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Indirect mass determination for the neutron-deficient nuclides ^{44}V, ^{48}Mn, ^{52}Co and ^{56}Cu

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Abstract

Mass excess values for ^{44}V, ^{52}Co and ^{56}Cu are derived indirectly using the mirror symmetry and known data from beta-delayed proton spectroscopy. The new mass excess obtained by using the energy conservation for ^{48}Mn is $-29\,303(14)$ keV, which is an improvement by about an order of magnitude compared to the AME'12 value. Compared to previously known data, the new proton separation energy for ^{45}Cr causes a ~ 3.5 times smaller matter flow through the Ca–Sc cycle during the rp-process. Obtained proton separation energies for ^{52}Co and ^{56}Cu are about 500 keV larger than the AME'12 values. If confirmed, this would affect photo disintegration rates of ^{52}Co (γ, p) ^{51}Fe and ^{56}Cu (γ, p) ^{55}Ni reactions during the rp-process in X-ray bursts.

Keywords: Mass excess; Separation energy; Rp-process; Ca–Sc cycle

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1. Introduction

Masses are fundamental properties of atomic nuclei. They play an important role in nuclear structure and nuclear astrophysics research [1–3]. Recent experiments provided a wealth of new nuclear mass data either measured for the first time or with significantly improved precision and accuracy. The latest evaluation of the available experimental data is the Atomic-Mass Evaluation 2012 (AME'12) [4].

Many mass models and formulas were developed to date [1,3]. Of special interest here are the so-called local mass models, which are simpler and have much higher predictive precision as compared to global models. In this work we consider the Improved Garvey–Kelson mass relation (ImGK) [5], the Coulomb Displacement Energy mass relation (CDE) [6], and Isobaric Multiplet Mass Equation (IMME) [7]. The origin G–K formula was introduced based on the independent particle picture by Garvey and Kelson [8]. Assuming that the residual interaction between nucleons in the same level varies slowly with atomic number, thus, the residual interaction can be subtracted in formula. The CDE is the difference of binding energies between mirror nuclei, if nuclear force is charge symmetric, which can directly be related to the well-understood Coulomb force and calculated more precisely by theory [6]. The IMME was introduced by Weinberg et al. [7], which based on the isospin symmetry. States in isobars with the same isospin, spin and parity have very similar structure and can be considered to be members of an isobaric multiplet. Assuming the two-body nature for any charge-dependent effect and Coulomb force between the nucleons, the masses of the states in an isobaric multiplet are related by the IMME. These formulas are well suited to accurately describe nuclear masses in a restricted region on the nuclidic chart. An average uncertainty of $\sim$100 keV or smaller is expected for these models for neutron-deficient $A \sim 50$ nuclei.

The differences between experimental and theoretical masses are expected to have smooth trends and sudden irregularities may point to a change in nuclear structure. For example, the observed discrepancy between the experimental masses and predictions by the Isobaric Multiplet Mass Equation (IMME) for $A = 53$, $T = 3/2$ [9] isospin quartets in the fp-shell may indicate a possible breakdown of the IMME. In the ^{71}Kr mass region, a systematic deviation of the calculated Coulomb Displacement Energies (CDE) was explained as the onset of deformation [10].

However, differences can also be caused by experimental errors. A straightforward case is the existence of long-lived excited states, that cannot be resolved in the experiment and might thus lead to an erroneous result. For instance, the isomeric states in ^{44}Sc and ^{45}Sc are known to exist [11]. Because of the nuclear structure symmetry, one can expect isomers with excitation energies of 100–200 keV in the mirror nuclei ^{44}V and ^{45}Cr [12]. The masses for ^{44}V [13] and ^{45}Cr [14] were measured by storage-ring mass spectrometry. However, the achievable mass resolving power of $\sim 2\times 10^5$ [13,14] did not allow for resolving such isomers and their influence on the reported results needs to be checked. The case of ^{45}Cr was thoroughly discussed in Ref. [14]. The experimental ^{44}V mass excess was measured in the ESR to be $-23\,980^{+80}_{-380}$ keV [13]. By considering the unresolved isomer, the ground state mass value was evaluated in AME'12 to be $-24\,120(180)$ keV [4], which shifted the experimental mass by 140 keV, namely half of excitation energy of isomer, more details see Ref. [15]. However, because of the possible unresolved isomer, the reported accuracy has been questioned in Refs. [16,17].

2. Indirect mass determination

Masses for nuclides with $T_z = -1$ in the $A \sim 50$ mass region were measured directly by storage-ring mass spectrometry [13]. These masses can also be determined indirectly from energy