parent, which with few exceptions is different from the ground state. One such a region occurs for  $A > 225$ . Here, much is known about the energy distance between Nilsson particle levels [43]. Distances between a particular combination of such levels are quite similar in different nuclides. Thus, one may assume that, for the cases discussed here, a good estimate of the excitation energy can be obtained from a study of such differences. (This study should be limited to particle levels; hole levels may show other but irrelevant results.)

Several results in the present evaluation have been obtained with help of such Nilsson model estimates (table E). They are clearly distinguished from purely experimental information by the use of the special symbol “\*” in all tables in part I and II. In the table of isomers (table III), the levels are given with the suffix “p” (e.g.  $^{239}\text{Cm}^p$ ) used generally for pertinent non-isomeric levels. In addition, the results have influenced other estimates from the study of systematic trends as mentioned before. We feel that the results given here for the highest masses ( $A > 235$ ) are therefore more dependable than in our former work. Fig. 2 shows the changes in the mass values caused by this feature; as could be expected, the values indicate less binding (by a few 100 keV) than our earlier work.

In principle, such a study could also be made in the region  $A = 160\text{--}190$ . This has not yet been done for lack of time; also, the situation for the here very proton-rich nuclei involved is thought to be less clear-cut.

**Fig. 2.** Differences, for isotopes with  $Z \geq 100$ , between the 1993 mass values (resulting partly from a Nilsson model analysis: the stars) and the 1983 ones. Points indicate purely experimental values.

**Table E.** Estimated excitation energies and errors (in keV) of level populated by  $\alpha$ -decay, from Nilsson model, in the region  $A > 225$ .

Transition	Excitation Energy	
$^{231}\text{U}^p(\text{IT})^{231}\text{U}$	50	50
$^{239}\text{Cm}^p(\text{IT})^{239}\text{Cm}$	100	70
$^{241}\text{Cf}^p(\text{IT})^{241}\text{Cf}$	150	100
$^{245}\text{Cf}^p(\text{IT})^{245}\text{Cf}$	150	100
$^{247}\text{Fm}^p(\text{IT})^{247}\text{Fm}$	150	50
$^{249}\text{Fm}^p(\text{IT})^{249}\text{Fm}$	300	200
$^{251}\text{No}^p(\text{IT})^{251}\text{No}$	450	100
$^{253}\text{No}^p(\text{IT})^{253}\text{No}$	500	100
$^{255}\text{Fm}^p(\text{IT})^{255}\text{Fm}$	300	100
$^{255}\text{No}^p(\text{IT})^{255}\text{No}$	100	70
$^{257}\text{No}^p(\text{IT})^{257}\text{No}$	300	100
$^{257}\text{Rf}^p(\text{IT})^{257}\text{Rf}$	100	70
$^{259}\text{Rf}^p(\text{IT})^{259}\text{Rf}$	300	100
$^{261}\text{Nh}^p(\text{IT})^{261}\text{Nh}$	300	100

## 11. Special cases

### 11.1. The $^3\text{H}$ – $^3\text{He}$ atomic mass difference

Measurement of this mass difference has been stimulated by the strong interest in the determination of the neutrino mass. An evaluation of related data published in 1985 [44] lead to the conclusion that there was ‘*a rather good consistency within each of the three (experimental) methods but strong discrepancies among them*’. The situation has drastically improved. First, corrections to the Si(Li) experiments could be made, after careful study, by Redondo and Robertson [89Re04]. Second, a wealth of new precise data were obtained from new  $\beta$ -spectrometers at Zurich [86Fr09], Moscow [87Bo07], Tokyo [88Ka20], Los Alamos [89St05], New-York [91Bu12] and Mainz [93We03]; the most recent data of these groups give, for the  $\beta$ -spectrometer measurements, an acceptable ( $B = 1.25$ ) average of  $18591.2 \pm 1.1$  eV. Last but not least, the Penning-Trap measurements at Seattle [92Va.A] yielded a precise value for the mass difference ( $18590.1 \pm 1.7$  eV) in good agreement with the  $\beta$ -spectrometer average above, yielding an evaluated value of  $18591.0 \pm 1.0$  eV. This value is in very good agreement with the average found by Redondo and Robertson:  $18591 \pm 2$  eV.

## 11.2. The decay energy in $^{26}\text{Al}^m(\beta^+)^{26}\text{Mg}$

This case is often discussed as an important pure Fermi transition. Unfortunately, the result of the combination of two agreeing reported  $^{25}\text{Mg}(\text{n},\gamma)^{26}\text{Mg}$  reaction energies, two well agreeing  $^{25}\text{Mg}(\text{p},\gamma)^{26}\text{Al}$  ones, and the  $^{26}\text{Al}^m$  excitation energy gives a value 4232.69(0.08) keV which disagrees with the value 4231.93(0.15) derived from a  $^{26}\text{Mg}(\text{}^3\text{He},\text{t})$  comparison with  $^{14}\text{N}(\text{}^3\text{He},\text{t})^{14}\text{O}$ . A similar comparison with  $^{42}\text{Ca}(\text{}^3\text{He},\text{}^3\text{H})^{42}\text{Sc}$ , using for the latter the combination of results on the  $^{41}\text{Ca}(\text{n},\gamma)^{42}\text{Ca}$ ,  $^{41}\text{Ca}(\text{p},\gamma)^{42}\text{Sc}$  and  $^{40}\text{Sc}(\text{p},\gamma)$  reactions, yields a value 4232.26(0.35) keV, which does not really decide between the two values above. A measurement on the  $^{26}\text{Mg}(\text{p},\text{n})$  reaction by Barker *et al.* [84Ba.B], given in the table of input data but not used in the calculation, gives a value 4231.62(0.22) keV which seems to confirm the lower of the above values. The authors informed us, however, that newer measurements result in an about 0.9 keV higher value. Taking this all together, we must regretfully conclude that the error 0.07 keV assigned to the output 4232.49 keV of the full least-squares adjustment must be considered optimistic.

## 11.3. The $^{35}\text{S}(\beta^-)$ decay energy

This case has been investigated recently several times in connection with the report that a neutrino might exist with a mass of 17 keV. Unfortunately, the reported decay energies are so much different that we had to apply the procedure described in section 3.2 (see table B) to get an average value and dispersion of 167.20(0.12) keV. A value 166.90(0.23) keV can also be derived from the reported reaction energies for the  $^{34}\text{S}(\text{n},\gamma)$  and  $^{34}\text{S}(\text{p},\gamma)$  reactions. The disagreement is not disastrous; unfortunately, though, the most recent and probably most accurate  $^{35}\text{S}(\beta^-)$  decay energy values are all higher than the average given above. Combination with the fact that Barker *et al.* reported that their recent, unpublished measurements on the reaction  $^{34}\text{S}(\text{p},\text{n})^{34}\text{Cl}$  seem to indicate an even more significant difference with the combination of the reported results for  $^{33}\text{S}(\text{n},\gamma)^{34}\text{S}$  and  $^{33}\text{S}(\text{p},\gamma)^{34}\text{Cl}$  suggests that some more measurements on the validity of the errors in at least some reported (n, $\gamma$ ) and (p, $\gamma$ ) reaction energies could be valuable.

## 11.4. The data on $^{51}\text{Ca}$

In table F we give mass values for  $^{51}\text{Ca}$  atom with its nucleus in different states as found from time-of-flight mass measurements (first two items) and from measurements yielding  $^{51}\text{Ca}$  from bombardments of  $^{48}\text{Ca}$  with  $^{14}\text{C}$  or  $^{18}\text{O}$ . The comparison makes quite probable that the measurements of [85Be50] and [88Ca21] missed the ground-state. Since  $^{51}\text{Ca}$  is not expected to have states of such long half-lives that they would influence the direct mass measurements, one may accept that the first two items apply to the ground-state. Consideration of the [85Br03] data shows that



**Table F.** Mass values, in keV, of  $^{51}\text{Ca}$  atoms with the nucleus in different states.

Reference <sup>a)</sup>	State 1	State 2	St.3	St.4	St.5	St.6	St.7	St.8
90Tu01		-36140(330)						
93Se.A		-36240(370)						
80Ma40		-35940(150)		-34950	-34540	-34000		
85Be50				-34960			-32610	-31940
85Br03	-36120(120)	-35820	-35460	-35150	-34880			
88Ca21						-33950	-32710	-32010

<sup>a)</sup> References are under “References to table II”.

the reported most-bound level is only very weakly populated. We therefore choose to accept the items of ‘state 2’ as ground-state, realizing that thus the mass may have been overestimated by about 300 keV.

### 11.5. Light Pb isotopes

Though it is known that the magic number gap at  $Z = 82$  narrows drastically in going away from the magic neutron number  $N = 128$ , the  $\alpha$ -decay energies of even- $A$  Pb isotopes vary very smoothly with the mass number (see fig. 3). Thus, we feel very confident in extrapolating this course to  $A = 180$ , which is important since the mass of  $^{176}\text{Hg}$  is known (we even felt that we could rather confidently do the same for  $^{174}\text{Hg}$  and  $^{178}\text{Pb}$ ; important since their  $\alpha$ -descendant  $^{170}\text{Pt}$  has a known mass).

We then find that the known masses of light Pb nuclei with even mass numbers, including the two estimates just discussed, agree reasonably with a quadratic formula (see fig. 4). This gives a good method for estimating values for as yet unknown masses of in-between even- $A$  Pb isotopes. Also, it gives a reason to trust indeed the masses of  $^{170}\text{Pt}$  and  $^{176}\text{Hg}$  derived from the data just above  $^{146}\text{Gd}$  and discussed above (see sect. 9).

**Fig. 3.** Differences between the  $\alpha$ -decay energies of Pb isotopes and a quadratic function of the mass number. The jumps at  $A = 189, 187$  and  $185$  are connected with the deformed character of the ground-states of the daughters.

**Fig. 4.** Differences between the mass values for Pb isotopes and a quadratic function of the mass number. The mass values for  $^{178}\text{Pb}$  and  $^{180}\text{Pb}$  have been derived from the Pb  $\alpha$ -decay energies in fig. 3. The values for the odd mass Pb isotopes are compared with the pairing energy formula of Jensen, Hansen and Jonson [22], and with the older estimate  $12/\sqrt{A}$  MeV.

Interesting is the insight this comparison gives in the neutron pairing energy. As seen in fig. 4, the apparent pairing energy in  $^{181}\text{Pb}$ , the only very neutron rich odd  $A$  for which a purely experimental value is known, is not only larger than the old formula  $12/\sqrt{A}$  MeV, but even larger than the estimate of Jensen *et al.* [22]. As

said above, for even-odd isotopes one must expect that ground state  $\alpha$ -transitions could have been missed. Correcting for such a possibility, however, would lead to an even higher result for the pairing energy. An explanation might be, that in some cases the reported  $\alpha$ -energies belong to upper isomers, not fed in the preceding  $\alpha$ -transitions. But even taking this possibility into account, it seems that no large systematic errors due to missing ground state transitions exist for the pertinent  $\alpha$ -decay series.

### 11.6. The $^{187}\text{Tl}^m(\alpha)$ decay energy

In study of this decay, Wauters *et al.* [91Wa21] propose feeding to the  $9/2^-$  level at 12.3 keV, whereas we previously assumed feeding of the  $11/2^-$  level at 230.5 keV. The arguments developed in [91Wa21] for this assignment are very good ones, but the consequences for the regularity of the surface of masses and the plots of systematics are not very pleasant. If there were a real physical effect that would make  $^{183}\text{Au}$  230 keV less bound, then one would have to find a physical reason also for  $^{179}\text{Ir}$  to be 230 keV less bound (or alternatively  $^{187}\text{Tl}$  and  $^{191}\text{Bi}$  to be 230 keV more bound). Given this, one may wonder whether what is known presently about the particle-hole configurations and shapes for levels in  $^{183}\text{Au}$  and  $^{187}\text{Tl}$  could not be questioned, or whether some non very common effect is not occurring there. This matter certainly worth further investigations. In table II we retained provisionally the older assignment.

### 11.7. Nuclides with $N = 108$

A clear discontinuity of the surface of masses at  $N = 108$ , first pointed out by Barber *et al.* [45], has been re-examined recently by one of us [46] and shown to extend to isotopes of Hf, Ta, W, Re and Os and to have a magnitude of some 350 keV, as can be seen in figure 6 of part III. Whether this discontinuity is due to an energy gap above the deformed  $\frac{9}{2}^+$ [624] Nilsson level as interpreted by [45] or to a prolate to oblate (or possibly triaxial) shape transition as observed at higher  $Z$  (Au isotopes) by Savard *et al.* [47] render further investigations of the above mentioned  $Z = 72-76$  nuclides, in similar experiments, highly desirable. At the same time, mass measurements of nuclides with higher  $Z$  would allow to derive the magnitude and delimit the extension of the observed irregularity of the surface of masses.

We wish to thank our many colleagues who answered our questions about their experiments and those who sent us preprints of their papers. Very useful discussions with H.Keller, P.Kleinheinz, C.F.Liang, B.Roussi re and C.Thibault have been highly appreciated.

## References <sup>2</sup>

### References

- [ 1] A.H. Wapstra and G. Audi, Nucl. Phys. **A432** (1985) 1
- [ 2] A.H. Wapstra, G. Audi and R. Hoekstra, Nucl. Phys. **A432** (1985) 185
- [ 3] J.G. Hycakwy, J.N. Nxumalo, P.P. Unger, C.A. Lander, R.D. Peters, R.C. Barber, K.S. Sharma and H.E. Duckworth, Nucl. Instrum. Methods **A239** (1993) 423
- [ 4] F.L. Moore, D.L. Farmham, P.B. Schwinberg and R.S. van Dyck,Jr., Nucl. Instrum. Methods **B43** (1989) 425
- [ 5] A.H. Wapstra and K. Bos, At. Nucl. Data Tables **20** (1977) 1
- [ 6] G. Bollen, P. Dabkiewicz, P. Egelhof, T. Hilberath, H. Kalinowsky, F. Kern, H. Schnatz, L. Schweikhard, H. Stolzenberg, R.B. Moore, H.J. Kluge, G.M. Temmer, G. Ulm and ISOLDE collaboration, Hyperfine Interactions **38** (1987) 793.
- [ 7] A. Coc, R. Ferreau, C. Thibault, M. de Saint Simon, F. Touchard , E. Haebel, H. Herr, R. Klapisch, G. Lebéé, G. Petrucci and G. Stefanini, CSNSM-LRB-85-01 report, Orsay 1985
- [ 8] A.H. Wapstra, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues 1992, Inst. Phys. Conf. Series 132(1993)979
- [ 9] C. Borcea, G. Audi and J. Duflo, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues 1992, Inst. Phys. Conf. Series 132(1993)59; C. Borcea and G. Audi, Rev. Roum. Phys. **38** (1993) #45, to appear November 1993; CSNSM-9238 report, Orsay 1992.
- [10] A.H. Wapstra, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues 1992, Inst. Phys. Conf. Series 132(1993)125
- [11] H.J. Rose and G.A. Jones, Nature **307** (1984) 245
- [12] E.R. Cohen and A.H. Wapstra, Nucl. Instrum. Methods **211** (1983) 153
- [13] E.R. Cohen and B.N. Taylor, CODATA Bull. **63** (1986), Rev. Mod. Phys. **59** (1987) 1121
- [14] T.J. Quin, Metrologia **26** (1989) 69,  
B.N. Taylor and T.J. Witt, Metrologia **26** (1989) 47

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<sup>2</sup>References such as 84Sc.A, 89Sh10 or 93Ot.1 are listed under "References to table II".

- [15] B.N. Taylor and E.R. Cohen, *J. Res. Natl. Inst. Stand. Technol.* **95** (1990) 497
- [16] A. Rytz, *At. Nucl. Data Tables* **47** (1991) 205
- [17] A.H. Wapstra, *Nucl. Instrum. Methods* **A292** (1990) 671
- [18] M.L. Roush, L.A. West and J.B. Marion, *Nucl. Phys.* **A147** (1970) 235
- [19] P.M. Endt, C.A. Alderliesten, A.A. Wolters and A.G.M. van Hees, *Nucl. Phys.* **A510** (1990) 209
- [20] D.P. Stoker, P.H. Barker, H. Naylor, R.E. White and W.B. Wood, *Nucl. Instrum. Methods* **180** (1981) 515
- [21] A.H. Wapstra, unpublished
- [22] A.S. Jensen, P.G. Hansen and B. Jonson, *Nucl. Phys.* **A431** (1984) 393
- [23] J. van Lochum, C. de Laat and A.H. Wapstra, unpublished
- [24] Particle Data Group, 'Review of Particle Properties', *Phys. Rev.* **D45** (1992), part II
- [25] M.U. Rajput and T.D. Mac Mahon, *Nucl. Instrum. Methods* **A312** (1992) 289
- [26] M.J. Woods and A.S. Munster, NPL Report RS(EXT)95 (1988)
- [27] A.H. Wapstra, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues 1992, *Inst. Phys. Conf. Series* 132(1993)129
- [28] Y.V. Linnik, *Method of Least Squares* (Pergamon, New York, 1961); *Méthode des Moindres Carrés* (Dunod, Paris, 1963)
- [29] E.R. Cohen, *Phys. Rev.* **101** (1956) 1641
- [30] G. Audi, W.G. Davies and G.E. Lee-Whiting, *Nucl. Instrum. Methods* **A249** (1986) 443
- [31] F. Everling, L.A. König, J.H.E. Mattauch and A.H. Wapstra, *Nucl. Phys.* **25** (1961) 177
- [32] A. Gillibert, L. Bianchi, A. Cunsolo, A. Foti, J. Gastebois, Ch. Grégoire, W. Mittig, A. Peghaire, Y. Schutz and C. Stéphan, *Phys. Lett.* **B176** (1986) 317
- [33] D.J. Vieira, J.M. Wouters, K. Vaziri, R.H. Krauss, Jr., H. Wollnik, G.W. Butler, F.K. Wohn and A.H. Wapstra *Phys. Rev. Lett.* **57** (1986) 3253
- [34] W. Bambynek, H. Behrens, M.H. Chen, B. Crasemann, M.L. Fitzpatrick, K.W.D. Ledingham, H. Genz, M. Mutterer and R.L. Intemann, *Rev. Mod. Phys.* **49** (1977) 77

- [35] J.C. Hardy, L.C. Carraz, B. Jonson and P.G. Hansen, Phys. Lett. **B71** (1977) 307
- [36] P.M. Endt, Nucl. Phys. **A521** (1990) 1
- [37] R.G. Thomas, Phys. Rev. **80** (1950) 136, **88** (1952) 1109
- [38] J.B. Ehrman, Phys. Rev. **81** (1951) 412
- [39] M.S. Antony, J. Britz, J.B. Bueb and A. Pape, At. Nucl. Data Tables **33** (1985) 447;  
M.S. Antony, J. Britz and A. Pape, At. Nucl. Data Tables **34** (1985) 279;  
A. Pape and M.S. Antony, At. Nucl. Data Tables **39** (1988) 201
- [40] J. Blomqvist, P. Kleinheinz and J.P. Daly, Z. Phys. **A312** (1983) 27
- [41] H. Keller, N. Zeldes, P. Kleinheinz and E. Roeckl, Proc. Conf. Nucl. Far From Stability/AMCO9, Bernkastel-Kues1992, Inst. Phys. Conf. Series 132(1993)37
- [42] C.L. Duke, P.G. Hansen, O.B. Nielsen, G. Rudstam and ISOLDE, Nucl. Phys. **A151** (1970) 609;  
G.D. Alkhazov, A.A. Bykov, V.D. Wittmann, S.Yu. Orlov, and V.K. Tarasov, Phys. Lett. **157B** (1985) 350
- [43] Nuclear Data Sheets
- [44] G. Audi, R.L. Graham and J.S. Geiger Z. Phys. **A321** (1985) 533
- [45] R.C. Barber, J.O. Meredith, F.C.G. Southon, P. Williams, J.W. Barnard, K. Sharma and H.E. Duckworth, Phys. Rev. Lett. **31** (1973) 728
- [46] G. Audi, Workshop on Nuclear Structure of Light Nuclei Far From Stability - Experiment and Theory, Obernai, 1989, ed. G. Klotz, p. 113
- [47] G. Savard, J.E. Crawford, J.K.P. Lee, G. Thekkadath, H.T. Duong, J. Pinard, S. Liberman, F. Le Blanc, P. Kilcher, J. Obert, J. Oms, J.C. Putaux, B. Roussi re, J. Sauvage, and the ISOCELE Collaboration Nucl. Phys. **A512** (1990) 241

Table I  
**Influences on primary nuclei**  
 EXPLANATION OF TABLE

This table gives for each of the 812 primary nuclei the up to three most important contributing data and their *influences* ( $\times 100$ ) on its mass, as given by the flow-of-information matrix.

Nucleus	Nucleus (primaries only)		
Influence	<i>Influence</i> ( $\times 100$ ) brought to the determination of the mass of the nucleus, by the piece of data represented by the equation in following column		
Equation	In mass-doublet equation: H = $^1\text{H}$ , N = $^{14}\text{N}$ , D = $^2\text{H}$ , O = $^{16}\text{O}$ , C = $^{12}\text{C}$	In mass-triplet equation: Rb <sup>x</sup> , Rb <sup>y</sup> : different mixtures of two isomers, see table III.	In nuclear reaction: K <sup>m</sup> , Cs <sup>m</sup> , Cs <sup>n</sup> : upper isomers, see table III.

Table II  
**Input data compared with adjusted values**  
 EXPLANATION OF TABLE

The ordering is in groups according to highest occurring relevant mass number.

Item	In mass-doublet equation: $H = {}^1H$ , $N = {}^{14}N$ , $D = {}^2H$ , $O = {}^{16}O$ , $C = {}^{12}C$	In mass-triplet equation: $Rb^x$ , $Rb^y$ : different mixtures of two isomers, see table III.	In nuclear reaction: $K^m$ , $Cs^m$ , $Cs^n$ : upper isomers, see table III.
Input value	Mass doublet: value and its standard error in $\mu u$ . Triplet: value and its standard error as above but in keV. Reaction: value and its standard error in keV. The value is the combination of mass excesses $\Delta(M - A)$ given under 'item'. It is the author's experimental result and the author's stated uncertainty, except in a few cases for which comments are given and for some $\alpha$ -reactions where the errors have been increased to 50 keV for reasons mentioned in the text (see sect. 10).		
Adjusted value	Output of calculation. For secondary data ( $Dg = 2-13$ ) the adjusted value is the same as the input value and not given; also, the adjusted value is only given once for a group of results for the same reaction or doublet. Values and errors were rounded off, but not to more than tens of keV.  # Value and error derived not from purely experimental data, but at least partly from systematic trends. * No mass value calculated for the masses involved (only one datum).		
v/s	Deviation between input and adjusted value, given as their difference divided by the input error.		

Dg (see sect. 3)	<ul style="list-style-type: none"> <li>1. Primary data.</li> <li>2–13. Secondary data of different degrees.</li> <li>B. Well-documented data which disagree with other well-documented values.</li> <li>C. Data from incomplete reports, at variance with other data or with systematics.</li> <li>F. Study of paper raises doubts about validity of data within the reported error.</li> <li>R. Item replaced for computational reasons by an equivalent one giving same result.</li> <li>S. Estimates made by other authors, accepted and treated as systematics.</li> <li>U. Data with much less weight than that of a combination of other data.</li> </ul>
Sig	<i>Significance</i> ( $\times 100$ ) of primary data only (see sect. 4).
Main flux	Largest <i>influence</i> ( $\times 100$ ) and nucleus to which the data contributes the most (see sect. 4).
Lab	Identifies group which measured the corresponding item. Example of Lab key: MA3 Penning Trap data of Mainz-Isolde group. The numbers refer to different papers or even to groups of data within one paper.
CF	Consistency factor. The standard error given in the Input value column has been multiplied by this factor before being used in the least-squares adjustment.
Reference	<p>Reference keys:</p> <p>89Sh10 Results derived from regular journal. These keys are copied from Nuclear Data Sheets. Where not yet available, the style 93Ot.1 has been used.</p> <p>84Sc.A Result from abstract, preprint, private communication, conference, thesis or annual report.</p> <p>* A remark on the corresponding item is given below the block of data corresponding to the same (highest) <math>A</math>.</p> <p>,Y recalibrations of 65Ry01 for charged particles.</p> <p>,Z recalibrations of 91Ry01 for <math>\alpha</math> particles, 90Wa22 for <math>\gamma</math> in (n,<math>\gamma</math>) and (p,<math>\gamma</math>) reactions and 91Wa.A for protons and <math>\gamma</math> in (p,<math>\gamma</math>) reactions (see sect. 2).</p>

*Remarks.* For data indicated with a star in the reference column, remarks have been added. They are collected in groups at the end of each block of data in which the highest occurring relevant mass number is the same. They give:

1. Information explaining how the values in column 'Input value' have been



derived for papers not mentioning e.g. the mass differences as derived from measured ratios of voltages or frequencies - a bad practice - or the reaction energies or values for transitions to excited states in the final nuclei (for which better values of the excitation energies are now known).

2. Reasons for changing values (eg. recalibrations) or errors as given by the authors or for rejecting them (i.e. for labelling them B, C or F).
3. Value suggested by systematical trends and recommended in this evaluation as best estimate (see part I, sect. 4 and part III).
4. Separate values for capture ratios (see sect. 6).

**References to table II**  
USED CODEN IDENTIFIERS  
USED NON-CODEN IDENTIFIERS  
LIST OF REFERENCES

Table III  
**Identification of Isomers**  
EXPLANATION OF TABLE

This table gives information on cases where table II mentions more than one nuclear state. Element indications with suffix “m” or “n” indicate assignments to isomeric states. In several cases, the assignments to ground-state and upper isomer need not be correct (error in excitation energy comparable with its value); therefore half-lives, spins and parities (where known) have been added. A suffix “r” indicates a state from a proton resonance occurring in (p, $\gamma$ ) reactions. Suffixes “p” and “q” indicate non-isomeric levels, e.g. those ones for which the energy was derived from Nilsson model extrapolations. Suffixes “x” or “y” apply to mixtures of levels, e.g. occurring in spallation reactions (indicated spmix in last column) or fission (fsmix). With rare exceptions, excitation energies given below with errors of about 1 keV or less have been taken from the Nuclear Data Sheets or [36]; they are labelled ‘IT’ in the origin column. Other indications there allow to see which excitation energies follow from the present calculation.

$A$	Mass number $A = N + Z$ .
Elt.	Element symbol (for $Z > 103$ see part I, sect. 2).
Orig.	Origin of values for secondary nuclides. $z_p n_n$ : mass of ${}^A Z$ derived from mass of ${}^{A+Z+z}(Z+z)$ .

Special notations:

IT	when $z = 0, n = 0$ ;
+	when $z = +1, n = -1$ ;
-	when $z = -1, n = +1$ ;
$\epsilon p$	when $z = -2, n = +1$ ;
$+\alpha$	when $z = +2, n = +2$ ;
x	for distant connection.

Excitation Energy	Energy difference between levels adopted as higher level and ground state, and its error. In cases where the furthest-left significant digit in the error was larger than 3, values and errors were rounded off, but not to more than tens of keV. # in place of decimal point: values and errors estimated from systematic trends.
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$T$  Half-life: stbl = stable; s = seconds; m= minutes;  
h = hours; d = days; y = years;  
ms,  $\mu$ s, ns, ps =  $10^{-3,-6,-9,-12}$  seconds;  
ky, My, Gy, Ty, Py =  $10^{3,6,9,12,15}$  years.  
? : unknown or uncertain half-life

For isomeric mixtures:  
 $R$  = abundance ratio upper/lower levels;  
contamtn = non-isomeric mixture.

$J^\pi$  Reported or adopted values for spin and parity:  
Hi, Lo = high, low spin;  
am = same  $J^\pi$  as  $\alpha$ -decay parent;  
? : unknown or uncertain spin and/or parity.

For isomeric mixtures: mix (spmix and fsmix if coming from  
spallation and fission respectively).