Role of three-nucleon forces in neutron-rich nuclei beyond ^{132}Sn

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Motivations

- What is the balance between the role of 2NF and 3NF?
- Neutron-rich nuclei above ^{132}Sn provide a valid laboratory to study this topic
- To investigate the influence of three-body correlations on the monopole components of the shell-model hamiltonian

Our framework: the realistic shell model

- First step: choose a realistic nucleon-nucleon potential and renormalize short-range correlations
- Second step: choose a convenient model space
- Third step: derive an effective shell-model hamiltonian H_{eff} by way of the many-body perturbation theory
- Fourth step: diagonalize the shell-model hamiltonian in the chosen model space

L. C., A. Covello, A. Gargano, N. Itaco, and T. T. S. Kuo, Prog. Part. Nucl. Phys. **62** *(2009) 135*

The shell-model effective hamiltonian

A versatile way to derive $H_{\rm eff}$ is the time-dependent perturbative approach as developed by Kuo and his co-workers in the 1970s *(see T. T. S. Kuo and E. Osnes, Lecture Notes in Physics vol. 364 (1990))*

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In this approach the effective hamiltonian H_{eff} is expressed as

$$H_{\text{eff}} = \hat{Q} - \hat{Q}' \int \hat{Q} + \hat{Q}' \int \hat{Q} \int \hat{Q} - \hat{Q}' \int \hat{Q} \int \hat{Q} \int \hat{Q} \cdots ,$$

- The so-called $\hat{Q}$-box is a collection of irreducible valence-linked diagrams
- The integral sign represents a generalized folding operation

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- to renormalize the V_{NN} integrating out the high-momentum components of the potential - $V_{\mathrm{low-k}}$ or SRG approaches
- to resort to realistic potential derived from the chiral perturbation theory and defined only for momenta below a cutoff Λ

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Many-body forces recover what has been left out when constructing a nucleon-nucleon potential below a certain energy scale

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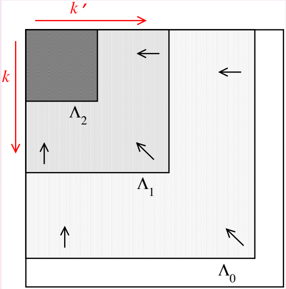
from EFT: we restrict the configurations of $V_{NN}(k, k')$ to those with $k, k' < k_{\mathrm{cutoff}} = \Lambda$



- Input V_{NN}: $V_{\rm low-k}$ derived from the high-precision NN CD-Bonn potential with two different cutoffs: $\Lambda = 2.1, 2.6$ fm^{-1}.
- $H_{\rm eff}$ obtained calculating the Q-box up to the 3rd order in $V_{\rm low-k}$.
- Model spaces:
  - For protons: $0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{1/2}$
  - For neutrons: $0h_{9/2}, 1f_{7/2}, 1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 0i_{13/2}$
- Single-particle energies are taken from the experiment: this will help to stress the role played by 3NF forces on the two-body residual interaction

One step backwards...

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Masses of exotic calcium isotopes pin down nuclear forces

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The properties of exotic nuclei on the verge of existence play a fundamental part in our understanding of nuclear interactions[1]. Exceedingly neutron-rich nuclei become sensitive to new aspects of nuclear forces[2]. Calcium, with its doubly magic isotopes ^{40}Ca and ^{48}Ca, is an ideal test for nuclear shell evolution, from the valley of stability to the limits of existence. With a closed proton shell, the calcium isotopes mark the frontier for calculations with three-nucleon forces from chiral effective field theory[3–6]. Whereas predictions for the masses of ^{51}Ca and ^{52}Ca have been validated by direct measurements[4], it is an open question as to how nuclear masses evolve for heavier calcium isotopes. Here we report the mass determination of the exotic calcium isotopes ^{53}Ca and ^{54}Ca, using the multi-reflection time-of-flight mass spectrometer[7] of ISOLTRAP at CERN. The measured masses unambiguously establish a prominent shell closure at neutron number $N = 32$, in excellent agreement with our theoretical calculations. These results increase our understanding of neutron-rich matter and pin down the subtle components of nuclear forces that are at the forefront of theoretical developments constrained by quantum chromodynamics[8].

Exotic nuclei with extreme neutron-to-proton asymmetries exhibit shell structures generated by unexpected orderings of single-particle motions. Their description poses enormous challenges, because most theoretical models have been developed for nuclei at the valley of stability. It is thus an open question how well they can predict new magic numbers emerging far from stability[9–11]. This is closely linked to our understanding of the different components of the strong force between neutrons and protons, such as the spin–orbit or tensor interactions, which modify the gaps between single-particle orbits[12], and of three-body forces, which are pivotal in calculations of extreme neutron-rich systems based on nuclear forces[2,13,14]. The resulting magic numbers, as well as the strength of the corresponding shell closures, are critical for global predictions of the nuclear landscape[15], and thus for the successful modelling of matter in astrophysical environments.

Three-body forces arise naturally in chiral effective field theory[8], which provides a systematic basis for nuclear forces connected via its symmetries to the underlying theory of quarks and gluons, namely quantum chromodynamics. Owing to the consistent description in effective field theory, there are only two undetermined low-energy couplings in chiral three-nucleon forces at leading and sub-leading orders. These are constrained by the properties of light nuclei ^{3}H and ^{4}He only, so that all heavier elements are predictions in chiral effective field theory. The present frontier of three-nucleon forces is located in the calcium isotopes, where the structural evolution is dominated by valence neutrons due to the closed proton shell at atomic number $Z = 20$ (refs 3, 5). These predictions withstood a recent challenge from direct Penning-trap mass measurements of ^{51}Ca and ^{52}Ca at TITAN/TRIUMF[4], which have established a substantial change from the previous mass evaluation and leave completely open how nuclear masses evolve past ^{52}Ca. This region is also very exciting because of evidence of a new magic neutron number $N = 32$ from nuclear spectroscopy[16–18], with a high 2^+ excitation energy in ^{52}Ca (refs 19, 20). These results are accompanied by successful theoretical studies based on phenomenological shell-model interactions[21,22], which are similar for the excitation spectra at $N = 32$ but disagree markedly in their predictions for ^{54}Ca and further away from stability.

Here we present the first mass measurements of the exotic calcium isotopes ^{53}Ca and ^{54}Ca. These provide key masses for all theoretical models, and unambiguously establish a strong shell closure, in excellent agreement with the predictions including three-nucleon forces.

The mass of a nucleus provides direct access to the binding energy, the net result of all interactions between nucleons. Penning traps have proven to be the method of choice when it comes to high-precision mass determination of exotic nuclei[23,24]. The mass m of an ion of interest with charge q stored in a magnetic field B is determined by comparing its cyclotron frequency $\nu_C = qB/(2\pi m)$ to that of a well-known reference ion, $\nu_{C,Ref}$. The frequency ratio $r_{ICR} = \nu_{C,Ref}/\nu_C$ (ICR, ion cyclotron resonance) then yields the mass ratio directly and thus the atomic mass of the isotope.

We have made a critical step towards determining the pivotal calcium masses by introducing a new method of precision mass spectrometry for short-lived isotopes. The developments and measurements were performed with ISOLTRAP[25], a high-resolution Penning-trap mass spectrometer at the ISOLDE/CERN facility. This method was used to confirm and even improve the accuracy of the recent mass measurements

Figure 1 | Experimental set-up. Main components relevant for the ^{53,54}Ca study: incoming ISOLDE ion beam, reference ion source, radio-frequency quadrupole (RFQ) buncher, multi-reflection time-of-flight (MR-TOF) mass spectrometer and (removable) time-of-flight ion detector.

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Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

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Atomic nuclei are finite quantum systems composed of two distinct types of fermion—protons and neutrons. In a manner similar to that of electrons orbiting in an atom, protons and neutrons in a nucleus form shell structures. In the case of stable, naturally occurring nuclei, large energy gaps exist between shells that fill completely when the proton or neutron number is equal to 2, 8, 20, 28, 50, 82 or 126 (ref. 1). Away from stability, however, these so-called 'magic numbers' are known to evolve in systems with a large imbalance of protons and neutrons. Although some of the standard shell closures can disappear, new ones are known to appear[2,3]. Studies aiming to identify and understand such behaviour are of major importance in the field of experimental and theoretical nuclear physics. Here we report a spectroscopic study of the neutron-rich nucleus ^{54}Ca (a bound system composed of 20 protons and 34 neutrons) using proton knockout reactions involving fast radioactive projectiles. The results highlight the doubly magic nature of ^{54}Ca and provide direct experimental evidence for the onset of a sizable subshell closure at neutron number 34 in isotopes far from stability.

The shell structure of the atomic nucleus was first successfully described more than 60 years ago[1]. However, the question of how robust the standard magic numbers are in unstable nuclei with a large excess of neutrons—often referred to as 'exotic' nuclei—has been one of the main driving forces behind recent nuclear structure studies that focus on changes in the shell structure, called 'shell evolution'. A noteworthy example is the disappearance of the $N = 28$ (neutron number 28) standard magic number in ^{42}Si (ref. 4), a nucleus that lies far from the stable isotopes on the Segrè chart. On the contrary, exotic oxygen isotopes[3] provide evidence for the onset of a new shell closure at $N = 16$, one that is not observed in stable nuclei. In both cases, the tensor force, a non-central component of the nuclear force, has a key role in describing the experimental spectra[5].

The region of the Segrè chart around exotic calcium isotopes has also contributed valuable input to the understanding of nuclear shell evolution over recent years owing to experimental advances. Enhanced excitation energies of first $J^{\Pi} = 2^+$ states (spin, J; parity, Π) and reduced γ-ray transition probabilities, which are good indicators of nuclear shell gaps, for ^{52}Ca (refs 6, 7), ^{54}Ti (refs 8, 9) and ^{56}Cr (refs 10, 11) provide substantial evidence for the onset of a sizable energy gap at $N = 32$. This result was recently confirmed by high-precision mass measurements on neutron-rich Ca isotopes[12]. In the framework of tensor-force-driven shell evolution[5], the $N = 32$ subshell closure is a direct consequence of the weakening of the attractive nucleon–nucleon interaction between protons (π) and neutrons (ν) in the $\pi f_{7/2}$ and $\nu f_{5/2}$ single-particle orbitals (SPOs) as the number of protons in the $\pi f_{7/2}$ SPO is reduced and the magnitude of the $\pi f_{7/2}$–$\nu f_{5/2}$ energy gap increases (Fig. 1a–c).

A question that has been asked frequently over recent years is whether or not the onset of another subshell gap occurs in exotic $N = 34$ isotones, which was suggested qualitatively more than a decade ago[13] on the basis of the general properties of nuclear forces. The onset of an appreciable subshell closure at $N = 34$ is illustrated in Fig. 1d, indicating an energy gap between the $\nu p_{1/2}$ and $\nu f_{5/2}$ SPOs in ^{54}Ca that is comparable to the separation of the $\nu p_{3/2}$ and $\nu p_{1/2}$ spin–orbit partners, which is also implied by recent theoretical results; see, for example, ref. 14. We stress, however, that no $N = 34$ subshell closure was reported in the experimental investigations of ^{56}Ti (refs 9, 15) or ^{58}Cr (refs 11, 16), and notable doubt on this magic number for Ca isotopes has been raised[17,18]. Indeed, as indicated in Fig. 2a, theoretical predictions of the energy of the first $J^{\Pi} = 2^+$ state for ^{54}Ca vary considerably, ranging from ~1 MeV in some cases to as high as ~4 MeV in others[14–16,19–24], despite exhibiting close agreement for lighter isotopes; for example, the predictions of the same theories lie within only 0.4 MeV of the empirical result for ^{52}Ca. Such stark discrepancies at $N = 34$ reflect the need for direct experimental input on the matter.

To address this issue, we report on an experimental study of ^{54}Ca to clarify the strength of the $N = 34$ subshell gap in nuclei farther from stability. The energies of nuclear excited states were investigated using proton knockout reactions involving ^{55}Sc and ^{56}Ti projectiles on a Be target at the Radioactive Isotope Beam Factory, Japan, operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. Experimental details are provided in Methods Summary. Particle identification plots indicating the radioactive species transported through the BigRIPS separator and ZeroDegree spectrometer[25], which were used to select and tag radioactive beam projectiles and reaction products, are presented in Fig. 3a and Fig. 3b, respectively. We emphasize that the intensity of the radioactive beam reported here, which was critical to the success of the experiment, is unique to the Radioactive Isotope Beam Factory. Excited-state energies were deduced using the technique of in-beam γ-ray spectroscopy.

The γ-rays measured in coincidence with ^{54}Ca projectiles produced through the one- and two-proton knockout reaction channels are presented in Fig. 4a. The γ-ray energies measured in the laboratory frame of reference have been corrected for Doppler shifts, and so the transitions appear at the energies they would in the rest frame of the nucleus. The most intense γ-ray line in the ^{54}Ca spectrum, the peak at 2,043(19) keV (error, 1 s.d.) in Fig. 4a, 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. Figure 4b shows a γ-ray spectrum obtained with the condition of a prompt coincidence (≤10 ns) with the 2,043-keV γ-ray, indicating that the weaker transitions were emitted in decay sequences involving the $2_1^+ \rightarrow 0^+$ ground-state transition. 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, as presented in the ^{54}Ca level scheme in the lower-right section of Fig. 4a. Placement of the 1,184-keV transition in the

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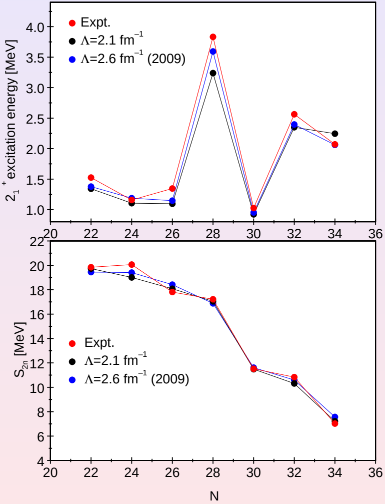
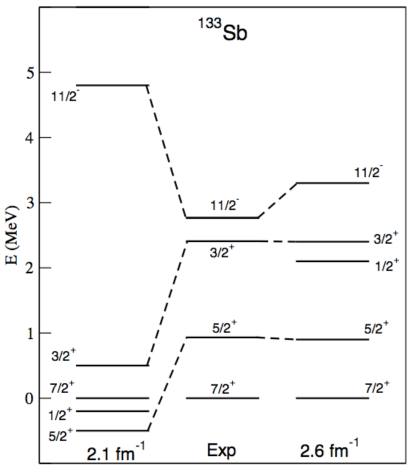
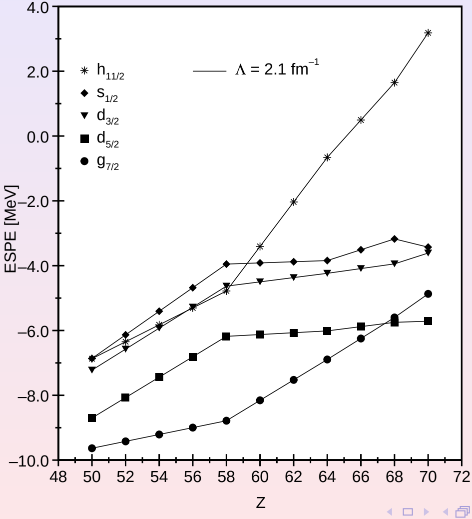
Results for the calcium isotopes



Single-particle states in ^{133}Sb



Effective single-particle energies of N=82 isotones



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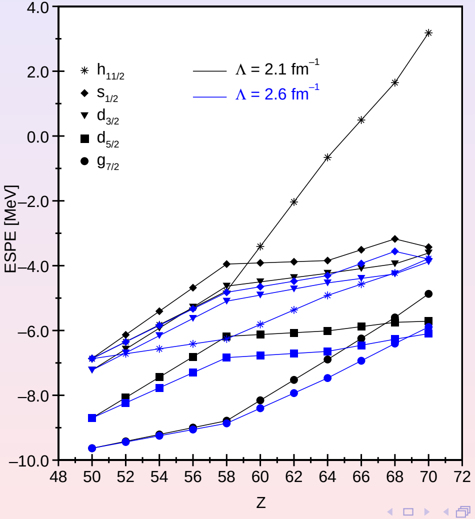
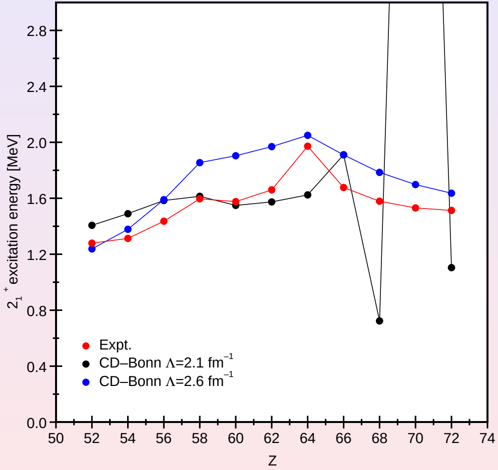
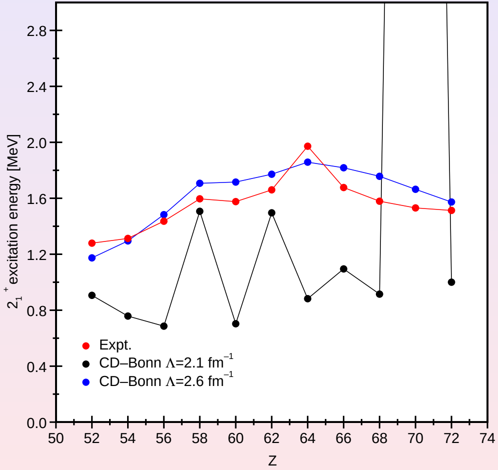


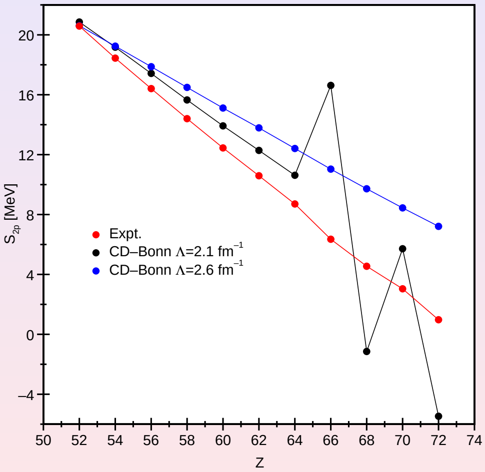
2_1^+ energies in N=82 isotones



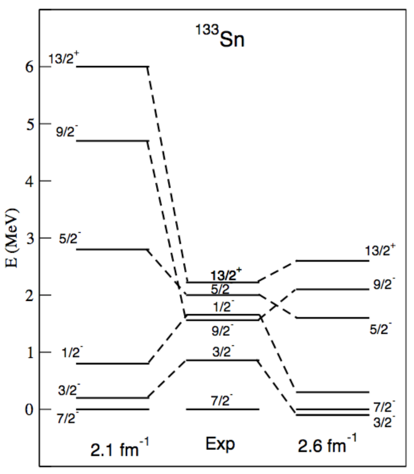
2_1^+ energies in N=82 isotones: theoretical s.p.e.



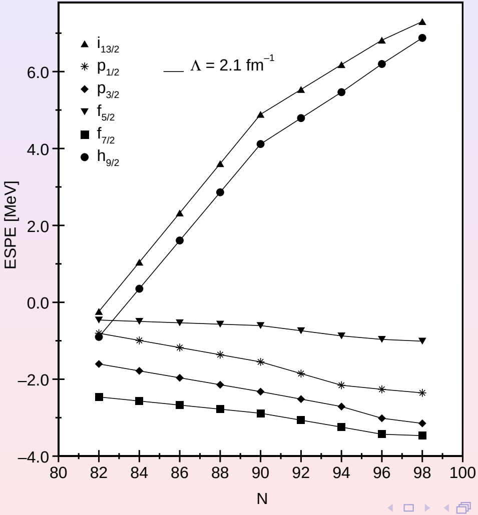
Two-proton separation energies of N=82 isotones



Single-particle states in ^{133}Sn



Effective single-particle energies of tin heavy isotopes



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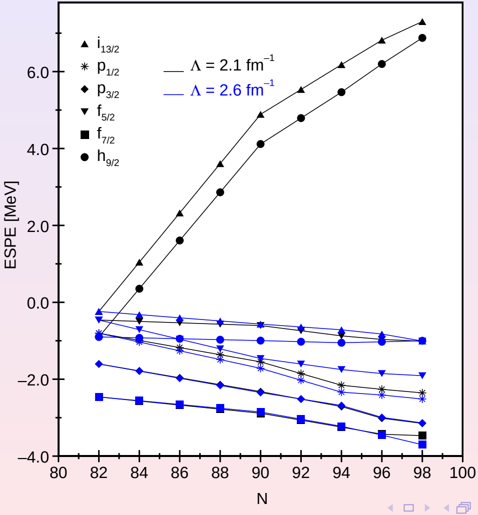
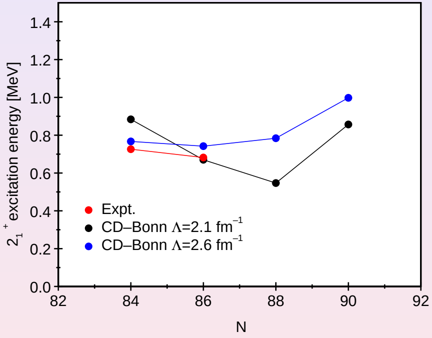
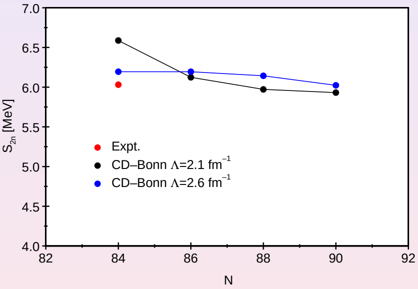


2_1^+ energies in heavy tin isotopes



Two-neutron separation energies of heavy tin isotopes



Cutoff (in fm^{-1})	P_D (in %)
2.1	3.96
2.6	4.49
∞	4.85

Summary

- Monopole components of the shell-model hamiltonian are affected by the lack of the inclusion of 3NF
- This seems to be far less important for model spaces built up by full HO major shells
- In nuclei above ^{132}Sn nucleon-nucleon potentials with a larger cutoff may reduce the role played by 3NF
- The latter effect is probaly connected to the tensor component of the input nucleon-nucleon potential