Selecting nuclides for mass measurements

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(November 15, 1994)

Abstract. We give some general directions and methods on how to select nuclides of interest for mass measurements. We discuss also more specific cases, as for example the very high precision mass measurements available now from Penning Trap spectrometers.

PACS number: 21.10.Dr

Introduction

The question of which are the most interesting nuclides for atomic mass measurements has often been put to us.

At present there are some 1850 nuclides for which the masses are known and some 6000 to 7000 nuclides predicted to exist. With no constraint on the

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question above, one might say that the latter numbers are part of the answer. More nuclides lying beyond the proton drip-line are also of interest, as shown for example in the study of the Thomas-Ehrmann shift [1].

Since giving a list of all possibly interesting nuclides is not feasable, the question will be better answered if it is formulated in a more specific way and accompanied by a list of possible nuclides that can be measured in the experimental set-up under consideration together with their associated accuracies. Selecting nuclides of interest is closely related to these practical informations, particularly to the latter point: for some fundamental nuclides, an accuracy of one part in 10^{10} is desirable, but for nuclides far from the region of stability, a few parts in 10^6 would already be satisfactory.

It seems therefore wiser to indicate here some general directions and methods that may help in locating which are the interesting nuclides in a given context. But we shall first examine some specific, well-defined cases.

1. Specific cases

1.1. Very high precision measurements

Several measurements with precisions at a level that have never been attained previously have been reported at this Nobel Symposium and more particularly those given by the MIT group [2] with precisions often better than 10^{-10}. This group has done a careful evaluation of their systematic errors and analysis of their data, thus achieving very satisfactory internal consistency checks. Their impressive report [3] is, in this sense, recommendably complete. Yet, they should not remain unchallenged: checks by another group, at the same level of precision, is highly desirable to strengthen the validity of their mass measurements, and transform these very precise measurements into very accurate ones.

The backbone of masses, along the valley of β-stability could be rebuilt to this level of accuracy by measurements for nuclides at regularly spaced mass numbers A (see also, in connection with this point, section 2.4).

We also like to point out that the quite precise mass values for ^{35}Cl and ^{37}Cl in the 1993 "Atomic Mass Evaluation" [4] (respectively 40 and 50 eV) are both essentially based on only one old mass doublet. A check would be desirable, also since these two nuclides are used in many mass-spectrometric measurements.

1.2. Very short-lived nuclides

Nuclides of interest occur along the astrophysical r-process path [5] and in the region of the rp-process, around A=60–80: in order to determine the formation ratios in this process, one needs to know the transition probabilities, which depend on the reaction energies [6].

Another incentive for measuring masses as far as possible from the valley of β-stability is to be able to test nuclear models at high N-Z where the presently available ones tend to show very large discrepancies [7].

1.3. Particular nuclides

Quite often, important problems in physics require knowledge of some particular masses, or the difference between the masses of two nuclides, to be known with high accuracy. Below we give some examples, some of which have received recently a satisfactory answer, while some others would benefit from still more precise measurements.

The mass-difference between ^{205}Tl and ^{205}Pb is important [8] in cosmochronology where this pair could represent a unique s-process chronometer. This mass-difference is also of importance for a possible solar neutrino detector since the probability of neutrino capture strongly depends on the transition energy: an error of 10 keV in energy results in a factor of 2 in the transition probability. As a matter of fact, a direct electron capture measurement [9] gave a value 41.4(1.1) keV for this desintegration energy, whereas five independent combinations of other reactions and decays connecting these two nuclides in complex patterns [10] were all consistent and resulted in a value 51.2(0.5)keV accepted in our evaluation (see [15], p. 325).

In the search for a possible neutrinoless double β-decay, for example between ^{76}Ge and ^{76}Se, one expects a peak at exactly the mass difference between the two nuclides. Knowledge of such differences with high accuracies provide stringent constraints in the data analysis.

Very accurate measurements of super-allowed β-decays energies, like in ^{14}O, ^{26}Al^{m}, ^{34}Cl, ^{38}K^{m}, ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co allow to determine [11] the vector coupling constant G_V and the first element V_{ud} of the Kobayashi-Maskawa mixing matrix as explained clearly by J. Byrne in this Nobel symposium [12] in the case of the neutron decay.

In the process of re-defining the kilogram unit of the MKSA system on an atomic scale, a very precise and accurate measurement of the mass of ^{28}Si is essential. In the last two years Penning-trap measurements have brought a 2-order of magnitude improvement in this mass, making it now known [3] with a precision better than 10^{-10}.

The parameters implied in the description of the so-called halo nuclides are strongly dependant on the binding energies. For example, in the quasi-molecular model [13], the key to the size of the halo is the separation energy S of the relevant particle(s), since the halo size scales directly with $1/S$. Also the differential Coulomb cross-section near 0° scales with $1/S^2$. A reasonably good accuracy (5 keV) on this energy is desirable for ^{11}Li and for other candidates for the particular structure of neutron or proton halo such as ^{33}Na (1n), ^{31}Ar (1p,2p), ^{35}K (1p), ^{61}Ga (1p), ^{114}Cs (1p), ^{149}Tm (1p), ^{189}Bi (1p) and $^{195-197}$At (1p). For the investigation of these very short-lived nuclides, a mass spectrometer able to operate in a time regime below 1 s (e.g. ref. [14]) would be useful.

1.4. Desired remeasurements

More measurements are needed in several cases to help solve particular inconsistencies as they appear from our evaluations. They shall not be reviewed here since they are already described in part IV of the most recent “Atomic Mass Evaluation” [15]. We repeat, though, that the most desirable measurements among them are those that would help solving the mercury problem (section 7 in [15]).

2. Some general directions and methods

2.1. Structures on the mass surface

A first general direction is given by the structures of the mass surface as can be observed for example on the plots given in part III of the “Atomic Mass Evaluation” [16]. By “structure” we mean a series of irregularities of the surface of masses that could be observed for several (or all) Z numbers at the same neutron number N and similarly for N or N-Z. The most striking examples are the shell closures. For example, figure 1 in ref. [16] shows the interest in measuring the mass of ^{23}N to strengthen or show the limits of the observed decrease of neutron binding energies for O, F and Ne after neutron number N=15 [17]. This effect is well taken into account by spherical Hartree-Fock calculations with the density functional method of Lombard [18] and has also been interpreted as due to the interplay between two-body interactions in the $d_{5/2}$ and $s_{1/2}$ neutron orbitals [19]. In the same figure one can see that ^{27}F seems too loosely bound compared to what is expected from the trends in neighboring nuclides. The three available data for this nuclide are neither precise nor in agreement. A better knowledge of this mass would allow to better estimate whether the doubly-magic ^{28}O has a chance to be neutron-stable or not [17].

Another example in figure 6 of ref. [16] points to N=108 and the importance of measuring the masses of Ir, Pt, Au and Hg isotopes around this neutron number ([15], section 11.7), especially since radii measurements on these nuclides indicate prolate to oblate (or possibly triaxial) shape transitions [20]. Their half-lives are not short, but a difficulty may be that existing isomers may influence the results of direct mass measurements. An excellent resolution, or otherwise an analysis of the appearent mass as a function of time will be required to get satisfactory results.

It would also be interesting to know if the double structure shown to exist by the ISOLTRAP experiment [21] in the light Cesium isotopes between N=63 and 72 would be present for neighboring elements, like Ba.

2.2. Irregularities on the mass surface

Another general direction can be given by observing local irregularities of the surface of masses. Each of them may point either to an erroneous measurement or to new physical behaviour. Remeasurement of these and of neighboring nuclides is therefore highly desirable. A list of the most important among them can be found in part I, tables B and C of the most recent "Atomic Mass Evaluation" [4]. Many more cases can be found by examining the figures in part III [16] (see e.g. ^{65}Fe and ^{66}Co).

2.3. Conflicting data

Mass measurements of interest are also those that would help solving conflicts among data. These are clearly identified in part IV, table II, of the "Atomic Mass Evaluation" [15] where they show large deviations v/s (see e.g. ^{115}Cd(β^-)^{115}In on p.280)

2.4. Checking connections

The last, but not least, general direction is given by the examination of the connections in masses among nuclides. We give below some examples of nuclides of interest selected from observing the diagrams of connections for the input data as in part I of the most recent Atomic Mass Evaluation (figures. 1a–1h of ref. [4]).

In selecting stable nuclides to be measured with the very highest precision, it pays to check the available connections between them from reaction energies. As an example, we mention the chain of neutron capture reactions and β-decay energies (the values in parentheses are the precisions of the connections, in keV):
^{132}Ba (0.4) ^{133}Ba (1.0) ^{133}Cs(0.08) ^{134}Cs (0.4) ^{134}Ba (0.12) ^{135}Ba(0.04) ^{136}Ba (0.03) ^{137}Ba (0.04) ^{138}Ba(0.04) ^{139}Ba
Measurement of one of these nuclides immediately also improves the other ones, as is illustrated by the fact that all of them had a precision of 6 keV in our 1983 mass table, but only 3 keV in our 1993 one. Perhaps even more important: measurement of more than one of them allows a desirable check on the accuracy, both of the mass measurements and of the mentioned reaction energies.

On the other hand, some nuclides are weakly connected to other, better measured isotopes. Thus ^{107}Ag, a nuclide of which the mass used to be of importance for the determination of the Farad through electrolysis [22], is given with a precision of 6 keV in our 1993 table, though nuclides with somewhat higher or lower mass numbers (^{109}Ag, ^{104}Rh) are given with precisions of 3 keV or even better. Elimination of such bad spots is desirable.

As for unstable nuclides, it is a pity that many series of α-decays are not connected to the system of nuclides for which the masses are known. Especially important among them are the series of even-Z even-A cases, since for them α-decays lead to the ground-states of the daughter nuclides and therefore give valuable values for the full decay energies (which, more often than not, is not the case for other A, Z combinations). Such series, as for example ^{152}Yb(3.1 s)–^{168}Pt, ^{164}Hf(1.8 m)–^{184}Pb(0.55 s) or ^{198}Pb(2.4 h)–^{218}U(1.5 ms), can be seen on figures 1e–1g of ref. [4]. In one such series, ^{150}Er(18.5 s)–^{170}Pt(6 ms), experimental mass values are given in our 1993 tables with reported precisions of 100 keV, and we suspect that all mass values in this series should be about 700 keV higher (see tables B and C of ref. [4]). In the case of the ^{170}W(2.42 m)–^{190}Po(10 ms) and the ^{178}Os(5.0 m)–^{198}Rn(50 ms) series, the reported precisions are quite low (350 keV and 200 keV) and demand drastic improvements. The cases mentioned have not particlarly small half-lives. But, evidently, cases further from stability with millisecond half-lives would also be quite interesting.

In connection with the case of N=108 discussed in section 2.1., it would be quite important to measure masses along the following α-decay series: ^{176}Os(3.6 m)–^{192}Po(34 ms), ^{180}Os(21.5 m)–^{200}Rn(1.06 s) and ^{190}Hg(20.0 m)–^{206}Ra(0.24 s).

Here also, measurement of more than one member in each series would provide valuable checks. For other than even-even series, measurement of more than one member could give information on the energies of final levels reached preferentially in the α-decays.

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