The atomic mass evaluation – present and future

M Wang 1,2, G Audi 2, B Pfeiffer3 and F G Kondev4
1. Institute of Modern Physics, CAS, 730000 Lanzhou, China
2. CSNSM-IN2P3, Bâtiment 104,108, 91405 Orsay Campus, France
3. GSI Helmholtzzentrum für Schwerionenforschung, Planckstr. 1, D-64291 Darmstadt, Germany
4. Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, USA
E-mail: amdc.wang@gmail.com

Abstract. The atomic mass evaluation (AME) is a reliable resource for the values related to the atomic masses. Since the publication of the latest version of AME in 2003, a large amount of new data emerged from mass measurements performed by Penning traps and storage rings, as well as from nuclear decay and reaction energy measurements. A new project called “AME-future” is currently ongoing and it is aimed at creation of new mass tables that will be published in 2013: AME2013. The present status of AME and its working structure are presented. With the newly included data, the mass surface for nuclei far from the valley of stability seems to lie higher than was anticipated earlier. The impact on astrophysical applications is discussed. Some examples describing correlations between masses are presented.

1. Introduction

The atomic mass, a fundamental property of nuclei, is widely used in basic nuclear physics and astrophysics research, as well as in other practical applications such as nuclear energy. In order to obtain the value of atomic masses, one just needs to look up the atomic mass tables [1], which are the core of the atomic mass evaluation (AME). The AME was created by Aaldert H. Wapstra in 1950’s and following this concept, a series of Mass Tables have been produced over the years, the most recent ones in 1983, 1993, and 2003.

In order to increase its contribution to the international nuclear research community, the Institute of Modern Physics (IMP) at Lanzhou (China) decided to ascertain the future of this long tradition in a program called “AME-Future” [2]. The corresponding memorandum was signed at the end of 2008 and in March 2009, M. Wang from IMP-Lanzhou arrived in Orsay and began to work with G. Audi on the next version of the AME.

The AME-Future project is defining a new working structure: a collaborative effort centered around a coordinator. In a first step, the production of the AME2013 Atomic Mass Table, the coordinator is G. Audi, with the strong support from M. Wang, detached by the IMP at Orsay. For the second step, the future of the AME will be at the IMP-Lanzhou, with Dr. Meng Wang as the new coordinator.

Around the coordinator, several contributors from different laboratories are contributing in searching the literature for new data and including them into AME. The contributors have the responsibility to evaluate the input data before including them and perform a full calculation for the adjustment to ensure the output is reasonable before transferring the new files to the coordinator. The
Figure 1. Nuclear charts with the mass uncertainties shown in a colour code for AME2003 (top) and present status (bottom).
coordinator includes the new information while checking their relevance, achieving thus the equivalence of a referee’s review. In this way, the number of errors is reduced to a lowest possible minimum. In parallel, each of the participants is assigned one or more of the main journals starting January 2004 for a systematic scan for possible missed papers.

Our structure is opened to all institutes, which would like to contribute some effort in the development of AME (with a minimum of 20% FTE). Presently, besides the IMP-Lanzhou, we have a solid contribution from the GSI-Darmstadt and ANL-Argonne, soon joined by the MPI-Heidelberg.

2. Present status about AME

2.1. General status of the present AME

In the AME, all available experimental data that are related to atomic masses (energy data or mass-spectrometric data) are collected and carefully examined. In principle, a single mass measurement establishes a relation between two or more nuclides, rather than the absolute mass itself. An extremely entangled network of relations is then established by combining all these experimental data, as illustrated in the Fig. 1 of AME2003 [3]. The weighted least-squares method is applied to solve the difficulties due to strong interconnections among the measurements. Then the best values for atomic masses are recommended. The influences of each individual measurement on the output of the AME are studied with the flow-of-information matrix, as well as the inconsistencies of the input data.

In the latest published version (AME2003), 2228 masses of the ground-state nuclides are obtained from more than 7000 experimental data. Since 2003, a huge amount of experimental data has emerged. Up to now, 2343 masses have been obtained from 9700 experimental data. The precision of masses of many nuclei has been improved, as shown in Fig. 1. At present, there are 275 masses with uncertainties below 1 μ, superseding 197 in AME2003. The best precision of the mass measurement that has been achieved is 7×10^{-12}, by Penning traps [4]. While most of the masses of many stable and some long-lived nuclides can be improved potentially, the priority is given to nuclides where there is a strong physics motivation.

In general, the agreement between the inertial mass measurements and energy data is good. It was used for testing the equivalence between the mass and energy [4]. Sometimes discrepancies may be found and decisions need to be made by the evaluators. An illustrative example is given by the recent, and yet unresolved, problem we encountered: the mass of 32Si. In AME2003, it was accepted that the

![Figure 2](image-url)
extraordinarily precise \((n,\gamma)\) measurement of the PTB group in Braunschweig [5] determines the mass of \(^{32}\text{Si}\), with a precision being given as 0.76 keV. But very recently, the MSU group [6] measured the masses of several nuclides including \(^{32}\text{Si}\), by using a Penning-trap. Their result is at 3.25 keV from the PTB result with a precision of 0.30 keV for \(^{32}\text{Si}\). The MSU measurements were internally cross-checked by combining various molecules and comparing to various references. On the other side, \((n,\gamma)\) measurements proved up to now to be quite reliable. We decided then to come back to the PTB-Braunschweig group and discuss the problem. Until this issue is resolved, it has been decided provisionally to not use the \((n,\gamma)\) data, but rather the Penning trap values.

### 2.2. Rising of the mass surface and the impact to astrophysics

The magnitude of changes along the line of stability is unlikely to affect the calculation of atomic weights significantly. However, for ridge of the valley of stability, we observe that the mass surface lays much higher (higher masses, less binding energies) than was believed earlier (see Fig.2). This behavior is largely due to an underestimation of earlier Q\(_{\beta}\) decay (and sometimes Q\(_{\alpha}\)) energy measurements, especially when going further away from stability.

Such significant changes in the masses that occur over wide regions are expected to have an impact on calculations where the data are used. An example of the impact of the rising of the wings of the mass surface on the r-process path of astrophysics was checked by performing static calculations as described in [7]. This approach allows to study the influence of nuclear data input on the r-process calculations, keeping the stellar parameters as Fe seed, neutron density \(n_n\), temperature and process duration constant. Fig.3 illustrates how the nuclidic production is affected when combining the masses from AME2003 or AME2010, respectively, with predictions from the FRDM mass model[8].

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**Figure 3.** Changes in the predicted abundances when keeping the same stellar parameters (neutron density \(n_n\), temperature and process duration). The experimental masses from AME are superimposed on the FRDM mass model [8]: AME2003 masses (black line) and AME2010 (red line). Crosses and error bars are for the observed abundances in the solar system [10]. The data are normalized to the \(A=130\) observed abundance.
Except at neutron magic numbers, no experimental masses are known in the r-process path. The newly measured masses closer to the valley of stability will impact future calculations (preferably full network calculations as described e.g. in [9]) through their influence on the extrapolation of masses toward the drip lines and future mass models.

3. Correlations between the masses

3.1. Correlations between the input data
Some of the input data from the same experimental group are correlated in some way. These correlations must be considered properly. Take the measurements of $^3$H and $^3$He from SMILETRAP as an example [11]. The masses of $^3$H and $^3$He are measured, with the uncertainties of 2.5 nu and 2.6 nu respectively, by using $^2$H$^+$ as mass reference. Since $^3$H and $^3$He were measured in the same way with the same reference, certain systematic uncertainties in the mass difference cancel to some large extent. A resulting uncertainty of 1.2 eV for the mass difference (essential for the neutrino mass out of the $^3$H $\beta$ decay) is obtained, which is much smaller than those of the individual masses. The final covariance matrix of this measurement is illustrated in the left part of Table 1, where the strong correlation between the masses of $^3$H and $^3$He is apparent. Notice that the same pair of masses are used by the CODATA group to adjust the fundamental physical constants [12]. But the correlation coefficient used in [12] is not completely correct (the right half of table 1), since only the correlation from the same reference mass was considered.

Table 1. The variances, covariance, and correlation coefficient of the values of the SMILETRAP relative atomic masses of $^3$H and $^3$He. The number in bold above the main diagonal is covariance, the numbers in bold on the main diagonal are the variances in squared nano atomic mass units and the number in italics below the main diagonal is the correlation coefficient. The right half of the table gives the corresponding values from reference [12].

|        | AME       | CODATA2006 |
|--------|-----------|------------|
| $^3$H  | 6.25      | 6.2500     |
| $^3$He | 5.64      | 0.1783     |
| $^3$H  | 0.887     | 6.74       |
| $^3$He | 0.0274    | 6.7600     |

Mass measurements with a Storage Ring are performed at GSI[13] and IMP-Lanzhou[14]. In these measurements the masses of a large number of nuclides are determined simultaneously in an interconnected manner. In principle, not only the measurements with a storage ring, but a number of other methods measure the correlations rather than the individual mass values. For example, in a recent paper [15], a series of masses is measured with the ($^3$He,t) reaction. In Fig.1 of this reference, each peak in the spectra corresponds to an excited or ground state of the certain nuclide. The masses of the nuclides were extracted from these complex correlations between these peaks. To include such correlations in AME is a challenging task and is under consideration.

3.2. Correlations between the output masses
Since each mass measurement establishes a relation between two or more nuclides, the atomic masses are strongly correlated. The covariance between the AME output masses must be considered properly, in order to use the mass values correctly, to evaluate the uncertainties and to perform statistical tests. In AME2003, a table of correlation matrix for the most precisely known very light nuclei was published (TABLE B in reference [1]). The table is required by CODATA group for the fundamental physical constants evaluation [12]. The total number of elements in the covariance matrix is about half a million and most of the values are insignificant. While the entire table is not worth publishing in the printed version together with the atomic mass tables, access to these values is nevertheless useful and will be provided at the AMDC website.
4. Perspective
A new version of the AME, AME2013 is planned to be published in 2013. A few months before the publication, a bulletin of the AMDC will be issued where a call will be made for results of works that might be published only after we perform the final “atomic mass adjustment” for AME2013.

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The founder of the AME, Prof. Aaldert H. Wapstra passed away at the end of 2006. He made essential contributions to AME2013 during the two years following the publication AME2003. In addition to his contributions over those two years and perhaps more significantly, this work is filled with his spirit.

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