Eur. Phys. J. A **25**, s01, 9–13 (2005)
DOI: 10.1140/epjad/i2005-06-198-5

EPJ A direct
electronic only

Atomic Mass Evaluation 2003

A.H. Wapstra[a]

National Institute of Nuclear Physics and High-Energy Physics, NIKHEF, P.O. Box 41882, 1009DB Amsterdam, The Netherlands

Received: 12 September 2004 /
Published online: 15 August 2005 –

Abstract. The new collection of atomic masses, AME, published in December 2003, comprises evaluated experimental masses and estimates for several unknown ones.

PACS. 21.10.Dr Binding energies and masses

1 Mass spectroscopy and reaction and decay energies

Several times in the past, most recently last year [1], we published what we thought were best values for atomic masses of nuclear ground states from experimental data. They were derived from measurements of atomic masses, and those of nuclear reactions and decays. Experimentalists invented recently three ways to make this task more complicated:

A. Mass measurements are now often made for rather far unstable nuclides. Nice! But not rarely the resolution was not sufficient to separate isomers. We therefore had to develop methods to derive valuable information on ground-state masses from such measurements.

B. Some groups, sometimes without saying so, used a definition for reaction energies different from the conventional one. They did accept Q as the conventional relation between the masses of initial and final nuclides (including those of the bombarding particle and the one leaving the final nuclide):

$$Q = M_i - M_f + M_p - M_s$$

but took M to be masses of bare nuclei, not those of neutral atoms. They called it "Q corrected for screening". Confusion resulted; even so much that in a certain paper investigating two reactions they gave, for the two reaction energies, values according to different definitions! And since our purpose is to calculate masses of neutral atoms, our input values have to be the ones according to the conventional definition. We therefore are sorry that even the Nuclear Data Group, in an issue on proton decay energies [2], used the unconventional definition!

C. Groups fail sometimes to realize that the data they give are insufficient for using them in an adequate way, anyhow for our purpose. I want to mention a curious example. Some very proton-rich nuclides decay by both proton and α emission, and have isomers that do the same. And the properties of proton decays then allow to derive a value for the isomeric excitation energy. If now, as not rarely occurs, one of the two α-decays feeds a ground state, the other its isomer, they then derive too a value for the excitation energy of that isomer. The values that they give for the four differences between four different states evidently form an overdetermined set. I will consider an example (see table 1) [3].

Table 1. Example of overdetermined input data (all keV).

$^{163}\mathrm{Re}^m$	$Q(\alpha) = 6568(5)$	$\leftarrow {}^{167}\mathrm{Ir}^m \rightarrow$	$Q(p) = 1246(7)$
	$E_{\mathrm{exc}} = 115.1(4.0)$		$E_{\mathrm{exc}} = 175.3(2.2)$
$^{163}\mathrm{Re}$	$Q(\alpha) = 6507(5)$	$\leftarrow {}^{167}\mathrm{Ir} \rightarrow$	$Q(p) = 1071(6)$

The excitation energy of $^{167}\mathrm{Ir}^m$ "has been determined from the measured proton energy difference, using the peak centroids and the energy dispersion". Evidently, they are correlated: the error in their difference is much smaller than follows from the separate errors. Use of all four data in our least squares evaluation would unduly decrease errors in the two $Q(\alpha)$'s, which must also be correlated: they yield a value for the difference in the two E_{exc}'s with an error of only $(4.0^2 - 2.2^2)^{0.5} = 3.3$. No exact solution for this problem can be derived from these experimental data. As best solution, we omit one of the four data and manipulate values and errors of the remaining three to yield final values differing not too much from those given by the authors.

2 Backbone

If desired in energy units, we used in our earlier atomic mass evaluations an unit based on accepting a standard constant in the Josephson relation between energy and

[a] e-mail: wapstra@nikhef.nl

Table 2. Conversion of mass units to energy ones.

was	1 u = 931 493 860 (70) eV_{90}
[4]	1 u = 931 494 009.0 (7.1) eV_{90}
was	1 eV_{90} = 1.000 000 006 (63) eV
[4]	1 eV_{90} = 1.000 000 004 (39) eV

Table 3. Proton-neutron capture gamma-ray energy values.

[6]	2224 589.0 (2.2) eV_{90} = 2388 176.8 (2.4) nu
[5]	2224 566.0 (0.4) eV_{90} = 2388 169.95 (0.42) nu

frequency. For our 2003 mass evaluation we considered whether this was still useful. As a point of departure we used the recent evaluation of natural constants by Mohr and Taylor [4] (see table 2). The resulting differences with earlier data are important only in very few cases. On the other hand, a relatively larger difference was caused when a remeasurement of the γ-rays emitted in the H(n, γ) reaction [5] revealed an error in the earlier results [6] (see table 3). The difference has a consequence for all reported (n, γ) reactions; among them for the ^{14}N(n, γ)^{15}N one. But in this case, new mass spectroscopic measurements for ^{14}N and ^{15}N also gave new results not quite agreeing with earlier ones. This is important since ^{14}N(n, γ)^{15}N is often used for calibrating (n, γ) results. Even though for several of them the differences are not large, they add up along the line of stability, the "back-bone". For that reason we made the necessary correction in many cases. Unfortunately, lack of time and of the neccessary information prevented us doing so for a large number of new measurements presented to us, in preliminary shape, by Firestone *et al.* [7]. We hope that their final report will allow us to treat them in the way they deserve.

Use of Penning traps resulted in better values for several light elements. Among them were the measurements on ^{14}N and ^{15}N just mentioned. Checks showed that the new results were very dependable. Yet following difficulty remains. The new mass measurements for the stable helium isotopes differ somewhat more from the previous ones than their error estimates. And especially for measurements on ^{3}He, discussions with the authors [8] indicated that the claimed errors must be considered optimistic. It is hoped that new measurements will clear the situation.

3 The TOFI mass values

Measurements in Los Alamos, using flight time measurements on reaction products, were mentioned at ENAM1998 [9]. The authors were so kind to give us a list of resulting useful mass values of nuclides from ^{44}Sc to ^{77}Zn, with precisions of the order of a few times 100 keV. It is a pity that no discussion of them has yet appeared in the open literature. We accepted the data as reported, but feel that at least some results should be checked with newer instruments.

4 Mass values from the Isobaric Multiplet Mass Equation

In the region $A < 60$ several atomic mass values have been reported that were derived with help of data on delayed proton decays. Such measurements may give mass values of isobaric analogues of ground-states of proton-rich nuclides. Use of a quadratic Isobaric Multiplet Mass Equation, combining such results with those for other isobaric analogues, then yield a value for that proton-rich nuclide. It was reported [10] that for $A = 33$ the IMME gave a wrong result. But later work showed that the discrepancy disappeared when one of the other measurements involved was repeated. Yet, we decided that we would use such results only as indication for a value chosen for that mass but reported by us as derived from systematics. Mass values derived from symmetry relations were treated in a similar way. Another source of usefull information were measurements on proton decays. Even if the ground-state decay energy could not be determined, measurement of the half-lives allowed to get estimates for the decay energies, as shown, *e.g.*, by Janas *et al.* [11].

5 Mass values from Penning traps

The measurements on very light isotopes are not the only valuable new results using Penning traps. Many results have been reported, both near stability but also far removed, even up to very proton-rich ones. As an example I want to mention the new ^{133}Cs results [12]. It is now known with a precision of 22 eV - but the new value is 5 keV higher than the one we gave in our earlier evaluation, to which an error of 3 keV was assigned. Very precise values have now also been reported for ^{23}Na, ^{85}Rb, ^{87}Rb [12], ^{36}Ar [13] and ^{76}Ge and ^{76}Se [14]. For early mass spectroscopic results, which mostly formed overdetermined sets, we found in their least-squares evaluations that, as a rule, the assigned errors were underestimated by, mostly, some 50%. We took this into account in our evaluations of their combinations with one another and with reaction and decay energy results. The just-mentioned Penning trap results also form an overdetermined set. We were pleased to find, that for them the consistency factor did not differ significantly from unity.

The ISOLTRAP group continued their measurements with a Penning trap. New data, with a precision only slightly worse than 10 keV, became available for nuclides from ^{114}Xe to ^{154}Dy [15,16]; and from ^{182}Hg to ^{203}At [17].

6 Other new mass measurements. The problem with isomers

In Darmstadt [18], measurements were started with, essentially, the same technique as TOFI, but using a far larger instrument. Data were given for nuclides from ^{79}Kr up to ^{208}Po. The claimed precision was, in some cases, as good as a few tens of keV's. The new measurements

were made with resolutions insufficient to separate isomers, with a few exceptions. And in checking this feature, the authors found some surprises. In measurements with a time resolution of some 8 seconds, one does not expect to see isomers with ten times smaller half-lives. Yet, the GSI group [18] observed the isomers in ^{149}Dy and ^{151}Er, with reported half-lives of about 1/2 s! (The excitation energies were about 2.5 MeV.) But these half-lives refer to neutral atoms. The measurements, however, were made on fully stripped nuclei. And because of the large conversion coefficients of the relevant isomeric transitions, these isomeric nuclei in their stripped states live long enough! As decided seven years ago, we collected data on decay properties of nuclei in ground- and isomeric states and published these. An updated version of this work is contained in the 2003 Atomic Mass Evaluation [1]. It should be realized that the half-lives given there refer to neutral atoms. A least squares evaluation of a combination of these new mass spectroscopic results with decay energies, discussed below, did not indicate a necessity for correction to their errors as mentioned above. The total result of these measurements is, that mass values for proton-rich nuclides are much better known than earlier.

7 The old mercury difficulty

As shown in fig. 1 on page 193 of our 1985 mass evaluation [19] (see there for early references), mass spectroscopic data near mass numbers $A = 160, 180, 190, 190$ and 235 turned out to suggest 20–40 keV more stability than their combination with the Winnipeg data for mercury isotopes [20] and available connecting reaction and decay energies. But an adjustment of them not using the mercury data gave acceptable results; except of course for those mercury results which then came out some 20 keV high. But also the data for odd-A Hg isotopes deviated some 4 keV more than those for even-A ones. The latter were obtained in comparison with ions containing the rare ^{13}C isotope. This suggested that an intensity dependence might have affected these results, which we therefore did not accept. It is a pleasure to report that new Winnipeg results [21] on ^{183}W, ^{199}Hg and their combination, and also new Stockholm results [22] agree now very well with another. They also agree reasonably with the mentioned earlier accepted data. Towards lower masses, the situation is much improved due to those new Winnipeg data. Towards higher masses the situation is also better than before. Yet the earlier mass determinations of ^{232}Th, ^{235}U and ^{238}U together suggest more stability. A new, precise measurement in this region would be quite interesting!

8 New data on trans-uranics

Somewhat unfortunately, names of most elements with $Z = 104$–109 earlier proposed, and accepted in the 1995 update of our 1993 evaluation were changed in 1997 [23]. Table 4 presents the differences. It also shows names and symbols for elements 110 and 111 that were proposed when the data of Darmstadt on element 110 [24] and 111 [25] were accepted recently as being a convincing discovery of these elements.

Table 4. Element names $Z > 103$.

Z	1995 evaluation		2003 evaluation	
104	Dubnium	Db	Rutherfordium	Rf
105	Joliotium	Jl	Dubnium	Db
106	Rutherfordium	Rf	Seaborgium	Sg
107	Bohrium	Bh	unchanged	Bh
108	Hahnium	Hn	Hassium	Hs
109	Meitnerium	Mt	unchanged	Mt
110	No name yet	–	Darmstadtium	Ds
111	No name yet	–	Roentgenium	Rg

Table 5. Characteristics reported for element 112 and its daughters.

A	Z	Ref. [27]		Ref. [28]	
277	112	700 μs	11.3 MeV		
273	110	210 μs	11.1 MeV		
269	108	21 s	9.2 MeV		9.0 MeV
265	106	13 s	8.7 MeV	10 s	8.7 MeV
261	104	11 s	8.5 MeV	2 s	8.5 MeV
		one case SF		one case SF	
257	102	15 s	8.3 MeV	56 s	8.2 MeV

Until recently, the reports [26,27] on element 112 were not accepted as sufficiently convincing. But recently it was confirmed [28] that the (supposed) daughters [27] showed compatible decay characteristics, see table 5. And chemistry confirmed [28] that the claimed grand-daughter belongs indeed to element 108.

A Dubna group reported [29,30,31] results interpreted as belonging to elements 114 and 116. This has not been accepted as sufficiently convincing. Indeed, Armbruster [32] expressed serious doubts in their correctness. It may be hard to interpret them otherwise. But care is necessary, as showed by the fact that an earlier claim for discovery of an isotope of element 118 by a Berkeley group had to be withdrawn [33].

Very shortly after closing the inputs for our 2003 mass adjustment, a Dubna- Livermore group [34] reported synthesis of isotopes of the new elements 115 and 113, the latter as α-decay daughters of the former. In the three observed ^{288}115 chains and the one of ^{287}115, α-decay daughters were observed down to isotopes of $Z = 105$ which decayed by spontaneous fission. I do not see reasons to doubt the observations; but no earlier information on the claimed daughters is available. The Dubna group strengthens their claim by remarking that the observed α-decay energies for the, supposedly, $Z = 109$ and 107 daughters agree well with theoretical results. But, on the other hand, those for their $Z = 111, 113$ and 115 ancestors are several hundreds of keV lower. They explain this by assuming that for them the observed α-rays feed excited levels. Even more recently [35] it came to our attention, that a Dubna-Livermore group found evidence for element 118. With deep interest, we await future developments in this region.

The author thanks the institute NIKHEF for permission to use their facilities, and especially Mr K. Huyser for his indispensable and always prompt help.

References

1. G. Audi, O. Bersillon, J. Blachot, A.H. Wapstra, Nucl. Phys. A **729**, 3 (2003); A.H. Wapstra, G. Audi, C. Thibault, Nucl. Phys. A **729**, 129 (2003); G. Audi, A.H. Wapstra, C. Thibault, Nucl. Phys. A **729**, 337 (2003).
2. A.A. Sonzogni, Nucl. Data Sheets **95**, 1 (2002).
3. C.N. Davids, P.J. Woods, J.C. Batchelder, C.R. Bingham, D.J. Blumenthal, L.T. Brown, B.C. Busse, L.F. Conticchio, T. Davinson, S.J. Freeman, D.J. Henderson, R.J. Irvine, R.D. Page, H.L. Pentillä, D. Seweryniak, K.S. Toth, W.B. Walters, B.E. Zimmerman, Phys. Rev. C **55**, 2255 (1997).
4. P.J. Mohr, B.N. Taylor, J. Phys. Chem. Ref. Data **28**, 1713 (1999).
5. E.G. Kessler jr., M.S. Dewey, R.D. Deslattes, A. Henins, H.G. Börner, M. Jentschel, C. Doll, H. Lehmann, Phys. Lett. A **255**, 221 (1999).
6. G.L. Greene, E.G. Kessler jr., R.D. Deslattes, H. Börner, Phys. Rev. Lett. **56**, 819 (1986).
7. R.B. Firestone, R.M. Lindstrom, G.L. Molnar, S.M. Mughabghab, A.V.R. Reddy, Z. Revay, V.H. Than, C.M. Zhou, R. Paviotti-Corcuera, private communication.
8. R.S. Van Dyck jr., private communication.
9. Y. Bai, D.J. Vieira, H.L. Seifert, J.M. Wouters, in *ENAM98: Exotic Nuclei and Atomic Masses*, edited by B.M. Sherrill, D.J. Morrissey, C.N. Davids, AIP Conf. Proc. **455**, 90 (1998) and private communication.
10. F. Herfurth, J. Dilling, A. Kellerbauer, G. Audi, D. Beck, G. Bollen, H.-J. Kluge, D. Lunney, R.B. Moore, C. Scheidenberger, S. Schwarz, G. Sikler, J. Szerypo, ISOLDE, Phys. Rev. Lett. **87**, 142501 (2001).
11. Z. Janas, C. Chandler, B. Blank, P.H. Regan, A.M. Bruce, W.N. Catford, N. Curtis, S. Czajkowski, Ph. Dessagne, A. Fleury, W. Gelletly, J. Giovinazzo, R. Grzywacz, M. Lewitowicz, C. Longour, C. Marchand, C. Miehé, N.A. Orr, R.D. Page, C.J. Pearson, M.S. Pravikoff, A.T. Reed, M.G. Saint-Laurent, J.A. Sheikh, S.M. Vincent, R. Wadsworth, D.D. Warner, J.S. Winfield, Phys. Rev. Lett. **82**, 295 (1999).
12. M.P. Bradley, J.V. Porto, S. Rainville, J.K. Thompson, D.E. Pritchard, Phys. Rev. Lett. **83**, 4510 (1999).
13. T. Fritioff, G. Douysset, Phys. Scr. **67**, 276 (2003).
14. G. Douysset, T. Fritioff, C. Carlberg, I. Bergström, M. Björkhage, Phys. Rev. Lett. **86**, 4259 (2001).
15. J. Dilling, F. Herfurth, A. Kellerbauer, G. Audi, G. Bollen, H.-J. Kluge, R.B. Moore, S. Schwarz, G. Sikler, ISOLDE, Eur. Phys. J. A **22**, 163 (2004).
16. D. Beck, F. Ames, G. Audi, G. Bollen, F. Herfurth, H.-J. Kluge, A. Kohl, M. König, D. Lunney, I. Martel, R.B. Moore, H. Raimbault-Hartmann, E. Schark, S. Schwarz, M. de Saint Simon, J. Szerypo, ISOLDE, Eur. Phys. J. A **8**, 307 (2000).
17. S. Schwarz, F. Ames, G. Audi, D. Beck, G. Bollen, C. De Coster, J. Dilling, O. Engels, R. Fossion, J.-E. Garcia Ramos, S. Henry, F. Herfurth, K. Heyde, A. Kellerbauer, H.-J. Kluge, A. Kohl, E. Lamour, D. Lunney, I. Martel, R.B. Moore, M. Oinonen, H. Raimbault-Hartmann, C. Scheidenberger, G. Sikler, J. Szerypo, C. Weber, ISOLDE, Nucl. Phys. A **693**, 533 (2001).
18. Y. Litvinov, Ch. Scheidenberger *et al.*, private communication.
19. A.H. Wapstra, G. Audi, R. Hoekstra, Nucl. Phys. A **432**, 185 (1985).
20. K.S. Kozier, K.S. Sharma, R.C. Barber, J.W. Barnard, R.J. Ellis, V.P. Derenchuk, H.E. Duckworth, Can. J. Phys. A **58**, 1311 (1980).
21. D.K. Barillari, J.V. Vaz, R.C. Barber, K.S. Sharma, Phys. Rev. C **67**, 064316 (2003).
22. T. Fritioff, H. Bluhme, R. Schuch, I. Bergström, M. Bjorkhage, Nucl. Phys. A **723**, 3 (2003).
23. Commission on Nomenclature of Inorganic Chemistry, Pure Appl. Chem. **69**, 2471 (1997).
24. S. Hofmann, V. Ninov, F.P. Heßberger, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött, A.G. Popeko, A.V. Yeremin, A.N. Andreyev, S. Saro, R. Janik, M. Leino, Z. Phys. A **350**, 277 (1995).
25. S. Hofmann, V. Ninov, F.P. Heßberger, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött, A.G. Popeko, A.V. Yeremin, A.N. Andreyev, S. Saro, R. Janik, M. Leino, Z. Phys. A **350**, 281 (1995).
26. S. Hofmann, V. Ninov, F.P. Heßberger, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schott, A.G. Popeko, A.V. Yeremin, S. Saro, R. Janik, M. Leino, Z. Phys. A **354**, 229 (1996).
27. S. Hofmann, F.P. Heßberger, D. Ackermann, G. Münzenberg, S. Antalic, P. Cagarda, B. Kindler, J. Kojouharova, M. Leino, B. Lommel, R. Mann, A.G. Popeko, S. Reshitko, S. Saro, J. Uusitalo, A.V. Yeremin, Eur. Phys. J. A **14**, 147 (2002).
28. A. Türler, Ch.E. Düllmann, H.W. Gäggeler, U.W. Kirbach, A.B. Yakushev, M. Schädel, W. Brüchle, R. Dressler, K. Eberhardt, B. Eichler, R. Eichler, T.N. Ginter, F. Glaus, K.E. Gregorich, D.C. Hoffman, E. Jäger, D.T. Jost, D.M. Lee, H. Nitsche, J.B. Patin, V. Pershina, D. Piguet, Z. Qin, B. Schausten, E. Schimpf, H.J. Schött, S. Soverna, R. Sudowe, P. Thörle, S.N. Timokhin, N. Trautmann, A. Vahle, G. Wirth, P.M. Zielinski, Eur. Phys. J. A **17**, 505 (2003).
29. Yu.Ts. Oganessian, A.V. Yeremin, A.G. Popeko, S.L. Bogomolov, G.V. Buklanov, M.L. Chelnokov, V.I. Chepigin, B.N. Gikal, V.A. Gorshkov, G.G. Gulbekian, M.G. Itkis, A.P. Kabachenko, A.Yu. Lavrentev, O.N. Malyshev, J. Rohac, R.N. Sagaidak, S. Hofmann, S. Saro, G. Giardina, K. Morita, Nature **400**, 242 (1999).
30. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, I.V. Shirokovsky, Yu.S. Tsyganov, G.G. Gulbekian, S.L. Bogomolov, B.N. Gikal, A.N. Mezentsev, S. Iliev, V.G. Subbotin, A.M. Sukhov, O.V. Ivanov, G.V. Buklanov, K. Subotic, M.G. Itkis, K.J. Moody, J.F. Wild, N.J. Stoyer, M.A. Stoyer, R.W. Lougheed, C.A. Laue, Ye.A. Karelin, A.N. Tatarinov, Phys. Rev. C **63**, 011301 (2001).
31. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, I.V. Shirokovsky, Yu.S. Tsyganov, G.G. Gulbekian, S.L. Bogomolov, B.N. Gikal, A.N. Mezentsev, S. Iliev, V.G. Subbotin, A.M. Sukhov, G.V. Buklanov, K. Subotic, M.G. Itkis, K.J. Moody, J.F. Wild, N.J. Stoyer, M.A. Stoyer, R.W. Lougheed, Phys. Rev. Lett. **83**, 3154 (1999).
32. P. Armbruster, Eur. Phys. J. A **7**, 23 (2000).

33. V. Ninov, K.E. Gregorich, W. Loveland, A. Ghiorso, D.C. Hoffman, D.M. Lee, H. Nitsche, W.J. Swiatecki, U.W. Kirbach, C.A. Laue, J.L. Adams, J.B. Patin, D.A. Shaughnessy, D.A. Strellis, P.A. Wilk, Phys. Rev. Lett. **89**, 39901 (2002).
34. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, I.V. Shirokovsky, Yu.S. Tsyganov, G.G. Gulbekian, S.L. Bogomolov, A.N. Mezentsev, S. Iliev, V.G. Subbotin, A.M. Sukov, A.A. Voinov, G.V. Buklanov, K. Subotic, V.I. Zagrebaev, M.G. Itkis, J.B. Patin, K.J. Moody, J.F. Wild, M.A. Stoyer, D.A. Shaughnessy, J.M. Kenneally, R.W. Lougheed, Phys. Rev. C **69**, 021601 (2004).
35. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, I.V. Shirokovsky, Yu.S. Tsyganov, G.G. Gulbekian, S.L. Bogomolov, B.N. Gikal, A.N. Mezentsev, S. Iliev, V.G. Subbotin, A.M. Sukov, A.A. Voinov, G.V. Buklanov, K. Subotic, V.I. Zagrebaev, M.G. Itkis, J.B. Patin, K.J. Moody, J.F. Wild, M.A. Stoyer, N.J. Stoyer, D.A. Shaughnessy, J.M. Kenneally, R.W. Lougheed, Nucl. Phys. A **734**, 109 (2004).