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The New Nuclear Magic Number From Level Structure 54Ca: A Systematic Literature Review

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ABSTRACT

The concept of "magic numbers" refers to specific occupation numbers in the shell structure of atomic nuclei that exhibit significant energy gaps for protons and neutrons. This study focuses on the magic numbers N and Z, which include 2, 8, 20, 28, 50, 82, and 126. Additional evidence suggests the existence of a new magic number at N = 34, with ^{54}Ca identified as a potential candidate. The objective of this research is to experimentally confirm the presence of the N = 34 magic number in ^{54}Ca using in-beam γ-ray spectroscopy. The study measures γ-rays emitted in coincidence with ^{54}Ca projectiles produced through one- and two-proton knockout reaction channels. The experimental data is compared to theoretical predictions from the distorted-wave impulse approximation (DWIA) reaction model, shell model calculations, and ab initio calculations using various interactions. Then, the results of direct mass measurements on neutron-rich calcium isotopes beyond neutron number 34 by using the time-of-flight magnetic-rigidity technique, demonstrate a significant energy gap between the neutron 2p1/2 and *1f*5/2 orbitals in ^{54}Ca, providing experimental support for the emergence of the N = 34 magic number and providing insights into the shell closure in calcium isotopes. This study contributes to a deeper understanding of atomic nucleus structure and the role of magic numbers in nuclear physics.

Keywords: magic number, nuclear shell structure, ^{54}Ca, γ-rays, GXPF1B, time-of-flight magnetic-rigidity technique

1. INTRODUCTION

Nuclear shell structure, as correctly described by Mayer and Jensen 70 years ago with the inclusion of an appropriate spin-orbit force, embodies the backbone of our understanding of the many-body structure of atomic nuclei. It is characterized by "magic numbers," which correspond to large energy gaps between single-particle orbitals of protons or neutrons. The magic numbers comprise Z or N equal to 2, 8, 20, 28, 50, 82, 126,..., where Z and N denote, respectively, proton and neutron numbers. The front line of nuclear structure physics moved gradually to nuclei with large N vs Z imbalance, known as exotic nuclei or rare isotopes (O. Haxel, et,al,. 1949, M. G. Mayer, 1949).

Many theoretical studies were intensively carried out to understand these structural changes in nuclei far from stability and to qualitatively predict the behavior of the nuclear structure near the drip line. As an important milestone, the emergence of a subshell closure at N = 34 remains a controversial topic. The formation of the N = 34 subshell gap was associated with the $f_{7/2}$-$\nu f_{5/2}$ (proton $f_{7/2}$-neutron $\nu f_{5/2}$) nucleon-nucleon attractive interaction (T. Otsuka, et,al,. 2001). When approaching Z = 20 from "above," the strength of the attraction between $\pi f_{7/2}$ and $\nu f_{5/2}$ becomes weaker due to the decreasing occupation of the $\pi f_{7/2}$ orbital. First indications for a sizable N = 34 subshell gap in ^{54}Ca were presented by the measured large $E(2_1^+)$ (D. Steppenbeck et al.,2013).

Therefore, this paper focuses on the literature on highlight the doubly magic nature of 54Ca (a bound system composed of 20 protons and 34 neutrons) using proton knockout reactions involving fast radioactive projectiles.

2. METHODOLOGY

A systematic literature review (SLR) is utilized here, which is a literature review that discovers, assesses, and interprets all data on a study issue to answer previously specified research questions (Patra, 2014). The literature search was restricted to items published between 2013 and 2023. The title and keywords "nuclear magic numbers" and "^{54}Ca" were used to search for publications in research databases at Sciencedirect, Pubmed, and Semantic Scholar.

The Preferred Reporting Item for Systematic Reviews and Meta-Analytic (PRISMA) technique was utilized. All publications that passed the selection procedure were examined and summarized based on the objectives, year of publication, document type, publication stage, keywords, and source type. The inclusion criteria are (1) studies on nuclear magic number of structure ^{54}Ca and (2) research articles published in peer-reviewed journals. The exclusion criteria include (1) studies not focusing on the ^{54}Ca structure and (2) articles containing a literature review or a meta-analysis. The search begins by analyzing the titles and abstracts of all search results and comparing them to predefined criteria.

3. RESULT

The research database search resulted in all keywords search results obtained 89 research articles in total, from Sciencedirect, 31 articles; Pubmed, 28 articles; and Semantic Scholar, 30 articles. After scanning the title, the same article was in three different databases. The results after deducting the duplicates are 87

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articles. Then, the results were excluded because publication time did not meet the criteria (43 articles), or they did not meet the topic criteria. Still, they were not focusing on the ^{54}Ca structure (40 articles). There are 3 articles included in the final literature review. The literature search is described in more detail in Figure 1.

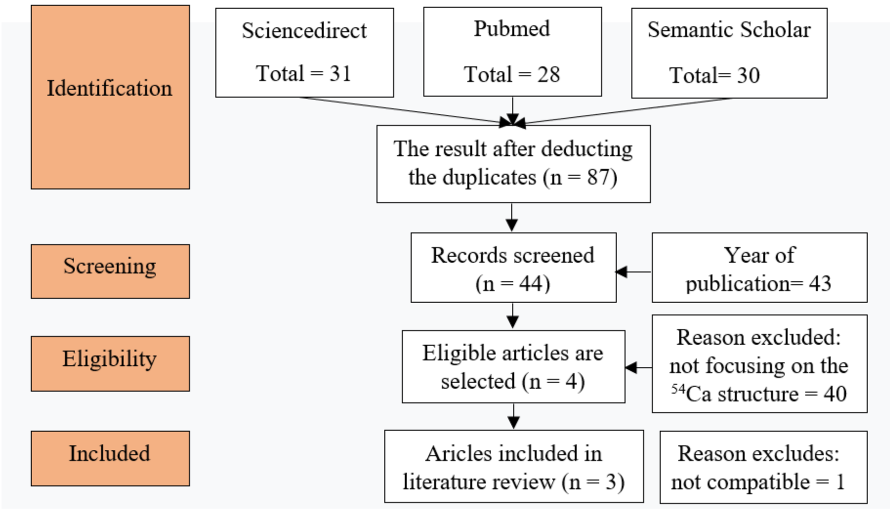

Figure 1. Literature review search method

Magic Number

The atomic nucleus has shell structures for both protons and neutrons with significant energy gaps occurring at particular occupation numbers. These numbers are called “magic numbers,”. The magic numbers, N, Z=2, 8, 20, 28, 50, 82, and 126. By adding only two more neutrons, also a N= 34 subshell gap was suggested by some theories (T. Otsuka, et,al,. 2001, M. Honma, et,al. 2005). One of them is at ^{54}Ca. In order to confirm experimentally the N = 34 new magic number using the technique of in-beam y-ray spectroscopy. The y-rays measured in coincidence with 54Ca projectiles produced through the one- and two-proton knockout reaction channels. The GXPF1 family of effective interactions has often been used. The GXPFIBs interaction, where the $vf^2_{5/2}$ pairing matrix element is shifted by -0.4 MeV from the GXPF1Br value so that the $vf^2_{7/2}$ and $vf^2_{5/2}$ fand pairing matrix elements can be better factorized by the orbital occupation number, (2j+1). Therefore use the GXPFIBs interaction. The experimental were reproduced by the DWIA reaction model together with structure input from the shell model calculation using GXPF1Bs interaction and ab initio calculations with $NNLO_{sat}$ and NN+3N(lnl) interactions. The distorted-wave impulse approximation (DWIA) formalism is used to analyze the one-neutron knockout reaction in inverse kinematics on a thick liquid hydrogen target. Two different NN+BM chiral interactions were employed: the $NNLO_{sat}$ introduced (A. Ekström, et.al., 2017) has provided accurate sat predictions of nuclear radii in several recent state-of-the-art ab initio calculations (T. Duguet, et.al,. 2017, R. Garcia, et,al,. 2016, V. Lapoux,et,al,. 2016). The second Hamiltonian is the newly developed NN+3N(Inl) with both local and nonlocal 3M regulators (Chen et al., 2019). Besides that, direct mass measurements can be performed for the first time on neutron-rich calcium isotopes beyond neutron number 34 by using the time-of-flight magnetic-rigidity technique. The atomic mass excesses of $^{55–57}Ca$ are determined for the first time to be −18650(160), −13510(250), and −7370(990) keV, respectively. We examine the emergence of neutron magicity at N=34 based on the new atomic masses. The new masses provide experimental evidence for the appearance of a sizable energy gap between the neutron $2p_{1/2}$ and $1f_{5/2}$ orbitals in ^{54}Ca (Michimasa et al., 2018).

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4. DISCUSSION

To know a new nuclear ‘magic number’ in ^{54}Ca by in-beam γ-ray spectroscopy. The γ-rays measured in coincidence with ^{54}Ca projectiles producedthrough the one and two-proton knockout reaction channels. The γ-ray energies measured in the laboratoryframe of reference have been corrected for doppler shifts, and so the transitions appear at the energies they would in the rest frame of thenucleus. The most intense γ-ray line in the ^{54}Ca spectrum, the peak at 2,043(19) keV (error, 1 s.d.) in Fig. 2, is assigned as the transition from the first 2^{+} state (2_1^+) to the 0^{+} ground state. In addition, two weaker transitions are located at 1,656(20) and, respectively, 1,184(24) keV. On the basis of the γ-ray relative intensities, the 1,656-keV transition is proposed to depopulate a level at 3,699(28) keV. Placement of the 1,184-keV transition in the level scheme is uncertain owing to ambiguity in coincidence measurements between the 1,656- and 1,184-keV lines. However, the appearance of a relatively low-energy peak (≤0.5 MeV) in the energy-gated spectrum. This peak is obscured in the spectrum because radiation is present. Although the precise energy of the peak is not reported here, owing to ambiguity caused by detector thresholds, the peak appears in the spectrum at an energy corresponding to the energy difference between the 1,656- and 1,184-keV transitions, which is 472(31) keV. Thus, it is probable that the 1,184- and ~472-keV transitions form a cascade that starts from the 3,699-keV level and runs in parallel to the 1,656-keV γ-ray, although the ordering of the 1,184- and ~472-keV transitions in the decay sequence cannot be specified here (D. Steppenbeck et al.,2013).

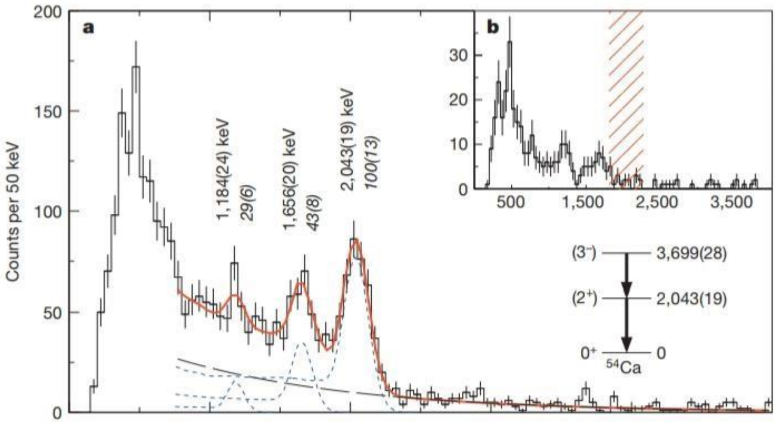

Figure 2. Doppler-corrected γ-ray energy spectra

Shell-model predictions of excited states for ^{54}Ca are presented in Fig. 3. Here we report calculations performed in the sd–fp–sdg model space (specifically, the $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$,$1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$ and $3s_{1/2}$ SPOs) using a modified GXPF1B. The GXPFIBs interaction, where the $vf^2_{5/2}$ pairing matrix element is shifted by -0.4 MeV from the GXPF1Br value so that the $vf^2_{7/2}$ and $vf^2_{5/2}$ fand pairing matrix elements can be better factorized by the orbital occupation number, (2j+1). Therefore use the GXPFIBs interaction, although there are no notable differences from GXPFIBr results. The remarkable agreement between the calculated cross sections and the experimental values supports the tensor-force-driven N = 34 magicity. It is interesting to note that as the E(2_1^+) of ^{54}Ca is 0.5 MeV lower than that of 52Ca, one may expect that the closed shell structure is weaker in ^{54}Ca than in ^{52}Ca. The shell-model calculated spectroscopic factor for the $vp_{1/2}$ orbital in ^{54}Ca ground state is 91% of the maximum value, being larger than the corresponding 89% for the $vp_{3/2}$ orbital in the ^{52}Ca ground state. This suggests a more robust subshell closure of N 34 than N = 32 (D. Steppenbeck et al.,2013).

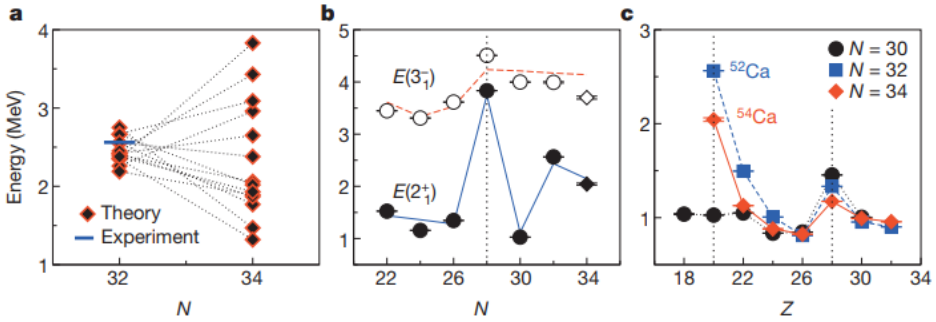

Figure 3. Systematics of excited-state energies in even–even Ca isotopes and neighbouring nuclei

The distorted-wave impulse approximation (DWIA) formalism was utilized, employing calculations based on the effective GXPF1Bs interaction and ab initio calculations using the NNLOsat and NN + 3N(lnl) interactions. The measurement results of exclusive transverse and parallel momentum distributions showcase the sensitivity of the one-neutron knockout reaction in inverse kinematics on a thick liquid hydrogen target. Additionally, reaction vertices were reconstructed to assign spin-parity to the final states (Chen et al., 2019).

The experimental data obtained align with the DWIA reaction model, employing input structure from shell model calculations with the GXPF1Bs interaction and ab initio calculations using the NNLOsat and NN + 3N(lnl) interactions. To determine the experimental spectroscopic factors, a comparison was made with the calculated single-particle cross-sections (σsp) and neutron momentum distributions derived from the p1=2, p3=2, and f5=2 orbitals occupied in each final state of 53Ca. The experimental spectroscopic factors for the 1/2-, 3/2-, and 5/2- states were determined as 2.2(2)(3), 3.1(2)(5), and 0.23(7)(3), respectively, further confirming the presence of the N = 34 "magic" number. The DWIA approach utilized in this study has been previously employed and successfully reproduced experimental data. These findings contribute to a more comprehensive understanding of atomic nucleus structure and affirm the N = 34 shell closure in calcium isotopes that are abundant in neutrons (Chen et al., 2019).

The present experimental study of the magic nature of neutrons in ^{54}Ca with the first mass measurements of $^{55–57}$Ca was performed at the Radioactive Isotope Beam Factory at RIKEN, which is operated by RIKEN Nishina Center and Center for Nuclear Study, the University of Tokyo. The masses were measured directly by the time-of-flight magnetic-rigidity (TOF-Bρ) method (D.J Vieira, 1986) with a flight path of approximately 100 m from the BigRIPS separator (T. Kubo, 2003) to the SHARAQ spectrometer (T. Uesaka, 2012).

Figure 4(a) shows the measured m/q spectrum of the reference masses and Ca isotopes, where the masses of underlined nuclei are newly determined in the present experiment. A root-mean-square resolution of 9.85 × 10−5 was achieved for ^{55}Ca. Figure 4(b) shows the m/q differences of the present measurement and the reported values in the AME2016 database (M. Wang, 2017). The m/q values of the reported isotopes were systematically reproduced within an error of 6.1 keV/e, which is perceived as the systematic error (A. Gillibert, 1986) in this measurement. The systematic error of the Z-dependence correction was estimated to be 3.3 keV=e for Ca isotopes from the errors of the deduced correction function. The neutron-rich calcium isotopes yielded 3379 events for ^{55}Ca, 619 events for ^{56}Ca, and 29 events for ^{57}Ca, respectively. The atomic mass excesses of $^{55–57}$Ca were determined to be −18650(160), −13510(250), and −7370(990) keV (Michimasa et al., 2018).

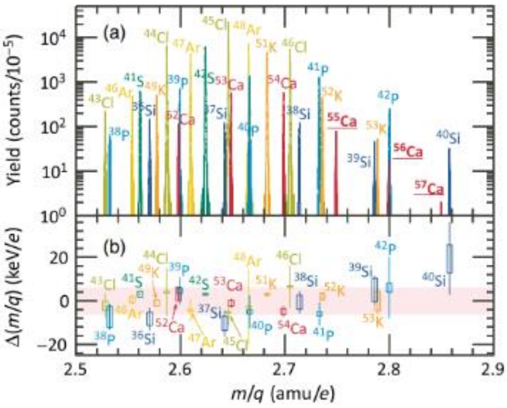

Figure 4. Measured m/q spectrum of the reference masses and Ca isotopes

Figure 5(b) shows the differences between theoretical and experimental S_{2n} values. The AME2016 evaluations for $^{55–57}$Ca are consistent with the present results, within 1σ errors. The calculations with the MBPT and KB3G interactions reproduce the present results well. The calculations by modified SDPF-MU and IM-SRG predict $^{55–57}$Ca will be loosely bound, though they provide good agreements for 48–54Ca. The FRDM12, HFB24, and KTUY05 models show a similar trend. They predict smaller values around N = 28 and 32 and larger values at N = 35 and 36 (Michimasa et al., 2018).

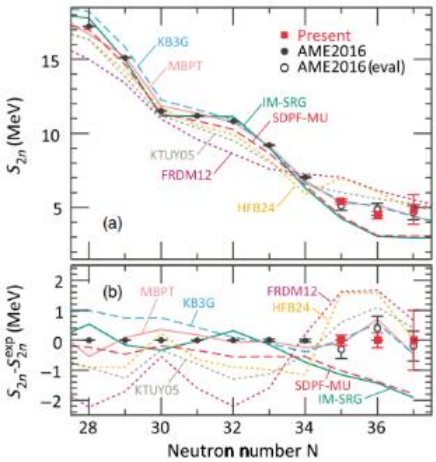

Figure 5. The differences between theoretical and experimental S_{2n} values

We now discuss the magic nature at N = 34 in Ca isotopes based on the measured atomic masses. In a simple picture, the magic number is illustrated by an occupation number of a nucleon, at which energetically lower single-particle orbitals are completely filled and an additional nucleon settles in an upper orbital with a large energy gap. This picture of a magic number is known to be too simple in the theoretical point of view since real nucleons contained in a nucleus strongly interact with each other. Empirical indexes for evaluating the energy gap of the single-particle spectrum in nuclei have been suggested based on experimental systematics and theoretical understanding.We describe the magic nature of Ca isotopes by using the empirical mass filters (D. Lunney, 2003).

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The systematic trend of the δe shell gap for neutron-rich Ca isotopes is shown in Fig. 6(a) and compared to the same theoretical predictions as shown in Fig. 5. The δe value of ^{54}Ca is comparable to that of ^{52}Ca and slightly smaller than that of ^{48}Ca. This denotes that ^{54}Ca has a magic nature of neutrons, as is the case with ^{52}Ca. The δe value of ^{56}Ca is smaller than those of ^{48,52,54}Ca, having the neutron magicity, and thus it is suggested that in ^{56}Ca occupied and unoccupied neutron orbitals are packed near the Fermi surface. The theories cannot completely reproduce the evolution of δe of Ca isotopes as a function of the neutron numbers. The KB3G calculations show a reduction of δe from N = 32 to 34. The MBPT calculations reproduce well the energy gaps in ^{52,54}Ca; however, the δe of ^{48}Ca is smaller than those of ^{52,54}Ca. The IM-SRG prediction reproduces the data with relatively good accuracy in this region, but its variation is slightly larger than in the experiment (Michimasa et al., 2018).

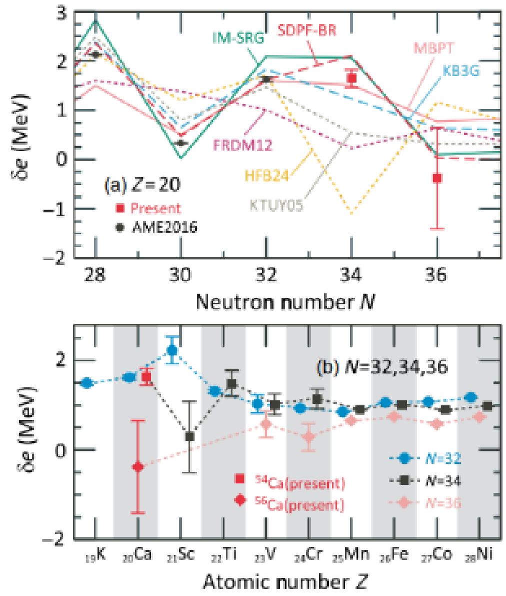

Figure 6. Systematics of the empirical energy gaps (δe) of single particle spectra

Figure 6(b) shows the δe shell gaps for N = 34 (square) and 36 (diamond) as a function of the atomic number in comparison with N = 32 (circle). The present values are shown as red symbols. The other values were obtained from the AME2016 database and the newly reported masses in 52–55Ti isotopes (E. Leistenschneider, 2018). Along the N = 32 and 34 chains, the δe values in Ca increase by approximately 1.5 times compared to the constant values around Z = 25 (Mn). However, the small δe in 55Sc and the large δe in 53Sc suggest that in Sc isotopes the N = 32 energy gap emerges, but there is no gap at N = 34. Therefore, it is suggested that the energy difference between the ν(2$p_{1/2}$) and ν(1$f_{5/2}$) orbitals becomes large from Sc to Ca. Meanwhile, the δe values at N = 36 are small across Z = 20–28, and comparable to the δe of the N = 30 isotope, ^{50}Ca [see Fig. 6(a)]. Therefore, it is suggested that 56Ca has an open-shell character for neutrons similar to other N = 36 isotones. This is reasonably interpreted using a picture in which the valence neutrons partly fill the 1$f_{5/2}$ orbital beyond the N = 34 gap (Michimasa et al., 2018).

In conclusion, the atomic masses of the neutron-rich calcium isotopes $^{55–57}$Ca were measured by using the TOF-Bρ method and determined for the first time. By observation of the mass evolution in Ca isotopes beyond N = 34, the magic nature at N = 34 in the neutron-rich Ca region became evident. The energy gap of the single-neutron spectrum in ^{54}Ca was evaluated to be comparable with that in ^{52}Ca based on the experimental δe shell gaps. Also, it was experimentally shown that the energy gaps of single-neutron spectra in the N = 34 isotones become significant from Sc to Ca. The δe shell gap in ^{56}Ca suggests an open-shell character for neutrons. The δe values in ^{54,56}Ca indicate that the closure of the ν($2p_{1/2}$) orbital causes the magicity at N = 34 (Michimasa et al., 2018).

5. CONCLUSIONS

The determination of a new nuclear "magic number" in the calcium isotope ^{54}Ca through in-beam γ-ray spectroscopy. This study involves measuring γ-rays simultaneously with ^{54}Ca projectiles produced through one and two-proton knockout reaction channels. The γ-ray energies are corrected for Doppler shifts, allowing for analysis in the rest frame of the nucleus.

Shell-model predictions and calculations are presented, supporting the existence of a "magic" neutron number at N = 34 in calcium isotopes. These calculations utilize the sd–fp–sdg model space and a modified GXPF1B interaction. The study also compares the robustness of subshell closure between ^{54}Ca and ^{52}Ca, indicating a stronger closure at N = 34 in ^{54}Ca.

The study also involves mass measurements of $^{55–57}$Ca using the time-of-flight magnetic-rigidity (TOF-Bρ) method. The atomic mass excesses of these isotopes are determined, and the results align with evaluations in the AME2016 database. The neutron-rich calcium isotopes exhibit a systematic trend of the energy gap of the single-particle spectrum, denoted as δe, which is evaluated based on empirical mass filters. The δe values indicate the presence of magicity at N = 34 in ^{54}Ca, similar to ^{52}Ca. In ^{56}Ca, the δe value suggests an open-shell character for neutrons.

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