(*To be published in* Nuclear Physics A 595, Dec. 95)

The 1995 update to the atomic mass evaluation

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Abstract

This paper presents a complete list of "mass excesses", which is an update of the similar values in the 1993 Atomic Mass Evaluation, and a list of the isomeric transition energies which are best determined from a combination of masses. A list of new or revised experimental data for mass determination is also given. The significance of these data, and their possible deviation from earlier ones or from expectations are discussed. Adopted new procedures and policies are presented.

1. Introduction

In 1993, we published the "1993 Atomic Mass Evaluation" (Ame'93) [I]–[IV], a set of tables and graphs based on an evaluation of atomic masses from experimental data and, for a few nuclides, from values obtained by extrapolation.

The present work is the first update of those tables in a regular series as announced in Ame'93. Updates are accompanied by electronic versions of the full mass table and tables of reaction and separation energies, distributed by the newly created Atomic Mass Data Center (AMDC) and by the usual nuclear data centers as for the 1993 ones [1]. The published version of the present update contains only a full list of atomic mass excesses ($M - A$) (Table I) and of isomeric excitation energies (Table II), a list of new or revised experimental data (Table III), and comments on the new data and their evaluation. A list of references for these data is also given in Table III. The next update is foreseen in 2 years and will be followed by a full publication of the AME in 1999.

The mass excess values given in Table I are expressed in energy units. For the precise meaning of the energy unit we refer to [IV], Section 2. Full mass values or nuclear binding energies can be calculated as described in Section 3.

In the description below quoted works that are also referenced in Table III are given in the same Nuclear Data Sheets style as there.

The cut-off date for the data from literature used in the present Ame'95 evaluation was April 30, 1995. Preprints and private communications that were received until June 30, 1995 have also been included. The final calculation was performed in October 1995.

2. New features

In Ame'93, the table of masses and of nuclear-reaction and separation energies gave values *"derived from all experimental data"* where available. Special tables (Table B and Table C in [I]) gave cases where, based on an analysis of systematic trends of masses, or of mass differences like decay energies and neutron and proton binding energies, we recommended to replace some particular (see Section 9) experimental data by values considered more dependable. In the present Tables I and II, these more widely used *"best recommended values"* for masses and isomeric excitation energies are given. Table IV lists the few new or removed cases in this category, and the consequences on the mass values if the deviating data were used. The table of masses derived from "all experimental data" is, as usual, available electronically.

The names and the chemical symbols of the elements 104 to 109 as recommended recently by the Commission on Nomenclature of Inorganic Chemistry of the International Union of Pure and Applied Chemistry (IUPAC) were used: 104 dubnium (Db), 105 joliotium (Jl), 106 rutherfordium (Rf), 107 bohrium (Bh), 108 hahnium (Hn), and 109 meitnerium (Mt). This choice is made for convenience and does not express a preference. For the elements 110 and 111 we use the provisional symbols Xa and Xb.

Among the new features in this evaluation, our policies in the treatment of isomers has been improved. As in Ame'93, we present a list of excited states involved in this evaluation (Table II). However, excitation energies following from precision γ-ray measurements are combined, where necessary, with reaction energies to the relevant state. Thus, such energies are only mentioned in remarks to the table of input data. Excitation energies obtained from combination of masses of different nuclides are best determined from the evaluation of masses. Therefore we think it useful to give, in each of our updates, a full list of those excitation energies, as we do for the ground-state masses. Section 8 is devoted to the isomer issue and discusses further our policies, illustrated by some particular cases.

In making estimates for unknown masses we take into account all available experimental information. In particular, knowledge of stability or instability against particle emission or limits on proton or alpha emission yield upper or lower limits on the separation energies.

Table A: The most precise masses

	Mass excess (keV)		Atomic mass (μu)	
^{1}n	8071.3228	0.0022	1008664.9232	0.0022
^{1}H	7288.96940	0.00064	1007825.03214	0.00035
^{2}H	13135.7196	0.0010	2014101.77799	0.00036
^{3}H	14949.7942	0.0015	3016049.2675	0.0011
^{3}He	14931.2036	0.0014	3016029.30970	0.00086
^{4}He	2424.91109	0.00095	4002603.2497	0.0010
^{13}C	3125.01081	0.00095	13003354.8378	0.0010
^{14}C	3019.8923	0.0037	14003241.9884	0.0040
^{14}N	2863.41701	0.00083	14003074.00524	0.00086
^{15}N	101.43823	0.00085	15000108.89844	0.00092
^{16}O	−4736.9983	0.0015	15994914.6221	0.0015
^{20}Ne	−7041.9297	0.0019	19992440.1759	0.0020
^{28}Si	−21492.7931	0.0024	27976926.5327	0.0020
^{40}Ar	−35039.8897	0.0039	39962383.1232	0.0030

3. Table of mass excesses in keV*

Table I gives values in the keV* units defined in [IV], Section 2. Only for the most precise values, it is important that they are a fraction of a ppm different from the same quantities expressed in the international volt. The masses M in mass units u, and the binding energies B in keV* can be calculated using the relations:

$$\begin{aligned} M &= A + D/931493.86, \\ B &= Z \times D(\mathrm{H}) + N \times D(\mathrm{n}) - D \end{aligned}$$

with respective approximate standard deviation errors:

$$\begin{aligned} m &= \delta/931493.86, \\ b &= \sqrt{(Z \times \delta(\mathrm{H}))^2 + (N \times \delta(\mathrm{n}))^2 + \delta^2} \end{aligned}$$

in which D is the mass excess $[M(\text{in u}) - A]$, in keV*, and δ its one standard deviation error, as given in Table I. In almost all cases the error contribution due to H can be neglected, but that due to the neutron makes, in a few cases, the values of B less precise than their corresponding D.

For the most precise masses the formula for calculating m is not exact. Table A gives for them values of both mass excesses and atomic masses with increased significant digits.

The uncertainties in mass differences, e.g. the β-decay energies given in [I], cannot be derived correctly from the present tables. They can be found in the tables made available electronically [1]. In all but a few cases, they differ very little from the uncertainties given in [I] and [II].

A table of correlation coefficients as in [II] is not given here but is available electronically from the Atomic Mass Data Center [1].

4. New elements and a new (semi-) magic number

Very recently, the Darmstadt group [95Ho03], [95Ho.A] and [95Ho04] announced the discovery of isotopes ^{269}Xa, ^{271}Xb and ^{272}Xb of the elements 110 and 111. Earlier, a Berkeley group [95Gh04] had announced the possible observation of ^{267}Xa. Although the reported α-particle energies probably do not belong to branches to the ground-states of their daughters, they nevertheless give information of use for getting good estimates for the masses of very heavy nuclides.

Another important discovery in this region is due to a collaboration of Livermore and Dubna physicists who found the existence of a sub-shell closure at $N = 162$. In a first paper they reported the observation of two new isotopes of element $Z = 106$ and interpreted the results as evidence for extra stability at $Z = 108$ and $N = 162$ [94La22]. And at the ENAM'95 conference, Oganessian et al. [95Og.A] reported the discovery of ^{273}Xa, the first nuclide with $N = 163$, which exhibits a drastic increase of the α-energy, confirming the subshell closure at $N = 162$. Such an effect could be responsible for the amazing fact that the increasing probability for spontaneous fission, so evident for elements until $Z = 104$, is far less prominent than expected beyond this element. This closure was predicted by Cwiok et al. [2]. It is worth mentioning that, in a recent paper, Brenner et al. found, in an analysis of the first 2^+ states in even–even nuclides, that a spherical subshell might close at $N = 164$ [3]. It would be interesting to repeat this analysis with the assumption of a sub-shell closure at $N = 162$ as observed by [95Og.A].

5. New data from mass spectrometry

5.1. Stable nuclides

Data with high precision (of the order of 1 part in 10^{10}) are reported by the MIT group [94Di.A] using a Penning-trap spectrometer. A careful evaluation of the systematic errors and analysis of the obtained data allowed this group to achieve very satisfactory internal consistency checks. Their impressive report [94Di.A] is, in this sense, recommendably complete. Yet, they should not remain unchallenged: checks by another group, at the same level of precision, are highly desirable to strengthen the validity of their mass measurements, and transform these very precise measurements into very accurate ones. Some of their results were already used in the 1993 tables and have been revised only slightly (except for the ^{12}C+^{2}H–^{14}N combination). New is the result for ^{28}Si where 2 orders of magnitude in precision have been gained compared to Ame'93. From this result follow improved values for the other stable Si isotopes. This may become important in future for the definition of the mass unit, the kg. If it is defined in terms of the atomic mass unit, by accepting a defined value for the Avogadro constant, realization of a mass standard may be best done by constructing an ultrapure Si crystal. New also is the result for ^{15}N, of importance for the calibration of γ-ray energies (see Section 6.1).

Other groups working with Penning-trap spectrometers in Ohio and Stockholm have obtained results for D, ^{20}Ne, ^{22}Ne and ^{28}Si (and a preliminary value for the hydrogen mass) which confirm, at their respective level of accuracies, the corresponding more precisely known masses. Also interesting is the measurement of ^{86}Kr [95Ca.A] improving the accuracy of this mass by a factor of 4.

Classical mass-spectrometry on stable and nearly β-stable nuclides along the "backbone" is also producing results, like the new values for Xe, obtained at Winnipeg. Their planned measurements on Hg isotopes to solve the mercury problem (Section 7 in [IV]) are eagerly awaited.

5.2. Nuclides far from stability

The nuclides somewhat removed from the line of stability, especially the most exotic ones, are of interest in helping to determine the yet poorly known trends of the mass-surface, i.e. the behavior of the binding energies for large differences between numbers of neutrons and of protons. This is reflected in the excessively large deviations amongst the predictions of the models (see e.g. ref. [4]) notably along the astrophysical r-process paths. Yet, the longest isotopic chains known with fair precision (40 keV) does not exceed 28 nuclides (for Cs) or 33 in the case of Pb (though interrupted).

We must, in the first place, mention the new Penning trap measurements [95Ha.1], [95Bo.1] on heavy Rb, Sr, Cs and Ba isotopes, obtained after the move to the new ISOLDE facility. They led to drastically improved accuracies far from stability. For the lighter Rb isotopes, the differences with earlier data on isobaric Sr mass values agree quite well with the reported values for the Rb(β^-)Sr decay energies. This makes it even more amazing that the Sr values do not agree so well with the reported β-decay energies of these isotopes and their daughters. The dependability of the Penning-trap measurements after dismounting and reassembly of the apparatus is assessed by the perfect agreement obtained for the heavy Cs and Ba isotopes before and after the move. In our 1993 mass adjustment, the ^{91}Sr(β^-) decay energy was already one of the three somewhat severe difficulties mentioned in Section 3.2 of [IV]. Values of 2669(10) [53Am08], 2684(4) [73Ha11] and 2704.5(3.0) keV [80De02] were reported, to which one could add the McGill value 2709(15) [83Ia02]; but the new doublets implicate a value 2730(10) keV, higher than all of them. Re-studying the three papers mentioned, we found no reason to distrust the first two, measured with magnetic spectrometers. The third was measured with a semiconductor spectrometer; but we note that the error above is the one mentioned in the abstract and that the text mentions errors of 5 and 8 keV. But even the latter does not quite cover the difference with the mass spectrometer result. This is just one example, albeit the most worrisome, of difficulties we had with the new values. Our studies, together with that of Hartmann [94Ha.A], led to a revision of some error values reported by the authors in ref. [80De02] and of the consistency factors (see below) of some other mass-spectrometric data. The decay energy of ^{91}Rb(β^-) has also been increased due to the feeding of the 93.628 keV level in ^{91}Sr. Nevertheless, the overall consistency of the data in the $A = 88$–96 region leaves something to be desired.

A very recent improvement [5] in this Penning trap spectrometer allowed mass-measurements [95Be.A] of some rare-earth nuclides (^{143}Pm, ^{139,140,142,143}Sm and ^{143}Eu). The previously well determined masses are checked within the estimated uncertainties. Most interesting is the result obtained for ^{140}Sm for which in Ame'93 we gave a "recommended" mass 380 keV below the one derived from decay data: the new result agrees perfectly well with our estimate. The value obtained for ^{143}Eu is in very good agreement with the new result from St Petersburg [94Po26]; they both solve the earlier (slight) discrepancy among 3 β^+-decay energies for this nuclide (see [IV], p. 294): the value of [74Ch21] is now at 3.5σ from the adopted average. In these Penning trap experiments, contaminations give clear signatures and we can thus have confidence in the obtained results. For ^{154}Dy some doubt existed in the early analysis used here about a possible contamination, therefore we did not accept it in the present evaluation.

A new experiment by the SPEG group at GANIL has been mentioned recently [6] for proton-rich nuclides along the rp-process path, but unfortunately their analysis was not completed in time to be included in the present update. Also at GANIL, a new method using the CSS2 cyclotron [95Le.B] yielded the first direct mass-measurement of ^{100}In with a precision of 420 keV, in perfect agreement with the value found indirectly in its delayed-proton decay spectrum [95Sz01].

Last but not least, the ESR group [7] reported the measurement of a wealth of new masses in the p-rich region around Pb. They could not be used here, but it is expected that they will have an important contribution to the next update.

5.3. Mass-spectrometric consistency factors

In the past, we found reasons to increase errors reported for results obtained with classical mass spectrometers. This is not so for results reported with Penning trap instruments. Therefore, in this Ame'95 update, we no longer increase the errors reported for them. This is also true for the new ISOLTRAP measurements on Rb, Sr and rare-earth nuclides: they are accompanied by some new measurements on neutron-rich Cs and Ba isotopes which agree satisfactorily with reaction and decay data. We therefore decided for the time being, to accept these Penning trap measurements as they stand, and to live with the bad consistency reported in the previous section.

We found that on-line mass measurements of the Orsay-ISOLDE group performed in the early eighties agree somewhat less good with newer data than suggested by the "consistency factor" of 1.5 that we used earlier. We felt forced to increase it to 2.5. As a result a few mass values, for the most exotic nuclides, are now given with larger uncertainties than in Ame'93.

Also the mass measurements of the St-Petersburg group with the PRISM spectrometer [8], performed until now only for 7 isotopes of Rb, do not agree well with other data, exhibiting a systematic deviation with N and a large (v/s = 4.01) average discrepancy.

The calibration procedure in which elements (Zr, Nb, Mo) different from the measured Rb were used, may have resulted in different ionization locations in the source, which may be a reason for such an effect. No other measurements with the same spectrometer have been reported since then. The necessary consistency factor CF = 4 is such that these data are outweighed by the ensemble of all the other ones.

6. New reaction and decay data

Whereas mass-spectrometric data almost always yield experimental values for masses, it is not always so for energy measurements from decays or reactions. The latter may occur between nuclides for which no mass values can be determined. If then a later experiment determines the mass of one of them, the other one follows and sometimes even more. A nice example can be found in the determination of the isomeric excitation energy of ^{181}Os by the ISOCELE group [95Ro09]. The mass of the excited isomer being known from its β^+-decay, not only the ground-state mass of ^{181}Os is now known, but also the masses of ^{185}Pt from its α-decay to ^{181}Os, of ^{185}Au from its β^+-decay and of its α-daughter ^{181}Ir.

Among the newly (since the Ame'93) measured ground-state masses, one may note nuclides beyond the neutron drip-line (^{10}He and ^{16}B) by groups at RIKEN and at HMI, and beyond the proton drip-line (^{105}Sb) by the Berkeley group; and also very neutron-rich nuclides (^{134}Sn, ^{154,155}Nd and ^{199}Ir) at Studsvik, Idaho and Daresbury, and proton-rich ones (^{86}Mo, ^{100}In, ^{137}Sm, ^{139}Eu, ^{156}Er, ^{207,208}Ac, ^{211}Th, ^{213,214}Pa, ^{219}U and ^{228,229}Pu) by groups at Kyushu, Leuven, Dubna, GSI and Jyväskylä (with RITU).

Important information is also brought, as stated above, by new data not connected to known masses. Such is the case of the proton decay of ^{112}Cs, ^{167}Ir and ^{185}Bi (Daresbury and Argonne), the β^+-decay of ^{134,135}Pm (Dubna) and the α-decay of ^{172}Au (Daresbury). Also, in the region ($Z \geq 82, N \leq 126$), where not so many masses are known, the several α-decay energies measured at RITU plus some others from RIKEN, LBL and GSI help map the region; they are milestones awaiting connections to the backbone of masses.

Some very heavy nuclides and more especially new elements (see Section 4) have been identified and their half-lives and α-decay energies determined. With few exceptions the observed α lines do not connect ground-states, but they still give useful information in getting good estimates of the Q_α energies.

6.1. Gamma-ray recalibration

The mass spectrometric result on ^{15}N reported by the MIT group [94Di.A] (see Section 5.1) is of importance for the calibration of γ-ray energies. The change due to this result is rather larger than the uncertainty reported for the 1975 [9] value. The latter comes from notes on only one measurement left after the death of Lincoln Smith and the deviation is therefore not so surprising. Recent measurements on the ^{14}N(n,γ)^{15}N reaction by an Oak Ridge-Los Alamos group [94Ju.A] confirm the new value. It will lead to a recalibration of γ-rays in precise (p,γ) and (n,γ) reaction energies. On average, the energies are increased by about 6 ppm. The necessary corrections are numerous but only slight. They will be made in next update.

6.2. Proton emission

Several new cases have been investigated by groups at Argonne (Atlas), Berkeley, Daresbury and Garching. An older result on ^{121}Pr, not included in Ame'93, was a reason to add a number of estimated mass values between this nuclide and those given in [I]. In the estimates from systematic trends, proton decays are often quite useful in changing extrapolations into interpolations!

Noteworthy is the newly reported proton energy of ^{112}Cs which is smaller than that in ^{113}Cs, contrary to the normal increase with decreasing neutron numbers, probably reflecting a stronger neutron-proton pairing energy. Such an inversion is also observed for ^{108}I for which an upper limit of 500 keV is reported for the energy of the emitted protons. Moreover, in the latter case, since this energy must be positive, we represented this result as a measured value.

Interesting are also the new results of [95Da.A] on proton emission from nuclides up to ^{185}Bi. The results they found for proton emission of the two isomers of ^{167}Ir, and for their α-decay chains, may lead to a series of interesting isomeric excitation energies.

6.3. Other decays and reactions

Since the Ame'93 new α-energy measurements have been performed by groups at Leuven, Oak Ridge, Daresbury, Orsay and Dubna. The number of new results on β-energy measurements from groups at Buenos Aires, Dubna, GSI, Idaho, Jyväskylä, Notre-Dame, Studsvik, and elsewhere is also quite impressive. At the same time, some β^--decay data have been revised (see e.g. Section 9) often following a better knowledge of the decay schemes, or their errors have been re-evaluated (see e.g. Section 5.2). They are reported in Table III.

Quite important are the very precise differential reaction energies performed at Heidelberg on ^{40}Ar, by the Garching group on Th isotopes and also by the Tübingen-Indiana group on Hg isotopes. Thermal neutron capture γ-decays, that provide some of the most precise data, have been reported by groups at ILL and Latvia, for Ni and Ba isotopes. Among the latter we were worried by the strongly discrepant results (5.8σ) for ^{134}Ba by [93Ch21] when compared to the previous ones obtained at McMaster [90Is07] and Latvia [93Bo01]. We tend to trust the work of [90Is07] in which the calibration is carefuly described, whereas [93Bo01] who obtain the lowest value give no data on calibration. We decided to provisionally not use the latter result and live with the remaining discrepancy among the other two, which is treated by the procedure described in [IV], Section 3.2.

6.4. Final levels in α-decay

In α-decay, the energy of emitted α-particles is usually measured with good accuracy. For nuclides with an even number of protons and neutrons, the strongest branch always goes to the ground-state of the daughter. Unfortunately, this is not so for other nuclides and in many cases the energy level fed by the observed α-ray is not known. One then has only a lower estimate of the decay energy (except of course when the observed α-ray originates from an upper isomeric level).

In the region of deformation, where the Nilsson model holds, the "favored" and often most intense α-decay of an odd mass nuclide feeds the level in the daughter with the same Nilsson model quantum number assignment as in the parent. Mostly, this is not the ground state. For the region above $A = 225$, we noticed already for our 1993 mass evaluation that the distances between Nilsson particle levels in known cases did not vary greatly. We therefore made estimates, based on these systematics, of excitation energies of final levels in cases where they were not observed. In this way, we derived what we judged to be good estimates for the α-decay energies in such cases (see [10]). The values computed with the help of such estimates (and, for the rest, with purely experimental results) were indicated with a special symbol ($*$) different from that used for systematics ($\#$). This policy is generalized in this Ame'95 update.

Unfortunately, the systematics of Nilsson assignments to nuclides with odd numbers both of protons and neutrons is more complicated. We did not try to make a similar analysis for them. A first review of the deformed region $A = 155$–185 seems to indicate that extrapolations of excitation energies of Nilsson levels are less dependable there.

6.5. The ^{10}Li ground-state mass

The important question of which state is the ground-state often occurs in the mass evaluation. An example is given by ^{10}Li, which is unbound to particle emission and whose states are observed as resonances. Masses have been measured in recent experiments at MSU [94Yo01] and at HMI [95Bo.A]. The apparent discrepancies among their results, and also with previous studies, are due to the different selectivities of the reactions used. The mass measured by [95Bo.A] at 240(60) keV above the one neutron threshold unambiguously corresponds to a 1^+ state with the configuration of a $1p^{1/2}$ neutron resonance coupled to the $3/2^-$core of ^{9}Li. The main peak seen at MSU [94Yo01] at 540(60) keV corresponds to a p-wave neutron resonance, and thus most probably to the 2^+ state of the same configuration, while a much weaker 'non-conclusive' peak that would correspond to an s-wave resonance might be observed at a lower mass, less than 100 keV above threshold.

Combined results of two other experiments, at MSU [11] and at GSI [95Zi.1], give strong evidence for an s-wave strength rising towards the threshold that either could be interpreted as a final state interaction without the character of a resonance, or as a true resonance. In the latter case it would be most probably a 2^- state.

We accept here, provisionally and until improved measurements are performed, the proposal of P.G. Hansen [12] based on the GSI result of a true resonance with an excitation energy below 50 keV, corroborating the weak peak of Young [94Yo01] mentioned above. However, the user of our tables should keep in mind that the resulting adopted value for the ground-state mass of ^{10}Li is not final and that in the case where the s-wave strength near the threshold should be later proved not to be a resonance, the ground-state mass would be some 200 keV higher.

6.6. ^{99}Rh isomers

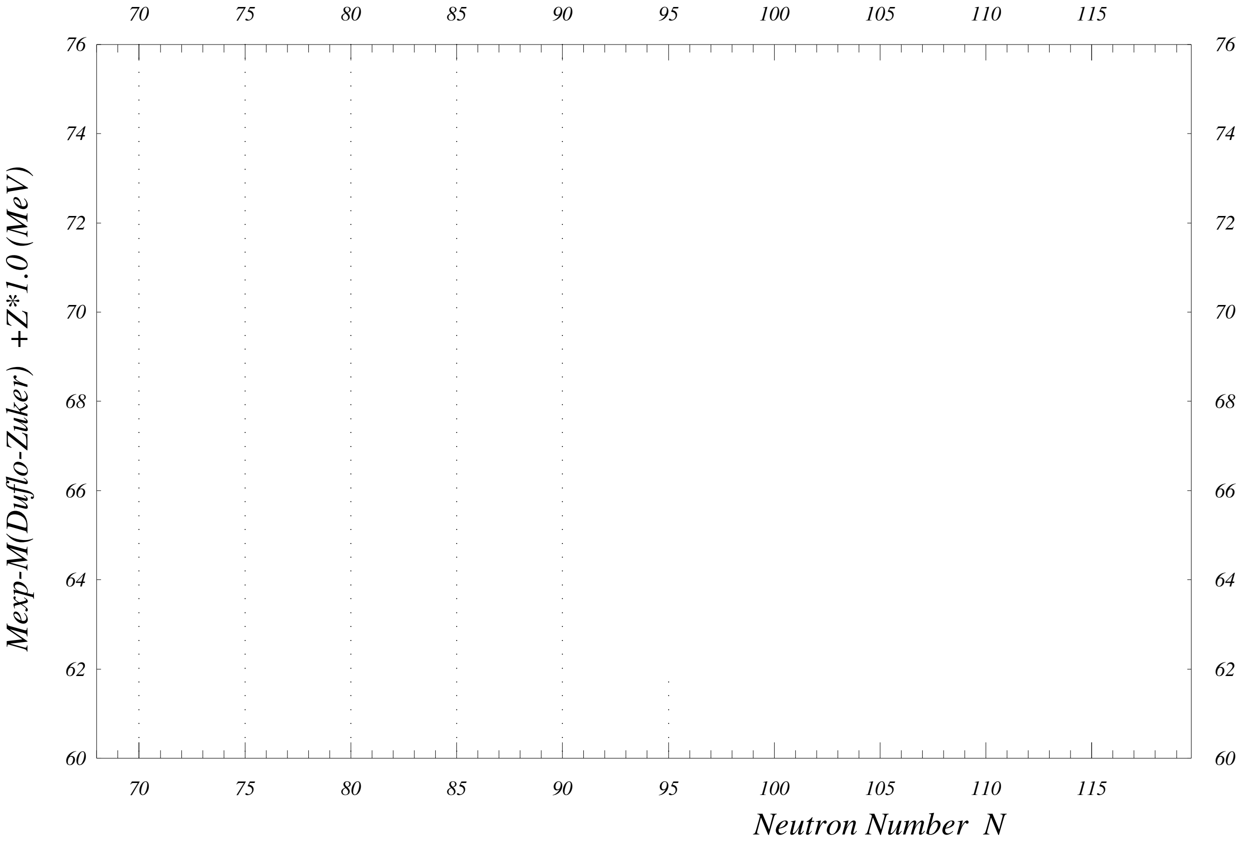
A new publication [13] confirms an earlier one of [69Ph01], that the 4.7 h $9/2^+$ isomer in ^{99}Rh is 64.3(.4) keV above the 16.1 d $1/2^-$ one. We had first accepted the [74An23] conclusion that the β-decay energy of the 16.1 d isomer is larger than that of the 4.7 h one; the data of [59To.A], given only in an abstract, we trusted less. Unfortunately, the J^π systematics (see Section 8) of ground-states and excited isomers for odd-Z, even-N nuclides in this region do not show a preference for either of the two alternatives. In view of the new result, we restudied the [59To.A] work. Their rather extensive γ-β coincidence data in combination with the modern decay scheme [14] lead to the conclusion that the decay energies calculated from the four [59To.A] β-branches agreed excellently and that the lower branches found in the singles β-spectrum by [74An23] must be considered mixtures and therefore should be given little weight. A happy consequence of the resulting changes is that some earlier bad agreements with other data almost disappear.

7. Estimated mass-values for nuclides far from stability

Quite often the users of our tables are interested in unknown nuclides that are within reach of the present accelerators and isotope separators technologies. We therefore decided to estimate values for all nuclides for which at least one piece of experimental information is available (e.g. identification or half-life measurement or proof of unstability towards proton or neutron emission). In addition, we want to achieve continuity of the set of nuclides for which we estimate mass values in N, in Z, in A and in $N-Z$. This set is therefore the same as the one defined for the NUBASE database [15]. As a result, the total number of nuclear ground states for which masses are given is increased from 2650 in Ame'93 to 2931. In estimating mass values for the new nuclides, some of the methods and tools described in reference [4] have been used, together with the predicted masses from the models of Groote–Hilf–Takahashi [16] and Duflo–Zuker [17], where only the spherical parts have been considered, as illustrated in Fig. 1 for the second model.

8. Treatment of excitation energies of isomers

The excitation energy of an isomer is derived either from measurement of γ-transition energies, or from a combination of reaction energies, particle decay energies and some-


Mexp-M(Duflo-Zuker) +Z*1.0 (MeV)
Neutron Number N
70
75
80
85
90
95
100
105
110
115
60
62
64
66
68
70
72
74
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