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Survey of Evaluated Isobaric Analog States

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Isobaric analog states (IAS) can be used to estimate the masses of members belonging to the same isospin multiplet. Experimental and estimated IAS have been used frequently within the Atomic Mass Evaluation (AME) in the past, but the associated set of evaluated masses have been published for the first time in AME2012 and NUBASE2012. In this paper the current trends of the isobaric multiplet mass equation (IMME) coefficients are shown. The $T = 2$ multiplet is used as a detailed illustration.

I. INTRODUCTION

A mass relationship can be observed in isobars belonging to the same isospin multiplet around $N = Z$. The ground state of a given nuclide may be identified as an excited state in the multiplet members. A full set of member states, known as isobaric analogue states (IAS) has, by definition, the same spin-parity and isospin. The main difference between their masses can be attributed to the charge symmetry of the nucleon-nucleon interaction [1] and may be used to explore the charge symmetry and charge independence of the nuclear interaction.

The mass of the nuclides around $N = Z$ can be considered to arise from a charge independent strong interaction and a charge dependent Coulomb component [2]. The charge dependence can be parameterized though the electric charge of the nucleus via the isospin quantum number. The isospin projection T_z for a given nuclide is written

$$T_z = \frac{N-Z}{2}, \tag{1}$$

where N and Z are the neutron and proton number respectively, and the atomic mass number A is $A = N + Z$. The total internal isospin T states can take the values

$$\frac{N-Z}{2} \leq T \leq \frac{N+Z}{2}. \tag{2}$$

The members of a given isospin multiplet T have projections T_z running from $-T$ to $+T$ and the mass M can be written as

$$M(A, T, T_z) = M_0 + E_C(A, T, T_z) + \Delta_{nH} T_z, \tag{3}$$

where Δ_{nH} is the neutron-^{1}H mass difference, E_c is the Coulomb energy, and M_0 is the charge-free nuclear mass [3].

Developments over several years lead to a simplified Coulomb energy description [4, 5], given by

$$\begin{aligned} E_C(A, T, T_z) = {} & E_C^{(0)}(A, T) \\ & - T_Z E_C^{(1)}(A, T) \\ & + [3T_Z^2 - T(T+1)] E_C^{(2)}(A, T), \end{aligned} \tag{4}$$

where $E_C^{(0)}$, $E_C^{(1)}$ and $E_C^{(2)}$ are isoscalar, isovector and isotensor Coulomb energies, respectively. The isobaric multiplet mass equation (IMME) [3, 5], for a given isobar, can be written in a quadratic form

$$M(T, T_z) = a + bT_Z + cT_Z^2, \tag{5}$$

where the coefficients a, b and c are related to the Coulomb energy with $a = M_0 + E_C^{(0)} - T(T+1)E_C^{(2)}$, $b = \Delta_{nH} + E_C^{(1)}$ and $c = 3E_C^{(2)}$.

In this paper the current trends of the IMME coefficients, a, b and c, based on the recent AME2012 [6, 7] ground state masses and NUBASE2012 [8] excited states are considered. In this preliminary study only the quadratic form of the IMME is studied, the inclusion of higher order terms being part of the next step in this work.

II. NUBASE NOTATION

IAS have been identified and labeled with a distinct notation in NUBASE2012. The $A = 38$ $T = 1$ and $T = 2$ isobaric series, only partly measured to date, has been

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chosen to provide a detailed example. The members of the $T = 1$ isospin triplet are ^{38}Ca, ^{38}K and ^{38}Ar, whereas the $T = 2$ quintuplet members are ^{38}Sc, ^{38}Ca, ^{38}K, ^{38}Ar and ^{38}Cl. The IAS of the ground state of ^{38}Cl should exist in ^{38}Ar, ^{38}K and ^{38}Ca. Since ^{38}K has excited levels which could be part of either the $T = 1$ or $T = 2$ multiplets for $A = 38$, extra notation is required to distinguish between the two expected IAS. The triplet and quintuplet IAS in ^{38}K are written as ^{38}K^i and ^{38}K^j, respectively, in which the superscripts i and j designate successively higher multiplet members, as shown in Fig. 1.

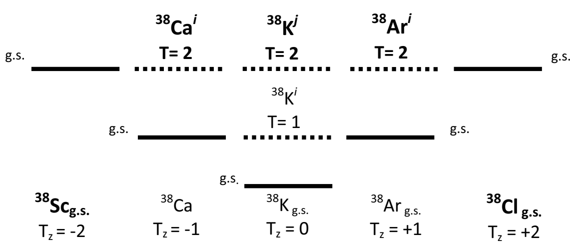

FIG. 1. Isobaric multiplet set for $A = 38$ and $T = 2$. Extra notation is required to distinguish between $T = 1$ and $T = 2$ IAS, with the i and j superscripts indicating successively higher excitation levels. The quintuplet is labeled in bold on the image and is composed of ^{38}Cl, ^{38}Ar^i, ^{38}K^j, ^{38}Ca^i and ^{38}Sc. ^{38}K^i, at a lower excitation energy, would naturally be the $T = 1$ IAS.

A. Special Isomer Cases

In several cases the IAS is also an isomer state, in these cases preference is given to the isomer notation. These cases are ^{16}N^m, ^{26}Al^m, ^{34}Cl^m, ^{38}K^m, ^{46}V^m, ^{50}Mn^m, ^{54}Co^m and ^{72}Ga^m.

III. NUBASE2012

Beyond the ground states naturally included in the 2012 Atomic Mass Evaluation (AME2012), reaction data for 107 excited states, based on experimental data from the last 50 years, have been included in NUBASE2012. The reaction Q-value is simply the difference in the total masses before and after the reaction, and is frequently the measured and calibrated experimental quantity. In NUBASE, the reaction data have been coded in their original form, that is, in the form of experimental Q-values. Thus, if the current accuracy of the ground state masses evolve, the available kinetic energy in the center of mass will automatically change; this is therefore a self-adjusting procedure. The initial and usually well measured Q-value will remain the same.

A. Recalibration of Calibrants

Many of the IAS experimental data come from high precision mass spectrometry. The experimental Q-value is typically deduced from a calibrated focal plane. The spectrometer calibration itself is done with respect to "well known" calibrants. A second order recalibration that could be relevant for some older published data concern measurements where the mass of the calibrant itself has changed. The necessity of such recalibration has yet to be evaluated in detail.

IV. COMPARISON WITH PREVIOUS IAS DATA

Several papers dedicated to the study of IAS and the determination of IMME coefficients for $T = \frac{1}{2}$ to $T = 2$ have previously been published. An extensive study was initially published in 1985 by Antony *et al.* [9], and more recently by Britz *et al.* [10] in 1998. Although more extensive measurements are now available, the main addition here, as compared to the 1998 situation, concerns the $T = 2$ data set. In 1998, only six isobaric multiplets between $A = 8$ and $A = 36$ had been studied, excluding $A = 12$ and $A = 16$ due to lack of data. This situation compares with today's data which cover fourteen multiplet sets in the range $A = 8$ to $A = 60$.

V. $T = 2$ QUADRATIC FITS

All $T = 2$ multiplets were fitted by a quadratic function, with the data uncertainties taken into account. The residuals, as shown in Fig. 2, are the difference between the result of the fit and the individual data points. An exact IMME quadratic description would be reflected by a residual centered on the zero value for each member of the multiplet. What is observed is a systematic lower precision for the most proton-rich nuclides. The residual value is sometimes positive, and sometimes negative, with no clear bias one way or the other. Eight out of the fourteen evaluated data points ($A = 28$, 36, 40, 44, 48, 52, 56 and 60) for the proton-rich members are handicapped by this lower precision. Higher precision measurements are required in order to discern whether higher order terms are more-or-less systematically required for the IMME to give a satisfactory mass description. Only then can we see if the IMME will retain predictive power beyond $T = 2$.

One clear-cut case concerns the $A = 32$ quintuplet where the ^{32}Ar ground state has been measured to a high precision ($\pm$1.8 keV), and therefore, being distanced at 6σ from the IMME fit, means that this quintuplet certainly requires higher order terms in order to obtain a reasonable description of the Coulomb energy.

IAS levels may also be displaced through interferences with nearby levels of the same spin-parity. In these cases the IAS is no longer concentrated in a single energy level,