The AME2003 atomic mass evaluation [*]

(II). Tables, graphs and references

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Abstract

This paper is the second part of the new evaluation of atomic masses AME2003. From the results of a least-squares calculation described in Part I for all accepted experimental data, we derive here tables and graphs to replace those of 1993. The first table lists atomic masses. It is followed by a table of the influences of data on primary nuclides, a table of separation energies and reaction energies, and finally, a series of graphs of separation and decay energies. The last section in this paper lists all references to the input data used in Part I of this AME2003 and also to the data entering the NUBASE2003 evaluation (first paper in this volume).

AMDC: http://csnwww.in2p3.fr/AMDC/

1. Introduction

The description of the general procedures and policies are given in Part I of this series of two papers, where the input data used in the evaluation are presented. In this paper we give tables and graphs derived from the evaluation of the input data in Part I.

Firstly, we present the table of atomic masses (Table I) expressed as mass excesses in energy units, together with the binding energy per nucleon, the beta-decay energy and the full atomic mass in mass units.

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The second table is the table of *influences* on primary nuclides (Table II). For each of the *primary* nuclides entering this evaluation, we give the three main data and their influences on the mass of this nuclide (see the definitions in Part I, Section 3).

Thirdly, we give a table for values and their estimated precision for the separation energies and reaction energies for twelve carefully selected combinations of nuclides. This selection, together with the β-decay energies above, yields all differences in masses between any pair of nuclei differing at most by 2 units in Z and N. A method is indicated in which many more reaction energy values can be derived from the present table.

The following series of graphs are then presented: two-neutron separation energies and α-decay energies as a function of neutron number, two-proton separation energies as a function of proton number and double β-decay energies as a function of mass number which are considered as the most illustrative ones for the systematic trends.

Finally, references to the input data used in Part I of this AME2003 and in NUBASE2003 in the first paper of this volume are given in the last section of this paper.

2. The atomic mass table

As in our previous work AME'93 [1]–[4] and AME'95 [5], the tables presented in this work give atomic masses and derived quantities. With very few exceptions, experimental 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. The same is true for the electron mass M_e involved, see Table A in Part I. This 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:

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

Nowadays, several mass measurements are made on fully or almost fully ionized particles. Then, a correction must be made for the total binding energy of all removed electrons $B_e(Z)$. They can be found in the table for calculated total atomic binding energy of all electrons of Huang et al. [6]. Unfortunately, the precision of the calculated values $B_e(Z)$ is not clear; this quantity (up to 760 keV for $_{92}$U) cannot be measured easily. Very probably, its precision for $_{92}$U is rather better than the 2 keV accuracy with which the mass of, e.g., ^{238}U is known. A simple formula, approximating the results of [6], is given in the review of Lunney, Pearson and Thibault [7]:

$$B_{el}(Z) = 14.4381 Z^{2.39} + 1.55468 \times 10^{-6} Z^{5.35} \, \text{eV} \tag{2}$$

Table A. The most precisely known masses.

	Mass excess (keV$_{90}$)		Atomic mass (μu)	
^{1}n	8 071.317 10	0.000 53	1 008 664.915 74	0.000 56
^{1}H	7 288.970 50	0.000 11	1 007 825.032 07	0.000 10
^{2}H	13 135.721 58	0.000 35	2 014 101.777 85	0.000 36
^{3}H	14 949.806 00	0.002 31	3 016 049.277 67	0.002 47
^{3}He	14 931.214 75	0.002 42	3 016 029.319 14	0.002 60
^{4}He	2 424.915 65	0.000 06	4 002 603.254 15	0.000 06
^{13}C	3 125.011 29	0.000 91	13 003 354.837 78	0.000 98
^{14}C	3 019.893 05	0.003 80	14 003 241.988 70	0.004 08
^{14}N	2 863.417 04	0.000 58	14 003 074.004 78	0.000 62
^{15}N	101.438 05	0.000 70	15 000 108.898 23	0.000 75
^{16}O	– 4 737.001 41	0.000 16	15 994 914.619 56	0.000 16
^{20}Ne	– 7 041.931 31	0.001 79	19 992 440.175 42	0.001 92
^{23}Na	– 9 529.853 58	0.002 73	22 989 769.280 87	0.002 93
^{28}Si	– 21 492.796 78	0.001 81	27 976 926.532 46	0.001 94
^{40}Ar	– 35 039.896 02	0.002 68	39 962 383.122 51	0.002 86

The atomic masses are given in mass units and the derived quantities in energy units. For the atomic mass unit we use the "unified atomic mass unit," symbol "u", defined as 1/12 of the atomic mass of one ^{12}C atom in its electronic and nuclear ground states and in its rest coordinate system. In our work energy values are expressed as electron-volt, using the *maintained* volt V$_{90}$. For a discussion see Part I, Section 2.

As mentioned in Part I, we no longer give values for the binding energies, $ZM_H + NM_n - M$, as we used to in earlier tables. Otherwise than before, its error equals that in the value of the mass excess, which makes its use unnecessary. We now give instead the binding energy per nucleon, which is of educational interest, connected to the Aston curve and the maximum stability around the 'iron-peak' of importance in astrophysics.

Due to the drastic increase in the precision of the mass values of the very light nuclei, the printing format of the mass table is not adequate. Table A gives, for the most precise among them, values of mass excesses and atomic masses. Conversion of the errors from μu to keV were obtained by:

$$\sigma^2_{M_{keV}} = (\sigma_{M_u} \times u)^2 + (M_u \times \sigma_u)^2 \tag{3}$$

where M_u is the mass excess in μu, and σ_u the error of u expressed in eV$_{90}$. The part

Table B. Correlation matrices for the most precisely known very light nuclei (in squared nano atomic mass units).

	n	H	D	^{4}He	^{13}C	^{14}N	^{15}N	^{16}O	^{28}Si
n	0.316817								
H	− 0.007978	0.010689							
D	0.124508	0.002709	0.127243						
^{4}He	0.000000	0.000000	0.000000	0.004011					
^{13}C	0.125909	− 0.007584	0.118352	0.000000	0.954145				
^{14}N	− 0.008911	0.012558	0.003645	0.000000	− 0.008470	0.384729			
^{15}N	0.094981	0.016262	0.111262	0.000000	0.090285	0.019496	0.558755		
^{16}O	− 0.001022	0.001377	0.000355	0.000000	− 0.000972	0.005718	0.002100	0.027039	
^{28}Si	0.227453	0.008282	0.235786	0.000000	0.216210	0.010584	0.653732	0.001078	3.761099

	n	H	D	^{3}H	^{3}He	^{16}O	^{20}Ne	^{23}Na	^{28}Si
n	0.316817								
H	− 0.007978	0.010689							
D	0.124508	0.002709	0.127243						
^{3}H	0.008197	0.000942	0.009139	6.116907					
^{3}He	0.009704	0.001116	0.010822	5.694194	6.743975				
^{16}O	− 0.001022	0.001377	0.000355	0.000122	0.000144	0.027039			
^{20}Ne	0.326227	0.014358	0.340650	0.024965	0.029563	0.001866	3.687126		
^{23}Na	− 0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	8.587458	
^{28}Si	0.227453	0.008282	0.235786	0.017163	0.020325	0.001078	0.633419	0.000000	3.761099

dependent on M_u is only important for very few nuclides.

3.   Influences on primary nuclides

Table II presents a list of all primary nuclides, and for each of these the main data contributing to its mass determination (up to the three most important ones) and the *influences* of these data on this nuclide.

This Table II complements the information given in the main table (Part I, Table I) where we display the *significance* (total flux) and the main *flux* of each datum. In other words, the flow-of-information matrix **F**, defined in Part I, Section 5.1, is (partly) displayed once along lines and once along columns.

4.   Nuclear-reaction and separation energies

The result of the least-squares adjustment of experimental data (reaction and decay energies and mass-spectrometric data) determining atomic masses of nuclides, as described in Part I, is not represented completely by the adjusted values of the input data given there and the resulting values of the atomic masses given in the Table I. A com-

plete representation would require reproduction of a matrix of correlation coefficents. Since this matrix contains $\frac{1}{2}N(N+1)$ elements in which $N = 847$, this is not very attractive.

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, ^{3}He and α. 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 [2], we present in Table III values for 12 such combinations and their standard errors. The β-decay energies are given in Table 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 B. When doing this, one should calculate the values to which these errors belong from the mass values (in μu), and not from the mass-excesses (in keV), in the mass table (Table I).

We have also prepared a table of neutron, proton and deuteron pairing energies, available from the AMDC [8], defined as:

$$P_n(A,Z) = \frac{1}{4}(-1)^{A-Z+1}[S_n(A+1,Z) - 2S_n(A,Z) + S_n(A-1,Z)]$$

$$P_p(A,Z) = \frac{1}{4}(-1)^{Z+1}[S_p(A+1,Z+1) - 2S_p(A,Z) + S_p(A-1,Z-1)]$$

$$P_d(A,Z) = \frac{1}{4}(-1)^{Z+1}[S_d(A+2,Z+1) - 2S_d(A,Z) + S_d(A-2,Z-1)]$$

S_n, S_p, and S_d are the neutron, proton and deuteron separation energies, the latter being defined as

$$S_d(A,Z) = -M(A,Z) + M(A-2,Z-1) + M(d) = -Q(\gamma,d),$$

and S_n, and S_p, are defined below in the Explanation of Table.

Remark: P_n is also sometimes written as:

$$P_n(A,Z) = \frac{1}{4}(-1)^{A-Z+1}[-M(A+1,Z) + 3M(A,Z) - 3M(A-1,Z) + M(A-2,Z)]$$

displaying thus more clearly the combination of the involved masses. And similarly for P_p and P_d.

5. Graphs of systematic trends

All the information contained in the mass table (Table I) and in the nuclear reaction and separation energy table (Table III) can in principle be displayed in a plot of the binding energy or the mass versus *Z*, *N*, or *A*. 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 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 defines 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 (see also Part I, Section 4). 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. 1–9);

2. the two-proton separation energies versus *Z*, with lines connecting the isotones (the same number of neutrons) (Figs. 10–17);

3. the α-decay energies versus *N*, with lines connecting the isotopes of a given element (Figs. 18–26);

4. the double β-decay energies versus *A*, with lines connecting the isotopes and the isotones (Figs. 27–36).

These graphs of systematic trends supersede earlier graphs [3].

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*, β-decay energy versus *A*, ...); they can all be built starting from the values in Table III. They cannot all be given in the present printed version, but they are retrievable from the *Web* distribution [8].

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, like a shell or subshell closure or an onset of deformation. But, if only one mass exhibits an irregular pattern, violating the systematic trends, then one may seriously question the correctness of the related data. See the discussion in Part I, Section 4.

6. List of references for the NUBASE2003 and AME2003 evaluations

Full references related to all the input data used in the present AME2003 evaluation, as well as in the NUBASE2003 evaluation (first article in this volume), are listed in a special table, at the end of this paper.

A list of identifiers for journals, books, conferences . . . is given first, as much as possible in the CODEN-style (see [9]). With one exception though, for the *Eur. Phys. Journal* for which we prefered the 'EPJAA' identifier, that we think more practical to use, than the 'ZAANE' identifier as adopted by the NSR.

The references were quoted, in both evaluations in the NSR [9] key number style, where available, and only for the regular journals. They are listed here by year of publication and first author name.

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[8]   The AME2003 files in the electronic distribution and complementary documents can be retrieved from the Atomic Mass Data Center (AMDC) through the *Web*: http://csnwww.in2p3.fr/amdc/

[9]   Nuclear Structure Reference (NSR): a computer file of indexed references maintained by NNDC, Brookhaven National Laboratory; http://www2.nndc.bnl.gov/nsr/