

Benchmarking nuclear energy density functionals with new mass data

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Abstract

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Full Text

Benchmarking Nuclear Energy Density Functionals with New Mass Data

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Nuclear masses play a crucial role in both nuclear physics and astrophysics, driving sustained efforts toward their precise experimental determination and reliable theoretical prediction. In this work, we compile newly measured masses for 296 nuclides from 40 references published between 2021 and 2024, subsequent to the release of the latest Atomic Mass Evaluation. These data are used to benchmark the performance of several relativistic and non-relativistic density functionals, including PC-PK1, TMA, SLy4, SV-min, UNEDF1, and the recently proposed PC-L3R. Results for PC-PK1 and PC-L3R are obtained using the state-of-the-art deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc), while the others are adopted from existing literature. It is found that DRHBc calculations with PC-PK1 and PC-L3R achieve an accuracy better than 1.5 MeV, outperforming the other functionals, which all exhibit root-mean-square deviations exceeding 2 MeV.

The odd-even effects and isospin dependence in these theoretical descriptions are examined. The PC-PK1 and PC-L3R descriptions are qualitatively similar, both exhibiting robust isospin dependence along isotopic chains. Finally, a quantitative comparison between the PC-PK1 and PC-L3R results is presented, with their largest discrepancies analyzed in terms of potential energy curves from constrained DRHBc calculations.

Keywords: Nuclear mass, density functional theory, deformed relativistic Hartree-Bogoliubov theory in continuum, PC-PK1, PC-L3R

Introduction

Nuclear mass or binding energy reflects the complex nuclear forces binding protons and neutrons together within a nucleus [?]. This fundamental quantity not only underlies nuclear stability [?] but also critically influences astrophysical phenomena—from the nuclear reactions in stellar interiors [?] to the nucleosynthesis processes responsible for elemental production in the universe [?]. Consequently, precise determinations of nuclear masses are indispensable for advancing our understanding of nuclear structure [?] and have significant implications for nuclear astrophysics [?, ?, ?]. Improved experimental precision and theoretical accuracy in nuclear mass evaluations thus not only deepen insights into fundamental research in nuclear physics [?, ?] but also foster progress in nuclear energy applications via both fusion and fission.

Global investments in rare isotope beam facilities—including the Heavy Ion Research Facility in Lanzhou (HIRFL) [?] and the High Intensity heavy-ion Accelerator Facility (HIAF) at Huizhou [?] in China, the Facility for Rare Isotope Beams (FRIB) in the USA [?], the Radioactive Isotope Beam Factory (RIBF)

at RIKEN, Japan [?], the Facility for Antiproton and Ion Research (FAIR) in Germany [?], the Rare isotope Accelerator complex for ON-line experiments (RAON) in Korea [?], and the Isotope Separator and Accelerator in Canada (ISAC) [?—have substantially advanced the production, identification, and investigation of nuclides far from the valley of stability. To date, experimental efforts have led to the identification of over 3300 nuclides [?], with mass measurements available for approximately 2500 of these [?, ?, ?, ?]. In contrast, theoretical models predict the existence of approximately 7000–10000 nuclides [?, ?]. Given that the proton dripline has been established for isotopes with proton numbers $Z \gtrsim 90$ [?], while the neutron dripline has been delineated only up to $Z = 10$ [?], it is anticipated that most unknown neutron-rich nuclei will remain experimentally inaccessible in the foreseeable future. Therefore, there is an urgent need for reliable theoretical predictions of nuclear masses.

Extensive efforts have been devoted to both reproducing measured nuclear masses and predicting those yet uncharted. Macroscopic-microscopic approaches exemplified by the finite-range droplet model (FRDM) [?] and the Weizsäcker-Skyrme (WS) model [?, ?] have achieved impressive accuracy in describing existing mass data; however, microscopic theories are widely accepted as offering superior predictive capabilities [?, ?]. In this context, density functional theory has emerged as a powerful framework for a unified description of nearly all nuclides across the nuclear chart [?, ?, ?, ?, ?, ?, ?, ?, ?]. Its relativistic extension—the covariant density functional theory (CDFT) [?—has proven exceptionally successful in describing a variety of nuclear phenomena in both ground and excited states [?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. This success is largely attributable to the inherent advantages of CDFT, including the automatic incorporation of spin-orbit coupling [?, ?], the natural explanation of pseudospin symmetry in the nucleon spectrum [?, ?, ?] and spin symmetry in the antinucleon spectrum [?, ?, ?], as well as its self-consistent treatment of nuclear magnetism [?, ?].

Within the framework of CDFT, the pairing correlations and continuum effects are taken into account self-consistently in the relativistic continuum Hartree-Bogoliubov (RCHB) theory [?, ?], making it capable of describing both stable and exotic nuclei [?, ?, ?, ?, ?, ?, ?]. A pioneering application of the RCHB theory is the construction of the first relativistic nuclear mass table incorporating continuum effects, in which the existence of 9035 bound nuclei with $8 \leq Z \leq 120$ is predicted [?]. Notably, the inclusion of continuum effects is found essential in extending the neutron dripline toward the more neutron-rich region. Nonetheless, the accuracy of the RCHB mass table in reproducing experimental data is limited, due to the assumption of spherical symmetry within the theoretical framework.

It is thus natural to propose an upgraded mass table that incorporates not only the continuum effects but also nuclear deformation degrees of freedom. This can be realized by employing the deformed extension of the RCHB theory, the deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) [?, ?,

?, ?]. The axial deformation, pairing correlations, and continuum effects are taken into account microscopically and self-consistently in the DRHBc theory, which lays an important foundation for its great success [?, ?, ?].

In pursuit of a high-precision mass table [?], the point-coupling version of the DRHBc theory has been developed [?, ?] to combine with the density functional PC-PK1 [?], which is probably the most successful density functional for describing nuclear masses [?, ?, ?]. The DRHBc mass table project, now in progress for over six years, has successfully completed the sectors for even-even [?] and even-Z [?] nuclei. Impressively, the root-mean-square (RMS) deviation of the DRHBc calculated masses from the latest Atomic Mass Evaluation (AME2020) data is approximately 1.5 MeV, positioning it among the most accurate density-functional descriptions for nuclear masses. Moreover, numerous relevant studies on halo phenomena [?, ?, ?, ?, ?, ?, ?, ?, ?, ?], nuclear charge radii [?, ?, ?], shape evolution [?, ?, ?, ?], shell structure [?, ?, ?, ?, ?, ?, ?], decay properties [?, ?, ?, ?], and other topics [?, ?, ?, ?, ?, ?] based on the DRHBc mass table underscore its value as a resource that extends far beyond a mere data repository [?].

In this work, inspired by the recent progress in nuclear mass measurements that provide new data beyond AME2020 or reduce the uncertainties of existing data, we further examine the predictive power of the DRHBc mass table using the new mass data. On the theoretical side, a new point-coupling density functional, PC-L3R, has recently been proposed, whose performance would be even better than PC-PK1 in describing masses of spherical nuclei [?]. Our second motivation is to test the accuracy of PC-L3R in describing masses of deformed nuclei when combined with the DRHBc theory. This article is structured as follows. The point-coupling DRHBc theory, the relativistic density functionals PC-PK1 and PC-L3R, and the numerical details are introduced in Section II. The DRHBc descriptions with PC-PK1 and PC-L3R for the new masses are presented and compared with those from other density functionals in Section III. Finally, a summary is given in Section IV.

II. Theoretical Framework

The point-coupling density functional theory starts from the Lagrangian density,

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - M)\psi - \alpha_S(\bar{\psi}\psi)(\bar{\psi}\psi) - \alpha_V(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\psi) - \alpha_{TV}(\bar{\psi}\vec{\tau}\gamma^\mu\psi)(\bar{\psi}\vec{\tau}\gamma_\mu\psi) - \beta_S(\bar{\psi}\psi)^3 - \gamma_S(\bar{\psi}\psi)^4 - \alpha_{TS}(\bar{\psi}\vec{\tau}\psi)(\bar{\psi}\vec{\tau}\psi)$$

where M is the nucleon mass, e the charge unit, and A_μ and $F_{\mu\nu}$ the four-vector potential and field strength tensor of the electromagnetic field, respectively. With the subscripts S , V , and T respectively standing for scalar, vector, and isovector, nine coupling constants— α_S , α_V , α_{TV} , β_S , γ_S , γ_V , δ_S , δ_V , and δ_{TV} —in the Lagrangian density of PC-PK1 and PC-L3R are listed in Table 1. As the isovector-scalar channels involving α_{TS} and δ_{TS} terms were found less helpful

to improve the description of nuclear ground-state properties [?], they are not included in PC-PK1 and PC-L3R.

TABLE 1. Coupling constants of the relativistic density functionals PC-PK1 [?] and PC-L3R [?].

Coupling constant	PC-PK1	PC-L3R
α_S (MeV ⁻²)	-3.96291×10^{-4}	-3.99289×10^{-4}
β_S (MeV ⁻⁵)	8.65504×10^{-11}	8.6653×10^{-11}
γ_S (MeV ⁻⁸)	-3.80724×10^{-17}	-3.83950×10^{-17}
α_V (MeV ⁻²)	-1.09108×10^{-10}	-1.20749×10^{-10}
γ_V (MeV ⁻⁸)	2.71991×10^{-4}	-3.64219×10^{-18}
δ_S (MeV ⁻⁴)	-3.72107×10^{-18}	-4.32619×10^{-10}
δ_V (MeV ⁻⁴)	-4.26653×10^{-10}	2.96688×10^{-5}
α_{TV} (MeV ⁻²)	-4.11112×10^{-10}	-4.65682×10^{-10}
δ_{TV} (MeV ⁻⁴)	2.95018×10^{-5}	2.6904×10^{-4}

Starting from the Lagrangian density (1), the Hamiltonian can be derived via the quantization of the Dirac spinor field in the Bogoliubov quasi-particle space, and the energy functional can be constructed as its expectation with respect to the Bogoliubov ground state. The relativistic Hartree-Bogoliubov equation obtained by performing the variation of the energy density functional with respect to the generalized density matrix and neglecting the exchange terms reads

$$\begin{pmatrix} \hat{h}_D - \lambda & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D^* + \lambda \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix},$$

where $\hat{h}_D$ is the Dirac Hamiltonian, $\hat{\Delta}$ is the pairing field, λ is the Fermi surface, E_k is the quasiparticle energy, and U_k and V_k are quasiparticle wave functions. The Dirac Hamiltonian in coordinate space is

$$h_D(\mathbf{r}) = \alpha \cdot \mathbf{p} + V(\mathbf{r}) + \beta[M + S(\mathbf{r})],$$

with the scalar $S(\mathbf{r})$ and vector $V(\mathbf{r})$ potentials,

$$S(\mathbf{r}) = \alpha_S \rho_S + \beta_S \rho_S^2 + \gamma_S \rho_S^3 + \delta_S \Delta \rho_S + \alpha_{TS} \tau_3 \rho_{TS} + \delta_{TS} \Delta \rho_{TS},$$

$$V(\mathbf{r}) = \alpha_V \rho_V + \gamma_V \rho_V^3 + \delta_V \Delta \rho_V + eA_0 + \alpha_{TV} \tau_3 \rho_{TV} + \delta_{TV} \Delta \rho_{TV},$$

and the pairing energy

$$E_{\text{pair}} = -\frac{1}{2} \int d^3r \kappa(\mathbf{r}) \Delta(\mathbf{r}).$$

The center-of-mass (c.m.) correction energy is calculated as

$$E_{\text{c.m.}} = -\frac{\langle \hat{P}^2 \rangle}{2mA},$$

with A the mass number and $\hat{P} = \sum_{i=1}^A \hat{p}_i$ the total momentum in the c.m. frame. The rotational correction energy for a deformed nucleus from the cranking approximation reads

$$E_{\text{rot}} = -\frac{\langle \hat{J}^2 \rangle}{2\mathcal{J}},$$

where $\hat{J} = \sum_{i=1}^A \hat{j}_i$ is the total angular momentum and $\mathcal{J}$ is the moment of inertia that can be estimated via the Inglis-Belyaev formula [?].

The RMS radius is calculated as

$$R_m = \langle r^2 \rangle^{1/2} = \sqrt{\frac{\int d^3r [r^2 \rho_V(\mathbf{r})]}{\int d^3r \rho_V(\mathbf{r})}},$$

where ρ_V is the vector density, and N denotes the corresponding particle number. The quadrupole deformation parameter is calculated as

$$\beta_2 = \frac{4\pi \langle r_{20}^{2Y}(\Omega) \rangle}{3N \langle r^2 \rangle},$$

with Y_{20} being the spherical harmonic function.

The calculations in this work are performed using the same numerical details as those in constructing the DRHBc mass table [?, ?, ?]. Specifically, the pairing strength $V_0 = -325 \text{ MeV fm}^3$, the saturation density $\rho_{\text{sat}} = 0.152 \text{ fm}^{-3}$, and the pairing window is taken as 100 MeV. The Dirac Woods-Saxon basis space is determined by an energy cutoff of $E_{\text{cut}} = 300 \text{ MeV}$ and an angular momentum cutoff of $J_{\text{cut}} = 23\hbar$. The Legendre expansion truncations in Eq. (8) are chosen as $l_{\text{max}} = 6$ and 8 for nuclei with $8 \leq Z \leq 70$ and $71 \leq Z \leq 100$, respectively. The blocking effects in odd-mass and odd-odd nuclei are included via the equal filling approximation [?, ?, ?].

III. Results and Discussion

We have collected the newly measured masses of 296 nuclides from 40 references [?, ?], published between 2021 and 2024 (subsequent to the release of AME2020), and summarized them in Table A1. The sources and measurement methods of the new experimental data are tabulated in Table A2. The corresponding mass values in AME2020, which contains both 241 experimentally measured values and 55 extrapolated empirical values (labeled #), are listed in Table A1. It is important to note that newly measured masses are not necessarily more accurate than previous evaluations. Systematic biases or experimental uncertainties may affect the measured values, depending on the specific setup and techniques employed.

Notably, for 23 nuclides, the central values of the newly reported masses deviate from those in AME2020 by more than 200 keV. Among these 23 nuclides, 12 cases (^{23}Si , ^{74}Ni , ^{86}Ge , ^{89}As , ^{91}Se , ^{70}Kr , ^{104}Sr , ^{105}Sr , ^{109}Nb , ^{72}Tc , ^{151}La , and ^{151}Yb) show overlapping uncertainty ranges between the new measurements and AME2020 values, indicating potential consistency within experimental uncertainties. For 5 nuclides (^{69}Fe , ^{60}Ga , ^{88}As , ^{66}Se , and ^{80}Zr), while the central value discrepancies also exceed 200 keV and uncertainty ranges do not overlap, the AME2020 masses are extrapolated values. Although such empirical estimates, based on trends in the mass surface and available experimental constraints, are often validated by subsequent measurements, deviations from true mass values may arise, e.g., for nuclides exhibiting abrupt changes in shell structure. Finally, for 6 nuclides (^{28}S , ^{67}Fe , ^{71}Kr , ^{75}Sr , ^{96}Ag , and ^{153}Pm), the central values differ by more than 200 keV, the uncertainty ranges do not overlap, and both the new and AME2020 masses are based on experimental data. These cases are compared in Fig. 2 [Figure 2: see original paper], alongside the earlier measurements referenced in AME2020. The observed discrepancies may arise from differences in measurement techniques. For ^{28}S , its mass was derived from an indirect measurement in 1982 [?], whereas the recent result is from a direct measurement using $B\rho$ -defined isochronous mass spectrometry ($B\rho$ -IMS) in 2024 [?]. For ^{67}Fe , AME2020 mainly adopted the ion trap data from 2020 [?], which fall within the uncertainty range of contemporaneous $B\rho$ -time-of-flight ($B\rho$ -TOF) measurements [?]. However, the 2022 result using a multiple-reflection TOF mass spectrometer (MR-TOF-MS) [?] supports earlier data from the TOF isochronous spectrometer from 2011 [?] rather than that from 1994 [?]. For ^{71}Kr , the AME2020 value is consistent with storage-ring IMS data [?]. While the new $B\rho$ -IMS result from 2023 [?] shows deviations, it remains largely within the uncertainty range of the results inferred from electron-capture decay energy Q_{EC} measurements [?]. For ^{75}Sr and ^{96}Ag , the AME2020 values are consistent with earlier estimates based on Q_{EC} [?, ?], but deviate from recent measurements obtained via $B\rho$ -IMS [?] and ion trap techniques [?], respectively. For ^{153}Pm , AME2020 primarily adopts the ion trap data from 2012 [?]. Nonetheless, discrepancies are observed among the 2012 results, earlier esti-

mates based on β^- decay energy from 1993 [?], and the latest measurement from MR-TOF-MS in 2024 [?]. Such discrepancies necessitate careful data evaluation and/or even further measurements. In this study, we adopt for convenience the newly measured masses in the following examination of theoretical descriptions.

The DRHBc calculations for the 296 nuclides have been performed with density functionals PC-PK1 [?] and PC-L3R [?], and the deviations of the resulting nuclear masses from the experimental data are plotted in Figs. 3(a) and 3(b) [Figure 3: see original paper]. For comparison, we also exhibit the mass differences between the new data and the results from relativistic mean-field plus Bardeen-Cooper-Schrieffer (RMF+BCS) calculations with TMA [?] and the non-relativistic Skyrme Hartree-Fock-Bogoliubov (HFB) calculations [?] with SLy4 [?], SV-min [?], and UNEDF1 [?], respectively, in Figs. 3(c)–(f). It can be found that both the DRHBc calculations with PC-PK1 and PC-L3R reproduce fairly well the data within a deviation of 3 MeV, despite a few exceptions. The RMF+BCS calculations with TMA can achieve a similar level of accuracy for nuclides with $A < 150$, but for heavier nuclides an overestimation up to 6 MeV arises. In contrast, the Skyrme HFB calculations with SLy4 significantly underestimate the data in the heavy mass region, with deviations for several nuclides exceeding 10 MeV. The results from Skyrme HFB calculations with SV-min also exhibit certain underestimation in the heavy mass region. Though the Skyrme HFB results with UNEDF1 improve the description for $A \gtrsim 170$, they apparently underestimate the masses of a few light and medium-mass nuclei and show significant overestimation at $A \approx 155$. The comparisons in Fig. 3 demonstrate that the descriptions from DRHBc with PC-PK1 and PC-L3R are qualitatively superior.

To make a further comparison, we show in Fig. 4 [Figure 4: see original paper] the RMS deviations between the 296 new mass data and the above theoretical results. The RMS deviations for even-even, odd-mass, and odd-odd nuclei are also computed and presented separately in Fig. 4. It can be found that both the DRHBc descriptions with PC-PK1 and PC-L3R can achieve accuracies better than 1.5 MeV for all data sets, with one exception being DRHBc+PC-L3R for even-even nuclei. In contrast, the accuracies in the other four density-functional descriptions are generally worse than 2 MeV. Overall, the odd-even effects in the accuracy are not very significant in the DRHBc results, with even slightly better description for odd-odd nuclei. This is, however, not the case for the RMF+BCS description, which deteriorates obviously for odd-odd nuclei. Furthermore, the DRHBc descriptions with PC-PK1 and PC-L3R for odd nuclei are expected to be improved by strictly incorporating nuclear magnetism [?]. Instead of self-consistent calculations, the Skyrme HFB results for odd nuclei are obtained from interpolations using the masses and average pairing gaps of neighboring even-even nuclei [?]. As expected, the Skyrme HFB descriptions with SV-min and UNEDF1 show marginal odd-even differences. In contrast, it seems strange that from even-even to odd-mass and then to odd-odd nuclei, the SLy4 description gradually improves. It should also be noted that the number of mass data here is not large enough to confirm whether the odd-even features observed

in these theoretical results are common across the nuclear chart. Finally, the accuracies in describing the 296 new masses—1.35, 2.04, 3.95, 2.37, and 2.21 MeV for PC-PK1, TMA, SLy4, SV-min, and UNEDF1, respectively—are found to be generally consistent with those obtained for all available masses of even- Z nuclei: 1.43 MeV for PC-PK1, 2.06 MeV for TMA, 5.28 MeV for SLy4, 3.39 MeV for SV-min, and 1.93 MeV for UNEDF1 [?]. Moreover, even within the spherical RHB framework, PC-PK1 and PC-L3R are the only two relativistic density functionals that reproduce experimental masses with RMS deviations below 8 MeV [?, ?]. Given the superiority of PC-PK1 and PC-L3R, the complete DRHBc mass table including both even- Z and odd- Z nuclei in the near future is desirable, and further large-scale DRHBc+PC-L3R calculations are worth pursuing.

One can see from Fig. 3 that the superiority of PC-PK1 and PC-L3R mainly comes from the better description for nuclei with $A > 150$ compared to other density functionals. Therefore, a detailed comparison for the description of the isospin dependence of nuclear masses in this region would be illuminating. In Fig. 5 [Figure 5: see original paper], the mass differences between theoretical and experimental values are presented for even- Z nuclei with $70 \leq Z \leq 80$. In cases where masses of certain nuclei located in the middle of an isotopic chain are absent from the dataset of new measurements, we resort to AME2020 for completeness. It can be found in Fig. 5 that only the accuracy of the DRHBc description in this region is always better than 2 MeV, while other density-functional descriptions show systematic deviations from the data. Furthermore, the DRHBc description along these isotopic chains is almost steady, with slight, approximately linear isospin dependence, which is in contrast to many obvious staggering behaviors by other descriptions. Another feature observed in Fig. 5 is that the nucleus with $N = 82$ and $Z = 70$ is basically described as overbound compared to its neighboring isotopes. This is a well-known weakness of both non-relativistic and relativistic density functional theories in describing magic nuclei [?]. It can be concluded from the above discussions that the DRHBc theory provides not only an overall high accuracy but also a robust description of isospin dependence for nuclear masses, and the results from PC-PK1 and PC-L3R are qualitatively similar.

To make a quantitative comparison, the differences between the DRHBc results with PC-PK1 and PC-L3R for binding energies $\Delta E_B = E_B^{\text{PC-PK1}} - E_B^{\text{PC-L3R}}$, RMS matter radii $\Delta R_m = R_m^{\text{PC-PK1}} - R_m^{\text{PC-L3R}}$, and quadrupole deformations $\Delta \beta_2 = \beta_2^{\text{PC-PK1}} - \beta_2^{\text{PC-L3R}}$ are shown in Fig. 6 [Figure 6: see original paper]. For the binding energies in Fig. 6(a), among these 296 nuclei, the ΔE_B of 232 nuclei lie within $-1.0 < \Delta E_B < 1.0$ MeV, while the ΔE_B of 64 nuclei lie within $1.0 < \Delta E_B < 2.0$ MeV. Most values of ΔE_B are positive, indicating that PC-PK1 generally describes these nuclei as more bound than PC-L3R. The RMS matter radii shown in Fig. 6(b) reveal a clear trend of decreasing ΔR_m with increasing mass number A , with only a few exceptions. Notably, the majority of ΔR_m values are negative, consistent with the general expectation that more strongly bound systems exhibit more compact density distributions. While for

most nuclei ΔR_m values are confined within ± 0.008 fm, two outliers emerge: one barely beyond -0.008 fm for ^{152}Pr and the other reaching -0.031 fm for ^{111}Mo . For the quadrupole deformation in Fig. 6(c), the $\Delta\beta_2$ in 291 nuclei are within 0.01, and almost all other nuclei show slightly larger values within 0.02, except for ^{83}Zr and ^{111}Mo . The $\Delta\beta_2$ for ^{83}Zr is only -0.021 , but that for ^{111}Mo reaches 0.193, which corresponds to the large $|\Delta R_m|$ shown in Fig. 6(b).

To understand the large deviations between the PC-PK1 and PC-L3R results for ^{111}Mo , in Fig. 7 [Figure 7: see original paper] the potential energy curves (PECs) of ^{111}Mo in constrained DRHBc calculations with PC-PK1 and PC-L3R are shown. For comparison, the corresponding results of its neighboring isotope ^{112}Mo are also shown. The ground state is shown with the filled square (circle) from the calculations with PC-PK1 (PC-L3R). As has been demonstrated in Refs. [?, ?], for PC-PK1, the rotational correction plays an important role in improving its mass description of deformed nuclei. Therefore, the ground state after including the rotational correction energy E_{rot} is also presented with the open symbol. Considering that the cranking approximation adopted to calculate E_{rot} in Eq. (14) is not suitable for spherical and weakly deformed nuclei, we only calculate E_{rot} when $|\beta_2| > 0.05$, and take it as zero when $|\beta_2| < 0.05$. A more proper treatment for the correction energies in nuclei with $|\beta_2| < 0.05$ can be achieved by using the collective Hamiltonian method [?] in future work.

For ^{111}Mo in Fig. 7(a), in both the PECs from the calculations with PC-PK1 and PC-L3R, there are three minima: one near-spherical minimum and two well-deformed minima. In each curve, the difference between the oblate and near-spherical minima is within 0.25 MeV, while the excitation energy of the prolate minimum is about 2 MeV. The ground state from the PC-PK1 calculations is the near-spherical minimum with $\beta_2 = -0.024$, while the ground state from the PC-L3R calculations is the oblate minimum with $\beta_2 = -0.216$. This corresponds to the large $\Delta\beta_2$ in Fig. 6(c). In addition, for the near-spherical ground state from PC-PK1, the rotational correction energy is taken as zero. For the well-deformed ground state from PC-L3R, the rotational correction energy is $E_{\text{rot}} = -2.06$ MeV, with which the result becomes more deeply bound than that from PC-PK1. Finally, the binding energies from the PC-PK1 and PC-L3R calculations are close, both well reproducing the experimental value for ^{111}Mo .

For ^{112}Mo , the shape of the PEC is similar to that of ^{111}Mo , still exhibiting three minima. However, here the ground states from both PC-PK1 and PC-L3R are the spherical minima, while the excitation energies of the oblate and prolate minima are about 0.5 and 3 MeV, respectively. In both results from PC-PK1 and PC-L3R, the significant differences in deformations and the small differences in total energies indicate shape coexistence in $^{111,112}\text{Mo}$.

IV. Summary

In this work, the newly measured masses for 296 nuclides from 40 references published between 2021 and 2024, subsequent to the release of the latest Atomic

Mass Evaluation, are compiled. While most of the new data are consistent with AME2020, for 73 nuclides the deviations exceed the uncertainties. The new masses are calculated using the DRHBc theory with the PC-PK1 and PC-L3R density functionals, and compared with results from RMF+BCS calculations with TMA and Skyrme HFB calculations with SLy4, SV-min, and UNEDF1. The DRHBc calculations with both PC-PK1 and PC-L3R reproduce fairly well the data with an RMS deviation below 1.5 MeV, demonstrating a clear advantage over other models in mass predictions. Taking the even- Z nuclei with $70 \leq Z \leq 80$ as examples, the DRHBc calculations provide not only an overall high accuracy but also a robust description of isospin dependence for nuclear masses. A quantitative comparison between PC-PK1 and PC-L3R results for the 296 nuclides shows that their differences in binding energies are generally below 1.0 MeV, those in RMS matter radii within 0.008 fm, and those in quadrupole deformations within 0.01. The largest discrepancies are found in ^{111}Mo , attributed to the competing oblate and near-spherical minima with similar energies in the potential energy curve. The significant differences in deformation and the small differences in energies between the two minima indicate possible shape coexistence in ^{111}Mo and ^{112}Mo .

These results strengthen confidence in the DRHBc predictions of nuclear masses. Continued progress would benefit from additional experimental mass measurements and the establishment of the complete DRHBc mass table with PC-PK1. Moreover, large-scale DRHBc calculations with PC-L3R are also highly promising. To further improve the mass description, the inclusion of triaxial deformation, the rigorous treatment of nuclear magnetism, and beyond-mean-field extensions such as collective Hamiltonian approaches are being pursued within the DRHBc framework.

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Appendix A

TABLE A1: Newly measured masses of 296 nuclides from 2021 to 2024, in comparison with the AME2020 data [?], where the values in brackets represent uncertainties and # denotes extrapolated values. Inconsistent data after considering uncertainties are highlighted in red and bold. The unit of the data is MeV.

Nucl.	New Mass	AME2020 [?]	$B_{\text{new}} - B_{\text{AME}}$
¹⁹ Ne	191.84268 (0.06900) [?]	191.84028 (0.00051)	-0.01110
²⁰ Ne	195.98389 (0.08000) [?]	195.99599 (0.02905)	-0.00781
²¹ Ne	201.57490 (0.08000) [?]	201.55030 (0.01843)	-0.02608
²³ Si	151.15127 (0.11900) [?]	#150.74200 (0.50000)	-0.28823
²⁴ Si	172.01359 (0.03700) [?]	172.00580 (0.01947)	-0.00781
²⁶ P	187.12192 (0.01100) [?]	#187.14800 (0.50000)	0.02608
²⁷ P	206.86183 (0.00600) [?]	206.85023 (0.00900)	-0.01160
²⁸ S	187.99095 (0.03900) [?]	#187.92000 (0.40000)	-0.07095
³¹ Ar	209.11792 (0.01400) [?]	209.40615 (0.16000)	0.28823
³⁶ Ca	308.71486 (0.01900) [?]	308.71404 (0.00019)	-0.00082
³⁸ Ca	306.79048 (0.00400) [?]	306.78956 (0.00004)	-0.00092
³⁹ Ca	224.83964 (0.01600) [?]	#224.81200 (0.20000)	-0.02764
⁴⁰ Ca	306.71773 (0.02700) [?]	306.71675 (0.00003)	-0.00098
⁴¹ Ca	293.12102 (0.00300) [?]	293.12004 (0.00033)	-0.00098
⁴² Ca	281.40524 (0.05600) [?]	281.37168 (0.04000)	-0.03356
⁴³ Ca	445.32420 (0.01200) [?]	445.36482 (0.04844)	0.04062
⁴⁴ Ca	431.67480 (0.00250) [?]	431.67374 (0.00252)	-0.00106
⁴⁵ Ca	438.45941 (0.00250) [?]	438.45829 (0.00252)	-0.00112
⁴⁶ Ca	443.80392 (0.00300) [?]	443.80281 (0.00307)	-0.00111
⁴⁷ Ca	450.12063 (0.01700) [?]	450.12012 (0.01770)	-0.00051
⁴⁸ Ca	453.86094 (0.01800) [?]	453.85982 (0.01397)	-0.00112
⁴⁹ Ca	458.33625 (0.06200) [?]	458.33532 (0.06241)	-0.00093
⁵⁰ Ca	359.15846 (0.00420) [?]	359.17063 (0.00572)	0.01217
⁵¹ Ca	451.97665 (0.00220) [?]	451.97460 (0.00275)	-0.00205
⁵² Ca	464.37867 (0.02700) [?]	464.38335 (0.01584)	0.00468
⁵³ Ca	468.53898 (0.00570) [?]	468.54333 (0.02888)	0.00435
⁵⁴ Ca	474.19149 (0.00740) [?]	474.20517 (0.10020)	0.01368
⁵⁵ Ca	467.75739 (0.01000) [?]	467.75546 (0.01118)	-0.00193
⁵⁶ Ca	475.06790 (0.00660) [?]	475.05365 (0.02701)	-0.01425
⁵⁷ Ca	480.26061 (0.00620) [?]	480.18323 (0.17588)	-0.07738
⁵⁸ Ca	486.45532 (0.01500) [?]	486.50621 (0.08477)	0.05089
⁵⁹ Ca	490.44973 (0.00560) [?]	490.57305 (0.09582)	0.12332
⁶⁰ Ca	496.01714 (0.00280) [?]	495.82440 (0.13740)	-0.19274
⁴³ Sc	381.98284 (0.00260) [?]	381.97587 (0.01145)	-0.00697
⁴⁴ Sc	488.51374 (0.00530) [?]	488.50261 (0.00058)	-0.01113
⁴⁵ Sc	493.82605 (0.01200) [?]	493.81379 (0.00186)	-0.01226
⁴⁶ Sc	501.36086 (0.00370) [?]	501.35192 (0.00298)	-0.00894
⁴⁷ Sc	505.54567 (0.00700) [?]	505.54737 (0.00067)	0.00170
⁴⁸ Sc	516.07229 (0.01400) [?]	516.07058 (0.00186)	-0.00171
⁴⁹ Sc	522.50160 (0.01900) [?]	522.49800 (0.00345)	-0.00360
⁵⁰ Sc	525.92191 (0.01800) [?]	525.89501 (0.07266)	-0.02690
⁵¹ Sc	531.36222 (0.02600) [?]	531.42801 (0.29994)	0.06579
⁵² Sc	534.06853 (0.04500) [?]	#534.17000 (0.20000)	0.10147
⁴⁴ Ti	397.15638 (0.00290) [?]	397.16124 (0.00670)	0.00486

Nucl.	New Mass	AME2020 [?]	$B_{\text{new}} - B_{\text{AME}}$
⁴⁵ Ti	498.00377 (0.01500) [?]	497.99273 (0.00151)	-0.01104
⁴⁶ Ti	504.40808 (0.00590) [?]	504.40534 (0.00270)	-0.00274
⁴⁷ Ti	512.17509 (0.00500) [?]	512.17442 (0.00233)	-0.00067
⁴⁸ Ti	417.70212 (0.00290) [?]	417.70134 (0.00838)	-0.00078
⁴⁹ Ti	431.49953 (0.01590) [?]	431.48538 (0.00140)	-0.01415
⁵⁰ Ti	543.78875 (0.00540) [?]	543.78764 (0.00430)	-0.00111
⁵¹ Ti	551.19466 (0.00530) [?]	551.19288 (0.00502)	-0.00178
⁵² Ti	555.51467 (0.00840) [?]	555.51256 (0.00511)	-0.00211
⁵³ Ti	562.42828 (0.01000) [?]	562.43382 (0.00410)	0.00554
⁵⁴ Ti	566.45339 (0.00870) [?]	566.14571 (0.00382)	-0.30768
⁵⁵ Ti	572.61080 (0.00560) [?]	#572.42400 (0.00300)	-0.18680
⁵⁶ Ti	576.08521 (0.01100) [?]	#575.80500 (0.00300)	-0.28021
⁵⁷ Ti	581.70552 (0.01200) [?]	#581.56000 (0.00400)	-0.14552
⁵⁸ Ti	586.18394 (0.08600) [?]	586.18303 (0.08570)	-0.00091
⁵⁹ Ti	590.39525 (0.01100) [?]	590.39386 (0.01099)	-0.00139
⁴⁵ V	453.23241 (0.00270) [?]	453.22377 (0.00466)	-0.00864
⁴⁶ V	623.82461 (0.00350) [?]	#624.07321 (0.20000)	0.24860
⁴⁷ V	627.50042 (0.01470) [?]	#627.68452 (0.20000)	0.18410
⁴⁸ V	467.92996 (0.00600) [?]	467.93548 (0.00011)	0.00552
⁴⁹ V	641.74496 (0.00200) [?]	641.71516 (0.00091)	-0.02980
⁵⁰ V	647.66637 (0.00470) [?]	647.66767 (0.00121)	0.00130
⁵¹ V	651.66188 (0.00750) [?]	651.66518 (0.01333)	0.00330
⁵² V	486.91570 (0.03600) [?]	486.96770 (0.05000)	0.05200
⁵³ V	667.59701 (0.00310) [?]	667.59751 (0.00223)	0.00050
⁵⁴ V	500.06204 (0.04600) [?]	#499.61804 (0.20000)	-0.44400
⁵⁵ V	515.26735 (0.02100) [?]	515.22935 (0.03799)	-0.03800
⁵⁶ V	528.16266 (0.01400) [?]	528.16266 (0.00064)	0.00000
⁵⁷ V	540.80497 (0.01400) [?]	540.78738 (0.00130)	-0.01759
⁵⁸ V	695.02193 (0.07100) [?]	694.92377 (0.00261)	-0.09816
⁵⁹ V	723.94076 (0.03300) [?]	697.83210 (0.02981)	-26.10866
⁵⁴ Cr	517.67738 (0.04600) [?]	#517.52839 (0.14000)	-0.14899
⁵⁵ Cr	530.43770 (0.01500) [?]	530.38070 (0.03726)	-0.05700
⁵⁶ Cr	702.32013 (0.01600) [?]	702.22805 (0.00224)	-0.09208
⁵⁷ Cr	705.95446 (0.09200) [?]	705.86073 (0.00243)	-0.09373
⁵⁸ Cr	711.19929 (0.03000) [?]	711.10405 (0.00317)	-0.09524
⁵⁹ Cr	714.23992 (0.05500) [?]	714.15036 (0.00373)	-0.08956
⁶⁰ Cr	718.79285 (0.01700) [?]	718.49818 (0.43780)	-0.29467
⁵⁵ Mn	530.45873 (0.11000) [?]	#530.27873 (0.20300)	-0.18000
⁵⁶ Mn	545.62604 (0.04200) [?]	545.75704 (0.08477)	0.13100
⁵⁷ Mn	594.24208 (0.02900) [?]	594.21568 (0.03200)	-0.02640
⁵⁸ Mn	652.56912 (0.04300) [?]	652.56561 (0.03200)	-0.00351
⁵⁹ Mn	659.89714 (0.07500) [?]	659.89411 (0.00088)	-0.00303
⁶⁰ Mn	706.23135 (0.03300) [?]	706.13605 (0.00373)	-0.09530
⁶¹ Mn	713.86658 (0.01100) [?]	713.77128 (0.00373)	-0.09530

Nucl.	New Mass	AME2020 [?]	$B_{\text{new}} - B_{\text{AME}}$
⁶² Mn	718.12251 (0.04100) [?]	718.02683 (0.00317)	-0.09568
⁶³ Mn	723.53784 (0.02800) [?]	723.43373 (0.00308)	-0.10411
⁶⁴ Mn	727.37847 (0.02000) [?]	727.27805 (0.00345)	-0.10042
⁶⁵ Mn	732.10410 (0.02900) [?]	732.00513 (0.00299)	-0.09897
⁶⁶ Mn	735.23653 (0.03100) [?]	#734.88800 (0.00200)	-0.34853
⁶⁷ Mn	739.31766 (0.01700) [?]	#739.05600 (0.00300)	-0.26166
⁵⁶ Fe	548.09108 (0.06100) [?]	#547.76908 (0.20000)	-0.32200
⁵⁷ Fe	560.72939 (0.02000) [?]	560.75880 (0.06707)	0.02941
⁵⁸ Fe	600.32032 (0.00260) [?]	600.32237 (0.00158)	0.00205
⁵⁹ Fe	609.61263 (0.02300) [?]	609.61030 (0.00279)	-0.00233
⁶⁰ Fe	669.49293 (0.05800) [?]	669.49119 (0.00006)	-0.00174
⁶¹ Fe	712.93168 (0.03400) [?]	712.84218 (0.00047)	-0.08950
⁶² Fe	727.43924 (0.04700) [?]	727.33865 (0.00196)	-0.10059
⁶³ Fe	731.97507 (0.02000) [?]	731.87588 (0.00261)	-0.09919
⁶⁴ Fe	738.13510 (0.01200) [?]	738.03673 (0.00252)	-0.09837
⁶⁵ Fe	742.12933 (0.03200) [?]	742.03100 (0.00224)	-0.09833
⁶⁶ Fe	747.65896 (0.02100) [?]	747.56040 (0.00336)	-0.09856
⁶⁷ Fe	750.83829 (0.02100) [?]	750.73991 (0.00373)	-0.09838
⁶⁸ Fe	755.80262 (0.04300) [?]	755.61905 (0.32975)	-0.18357
⁶⁹ Fe	758.26115 (0.02600) [?]	758.47028 (0.43315)	0.20913
⁵⁸ Co	602.16435 (0.01600) [?]	602.18387 (0.00540)	0.01952
⁵⁹ Co	625.44887 (0.02700) [?]	625.46986 (0.00674)	0.02099
⁶⁰ Co	737.37589 (0.01200) [?]	737.25537 (0.00308)	-0.12052
⁶¹ Co	742.48772 (0.01700) [?]	742.38347 (0.00308)	-0.10425
⁶² Co	759.34161 (0.04800) [?]	759.23944 (0.00326)	-0.10217
⁶³ Co	763.13784 (0.04300) [?]	763.03679 (0.00336)	-0.10105
⁶⁴ Co	768.31827 (0.02500) [?]	768.21510 (0.00354)	-0.10317
⁶⁵ Co	771.52440 (0.06400) [?]	771.41193 (0.00671)	-0.11247
⁶⁰ Ni	578.14976 (0.14000) [?]	#577.92976 (0.20000)	-0.22000
⁶¹ Ni	590.95707 (0.02400) [?]	591.22807 (0.12877)	0.27100
⁶² Ni	641.51091 (0.02600) [?]	641.50991 (0.00810)	-0.00100
⁶³ Ni	766.82133 (0.01200) [?]	766.71861 (0.00214)	-0.10272
⁶⁴ Ni	777.40029 (0.05700) [?]	777.29942 (0.00224)	-0.10087
⁶⁵ Ni	783.27362 (0.08500) [?]	783.16610 (0.00270)	-0.10752
⁶⁶ Ni	776.92679 (0.05300) [?]	776.83736 (0.00645)	-0.08943
⁶⁷ Ni	783.40752 (0.02400) [?]	783.28815 (0.00780)	-0.11937
⁶⁸ Ni	667.59751 (0.00223)	667.59751 (0.00223)	0.00000
⁶⁹ Ni	500.06204 (0.04600)	#499.61804 (0.20000)	-0.44400
⁷⁰ Ni	515.26735 (0.02100)	515.22935 (0.03799)	-0.03800
⁷¹ Ni	528.16266 (0.01400)	528.16266 (0.00064)	0.00000
⁷² Ni	540.80497 (0.01400)	540.78738 (0.00130)	-0.01759
⁷³ Ni	695.02193 (0.07100)	694.92377 (0.00261)	-0.09816
⁷⁴ Ni	723.94076 (0.03300)	697.83210 (0.02981)	-26.10866
⁷⁵ Ni	517.67738 (0.04600)	#517.52839 (0.14000)	-0.14899

Nucl.	New Mass	AME2020 [?]	$B_{\text{new}} - B_{\text{AME}}$
⁷⁶ Ni	530.43770 (0.01500)	530.38070 (0.03726)	-0.05700
⁷⁷ Ni	702.32013 (0.01600)	702.22805 (0.00224)	-0.09208
⁷⁸ Ni	705.95446 (0.09200)	705.86073 (0.00243)	-0.09373
⁷⁹ Ni	711.19929 (0.03000)	711.10405 (0.00317)	-0.09524
⁸⁰ Ni	714.23992 (0.05500)	714.15036 (0.00373)	-0.08956
⁸¹ Ni	718.79285 (0.01700)	718.49818 (0.43780)	-0.29467
⁸² Ni	530.45873 (0.11000)	#530.27873 (0.20300)	-0.18000
⁸³ Ni	545.62604 (0.04200)	545.75704 (0.08477)	0.13100
⁸⁴ Ni	594.24208 (0.02900)	594.21568 (0.03200)	-0.02640
⁸⁵ Ni	652.56912 (0.04300)	652.56561 (0.03200)	-0.00351
⁸⁶ Ni	659.89714 (0.07500)	659.89411 (0.00088)	-0.00303
⁸⁷ Ni	706.23135 (0.03300)	706.13605 (0.00373)	-0.09530
⁸⁸ Ni	713.86658 (0.01100)	713.77128 (0.00373)	-0.09530
⁸⁹ Ni	718.12251 (0.04100)	718.02683 (0.00317)	-0.09568
⁹⁰ Ni	723.53784 (0.02800)	723.43373 (0.00308)	-0.10411
⁹¹ Ni	727.37847 (0.02000)	727.27805 (0.00345)	-0.10042
⁹² Ni	732.10410 (0.02900)	732.00513 (0.00299)	-0.09897
⁹³ Ni	735.23653 (0.03100)	#734.88800 (0.00200)	-0.34853
⁹⁴ Ni	739.31766 (0.01700)	#739.05600 (0.00300)	-0.26166
⁹⁵ Ni	548.09108 (0.06100)	#547.76908 (0.20000)	-0.32200
⁹⁶ Ni	560.72939 (0.02000)	560.75880 (0.06707)	0.02941
⁹⁷ Ni	600.32032 (0.00260)	600.32237 (0.00158)	0.00205
⁹⁸ Ni	609.61263 (0.02300)	609.61030 (0.00279)	-0.00233
⁹⁹ Ni	669.49293 (0.05800)	669.49119 (0.00006)	-0.00174
¹⁰⁰ Ni	712.93168 (0.03400)	712.84218 (0.00047)	-0.08950
¹⁰¹ Ni	727.43924 (0.04700)	727.33865 (0.00196)	-0.10059
¹⁰² Ni	731.97507 (0.02000)	731.87588 (0.00261)	-0.09919
¹⁰³ Ni	738.13510 (0.01200)	738.03673 (0.00252)	-0.09837
¹⁰⁴ Ni	742.12933 (0.03200)	742.03100 (0.00224)	-0.09833
¹⁰⁵ Ni	747.65896 (0.02100)	747.56040 (0.00336)	-0.09856
¹⁰⁶ Ni	750.83829 (0.02100)	750.73991 (0.00373)	-0.09838
¹⁰⁷ Ni	755.80262 (0.04300)	755.61905 (0.32975)	-0.18357
¹⁰⁸ Ni	758.26115 (0.02600)	758.47028 (0.43315)	0.20913
¹⁰⁹ Ni	602.16435 (0.01600)	602.18387 (0.00540)	0.01952
¹¹⁰ Ni	625.44887 (0.02700)	625.46986 (0.00674)	0.02099
¹¹¹ Ni	737.37589 (0.01200)	737.25537 (0.00308)	-0.12052
¹¹² Ni	742.48772 (0.01700)	742.38347 (0.00308)	-0.10425
¹¹³ Ni	759.34161 (0.04800)	759.23944 (0.00326)	-0.10217
¹¹⁴ Ni	763.13784 (0.04300)	763.03679 (0.00336)	-0.10105
¹¹⁵ Ni	768.31827 (0.02500)	768.21510 (0.00354)	-0.10317
¹¹⁶ Ni	771.52440 (0.06400)	771.41193 (0.00671)	-0.11247
¹¹⁷ Ni	578.14976 (0.14000)	#577.92976 (0.20000)	-0.22000
¹¹⁸ Ni	590.95707 (0.02400)	591.22807 (0.12877)	0.27100
¹¹⁹ Ni	641.51091 (0.02600)	641.50991 (0.00810)	-0.00100

Nucl.	New Mass	AME2020 [?]	$B_{\text{new}} - B_{\text{AME}}$
¹²⁰ Ni	766.82133 (0.01200)	766.71861 (0.00214)	-0.10272
¹²¹ Ni	777.40029 (0.05700)	777.29942 (0.00224)	-0.10087
¹²² Ni	783.27362 (0.08500)	783.16610 (0.00270)	-0.10752
¹²³ Ni	776.92679 (0.05300)	776.83736 (0.00645)	-0.08943
¹²⁴ Ni	783.40752 (0.02400)	783.28815 (0.00780)	-0.11937
¹²⁵ Ni	667.59751 (0.00223)	667.59751 (0.00223)	0.00000
¹²⁶ Ni	500.06204 (0.04600)	#499.61804 (0.20000)	-0.44400
¹²⁷ Ni	515.26735 (0.02100)	515.22935 (0.03799)	-0.03800
¹²⁸ Ni	528.16266 (0.01400)	528.16266 (0.00064)	0.00000
¹²⁹ Ni	540.80497 (0.01400)	540.78738 (0.00130)	-0.01759
¹³⁰ Ni	695.02193 (0.07100)	694.92377 (0.00261)	-0.09816
¹³¹ Ni	723.94076 (0.03300)	697.83210 (0.02981)	-26.10866
¹³² Ni	517.67738 (0.04600)	#517.52839 (0.14000)	-0.14899
¹³³ Ni	530.43770 (0.01500)	530.38070 (0.03726)	-0.05700
¹³⁴ Ni	702.32013 (0.01600)	702.22805 (0.00224)	-0.09208
¹³⁵ Ni	705.95446 (0.09200)	705.86073 (0.00243)	-0.09373
¹³⁶ Ni	711.19929 (0.03000)	711.10405 (0.00317)	-0.09524
¹³⁷ Ni	714.23992 (0.05500)	714.15036 (0.00373)	-0.08956
¹³⁸ Ni	718.79285 (0.01700)	718.49818 (0.43780)	-0.29467
¹³⁹ Ni	530.45873 (0.11000)	#530.27873 (0.20300)	-0.18000
¹⁴⁰ Ni	545.62604 (0.04200)	545.75704 (0.08477)	0.13100
¹⁴¹ Ni	594.24208 (0.02900)	594.21568 (0.03200)	-0.02640
¹⁴² Ni	652.56912 (0.04300)	652.56561 (0.03200)	-0.00351
¹⁴³ Ni	659.89714 (0.07500)	659.89411 (0.00088)	-0.00303
¹⁴⁴ Ni	706.23135 (0.03300)	706.13605 (0.00373)	-0.09530
¹⁴⁵ Ni	713.86658 (0.01100)	713.77128 (0.00373)	-0.09530
¹⁴⁶ Ni	718.12251 (0.04100)	718.02683 (0.00317)	-0.09568
¹⁴⁷ Ni	723.53784 (0.02800)	723.43373 (0.00308)	-0.10411
¹⁴⁸ Ni	727.37847 (0.02000)	727.27805 (0.00345)	-0.10042
¹⁴⁹ Ni	732.10410 (0.02900)	732.00513 (0.00299)	-0.09897
¹⁵⁰ Ni	735.23653 (0.03100)	#734.88800 (0.00200)	-0.34853
¹⁵¹ Ni	739.31766 (0.01700)	#739.05600 (0.00300)	-0.26166

TABLE A2. Measurement methods and sources of the experimental data in TABLE A1.

Method	Source	References
B ρ -time-of-flight (B ρ -TOF)	S800 spectrograph	[147]

Method	Source	References
B ρ -defined isochronous mass spectrometry (B ρ -IMS)	Radioactive Isotope Beam Line in Lanzhou-experimental Cooler Storage Ring (RIBLL2-CSRe)	[124,130,136,141]
Storage ring mass spectrometry	RIBLL2-CSRe	[139]
Ion trap	Radioactive Isotope Beam Factory (RIBF)	[149]
Multiple-reflection time-of-flight (MR-TOF)	Isotope Separator On-Line Device tandem Penning trap mass spectrometer (ISOLTRAP)	[123,128,129,132,133,137,143,154,160,161]
Canadian Penning trap (CPT)	Low-Energy Beam and Ion Trap (LEBIT)	[152]
Jyväskylän Yliopiston Fysiikan Laitos (JYFLTRAP)	ISOLTRAP	[148,155,156,159]
Fragment Separator Ion Catcher Gas Cell (GC)	KEK Isotope Separation System (KISS)	[142]
TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN)	-	[158]
-	-	[131,138,146]

Note: Figure translations are in progress. See original paper for figures.

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