EPJ Web of Conferences **193**, 05001 (2018) https://doi.org/10.1051/epjconf/201819305001
FISSION 2017

(n,γ) reactions on rare Ca isotopes: Valence-hole - core-excitation couplings in ^{47}Ca

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Abstract. Recent results on the structure of ^{47}Ca will be presented. The nucleus of interest was populated via the cold-neutron capture ^{46}Ca(n,γ) reaction, on a rare ^{46}Ca target, during the EXILL experimental campaign at the nuclear reactor of Institut Laue-Langevin in Grenoble. High-resolution γ-ray spectroscopy, performed with a composite array of HPGe detectors, enabled the identification of new transitions deexciting states between the neutron-capture level and the ground state. Experimental data will be compared with a novel microscopic theoretical model, currently under development, specifically designed to describe the low-lying structure of odd-mass nuclei with one valence particle/hole outside a spherical doubly-magic core, using the Skyrme effective interaction self-consistently.

1 Introduction

Calcium isotopes provide an excellent laboratory to investigate the properties of medium-heavy nuclei as well as the evolution of nuclear structure between doubly-closed-shell systems and the hard-to-predict isospin-dependent features of neutron-rich nuclei [1–4].

Precise experimental information, including detailed γ spectroscopy, are strongly needed to outline the main characteristics of these isotopes and they are of fundamental importance to validate state-of-the-art theoretical models aimed at describing the structural properties and changes in this mass region. Ca nuclei are indeed the heaviest systems that can be approached by ab initio calculations, employing chiral two- and three-nucleon forces [5, 6], and they can be well addressed by large-scale shell-model calculations using modern effective interactions [7].

In this context, one-valence-neutron systems with respect to a spherical doubly-magic core (e.g. ^{47}Ca and ^{49}Ca) are noteworthy [8]. The low-lying structure of these nuclei is typically dominated by single-particle states which coexist with coupled configurations between the latter and the underlying core

excitations, in particular collective vibrations of the nuclear surface (phonons) [9]. This phenomenon is, for example, one of the main mechanisms driving the damping of giant resonances [10] and the quenching of spectroscopic factors [11]. While it was largely studied in the past, both experimentally and theoretically, in nuclei close to stability [9], it is still unclear how correlations associated with vibrational couplings evolve towards the neutron-rich side of the nuclide chart.
A proper description of particle/hole-vibration couplings is a major challenge in nuclear physics [12]. On one hand, the phenomenological perturbative approach turned out to be insufficient to account for systems characterized by strong couplings [9, 13], whereas shell-model calculations are strongly limited in the description of nuclear vibrations in medium-heavy nuclei from a microscopic point of view, due to the large increase of the configurations involved [14].
Recently, a novel theoretical framework was developed, where Hartree-Fock and Random Phase Approximation calculations are combined to describe one-valence-proton/neutron-core coupled states in odd-A nuclei, considering both collective and non-collective core excitations and using the Skyrme effective interaction in a self-consistent way. This model was successfully applied to interpret new experimental data on ^{49}Ca and ^{133}Sb [15, 16].
In this work, new results on the structure of the one-valence-hole ^{47}Ca nucleus, populated in the cold-neutron capture ^{46}Ca(n,γ) reaction on a rare ^{46}Ca target, will be discussed along with the ongoing developments of the aforementioned model to suitably treat one-hole-like states.

2 The ^{46}Ca(n,γ)^{47}Ca reaction at ILL

The experiment was performed at the PF1B cold-neutron facility at Institut Laue-Langevin (ILL) in Grenoble during the EXILL experimental campaign [17]. High-resolution γ-ray spectroscopy was performed using a highly-efficient HPGe array comprising 8 EXOGAM clovers [18], 6 large GASP detectors [19] and 2 clover detectors from ILL, resulting in a total photopeak efficiency of ≈ 6 % at 1.3 MeV.
In nature, ^{46}Ca is the isotope with the second-lowest natural abundance (only 0.004%) [1]. Thus, a highly enriched ^{46}Ca target was crucial to perform this experiment with satisfactory signal to background ratio. A 40.6-mg Ca(NO_3)$_2$ target, with 31.7% enriched ^{46}Ca, was prepared at Paul Scherrer Institute (see Tab. 1). The nitrate solution was directly dried in a thin teflon bag, which shows negligible neutron capture. After the non-destructive use in the EXILL campaign, this unique material was irradiated close to the core of the ILL reactor to produce GBq activities of ^{47}Ca/^{47}Sc for medical applications [20].

Isotope	Abundance (atom %)	σ (n,γ) (b)
^{40}Ca	60.5	0.4
^{42}Ca	0.63	0.7
^{43}Ca	0.15	6
^{44}Ca	5.35	0.9
^{46}Ca	31.7	0.7
^{48}Ca	1.57	1.1

Table 1. Ca isotopic composition of the ^{46}Ca target in the current experiment and (n,γ) cross sections [21]. The isotope of interest is marked in red.

[1] Only ^{3}He has a still lower natural abundance, but it can be enriched more easily by cryogenic means.

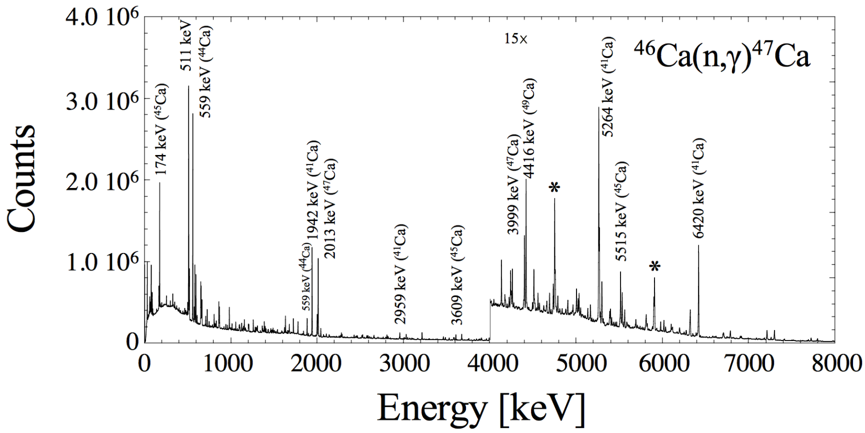

Figure 1. γ-ray spectrum measured in the cold-neutron capture ^{46}Ca(n,γ) reaction using a 40.6-mg Ca(NO_3)$_2$, ^{46}Ca-enriched target and with the condition of γ-ray multiplicity $M_\gamma \geq 2$. The majority of the observed γ-ray transitions were identified and they are labeled accordingly, along with the first- and second-escape peaks marked by stars.

The measured γ-ray spectrum, with the condition of γ-ray multiplicity $M_\gamma \geq 2$, is presented in Fig. 1. As expected, many transitions coming from (n,γ) reactions on other Ca isotopes, present in the target as contaminants, were also observed and they are labeled accordingly in the picture. Despite the complexity of the γ-ray spectrum, the 2013-keV high-energy transition, which deexcites the first $3/2^-$ state in ^{47}Ca and collects all the γ-ray flux from highly excited states, generates very clean coincidences in the γ-γ events. As a matter of fact, a total number of $\approx 10^9$ γ-γ coincident events were collected in $\approx$ 80 hours of beam time, which enabled precise γ-ray spectroscopy studies in this nucleus. The present experiment allowed us to observe and identify 3 new decay branches and 9 new γ rays which were assigned to ^{47}Ca, as displayed in Fig. 2. These new findings also confirm the neutron binding energy in this nucleus (S_n = 7276 keV), in agreement, within the error, with the value reported in literature [22].

Slow neutrons are typically captured in a relative L=0, S-wave, resulting in a $1/2^+$ spin-parity capture level if the target is an even-even nucleus in its 0^+ ground state. Therefore, since the high-energy electromagnetic decay most likely occurs through E1, M1 and E2 γ rays, a strict selection on the final angular momentum is normally expected which favors the population of $1/2^\pm$, $3/2^\pm$ and $5/2^\pm$ spin-parity states.

However, primary γ-rays deexciting the neutron-capture level are, in general, dominated by E1 electric dipole transitions. As a consequence, $5/2^{\pm}$ spin-parity assignment can be excluded for the 2876-, 4058-, 4450- and 4810-keV levels, as well as positive parities for lower spins, restricting the possibilities to spin-parity $1/2^{-}$ and $3/2^{-}$ only. This is consistent with the tentative values reported in literature [22].
The particular geometry of the γ array used in the EXILL experimental campaign made possible the study of γ-ray angular correlations at 0°, 45° and 90° (e.g.[23–25]), although the statistics collected in the present experiment was not enough to further characterize the observed γ rays in ^{47}Ca. However, the analysis is still on going in order to exclude the presence of additional weaker gamma-rays detected, especially in coincidence with the 2013-keV transition, which could possibly deexcite not-yet-observed states in ^{47}Ca.

3 The Hybrid Configuration Mixing Model

The experimental results will be interpreted by using a recent theoretical model, originally developed for odd-A nuclei with one valence particle outside a doubly-closed shell system [15], which is currently being extended to properly describe one-valence-hole nuclei. For this purpose, a microscopic Hamiltonian of Skyrme type, with no adjustable parameters, is used self-consistently to describe both single-hole states and their couplings with the excitations of the underlying doubly-magic core [26]. This model includes pure Hartree-Fock (HF) hole states, defined by

$$|(j_h m_h)^{-1}\rangle = (-)^{j_h+m_h} a_{j_h-m_h} |0\rangle \,, \tag{1}$$

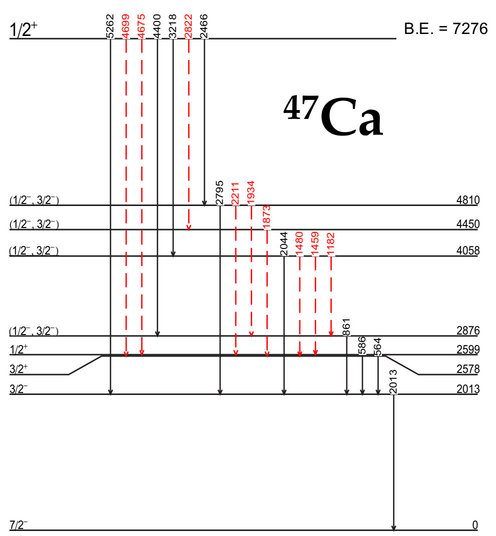

Figure 2. (Color online) Partial level scheme of ^{47}Ca as measured in the present experiment. Newly-observed γ-ray lines are marked in red.

and coupled states between the latter and collective and non-collective excitations of the core $|NJM\rangle$, emerging from Random Phase Approximation (RPA) calculations and defined by

$$
\begin{aligned}
&|(j_{h_1}m_{h_1})^{-1}\otimes NJM\rangle_{(j_h m_h)^{-1}} = \\
&= \sum_{j_{p'}j_{h'}} X^{(NJ)}_{p'h'} \sum_{\substack{m_{p'}m_{h'}\\ m_{h_1}M}} (-)^{j_{h'}-m_{h'}+j_{h_1}+m_{h_1}+j_h+m_h} \times \\
&\times \langle j_{h_1}m_{h_1}JM|j_h m_h\rangle \langle j_{p'}m_{p'}j_{h'}-m_{h'}|JM\rangle \times \\
&\times a_{j_{h_1}-m_{h_1}} a^{\dagger}_{j_{p'}m_{p'}} a_{j_{h'}m_{h'}} |0\rangle + \\
&- \sum_{j_{p'}j_{h'}} Y^{(NJ)}_{p'h'} \sum_{\substack{m_{p'}m_{h'}\\ m_{h_1}M}} (-)^{j_{h'}-m_{h'}+J+M+j_{h_1}+m_{h_1}+j_h+m_h} \times \\
&\times \langle j_{h_1}m_{h_1}JM|j_h m_h\rangle \langle j_{p'}m_{p'}j_{h'}-m_{h'}|J-M\rangle \times \\
&\times a_{j_{h_1}-m_{h_1}} a^{\dagger}_{j_{h'}m_{h'}} a_{j_{p'}m_{p'}} |0\rangle\,. \qquad (2)
\end{aligned}
$$

In the previous expressions, the $b^\dagger$ and b hole-creation and -annihilation operators are written in terms of the usual a and $a^\dagger$ fermion-annihilation and -creation operators (e.g. $b^\dagger_{jm_j} = (-)^{j+m_j}a_{j-m_j}$), $X^{(NJ)}_{p'h'}$ and $Y^{(NJ)}_{p'h'}$ are the forward and backward RPA amplitudes, respectively, and $|0\rangle$ is the even-even core. In the model space defined by (1) and (2), the following Hamiltonian is considered

$$
\begin{aligned}
H &= H_0 + V, \\
H_0 &= \sum_{j_h m_h} \epsilon_{j_h} a_{j_h-m_h} a^{\dagger}_{j_h-m_h} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^{\dagger}_{JM}\Gamma_{JM}, \\
V &= \sum_{\substack{j_h m_h\\ j_{h_1}m_{h_1}}} \sum_{NJM} h(j_h-m_h; j_{h_1}-m_{h_1}, NJM) \times \\
&\times (-)^{j_{h_1}+m_{h_1}} a^{\dagger}_{j_h-m_h} [a_{j_{h_1}-m_{h_1}} \otimes \Gamma^{\dagger}_{JM}]_{j_h-m_h}, \qquad (3)
\end{aligned}
$$

where H_0 is the mean-field solution of the Skyrme Hamiltonian for hole and RPA states (with $\Gamma^\dagger$ being the usual boson-creator operator) and V is the residual interaction among them, which is calculated by following the procedure outlined in [27].

The basis states described by (2) are, in general, nonorthogonal and overcomplete, hence violating the Pauli principle. This problem is overcome by introducing the overlap matrix N between the basis states in the Hilbert subspace of interest and by solving the Schrödinger equation

$$(H - NE)\Psi = 0, \qquad (4)$$

for the Hamitonian (3), in the reduced space defined by the eigenvectors of N corresponding to non-zero and positive eigenvalues only (see [15] and [28] for details).

Finally, the physical solutions of eq. (4) will contain pure hole states, hole states coupled to collective excitations of the core (phonons) or “shell-model-like" $1p - 2h$ configurations. As a result, this approach goes beyond models which include couplings with genuine vibrations only and provides a more realistic interpretation of one-valence-hole nuclei in the vicinity of doubly-magic systems.

Preliminary calculations were carried out for the ground state and the 2013-keV, $3/2^-$ first-excited state in ^{47}Ca, without including the overlap correction outlined above. The results suggest that the ground state has a pure single-hole character, with the $f^{-1}_{7/2}$ configuration as a dominant component of the wave function, whereas the $3/2^-$ state is predicted to be at 2869 keV of excitation energy and to be a member of the $(f^{-1}_{7/2} \otimes 2^+)$ multiplet, arising from the coupling between a $f_{7/2}$ hole and the 2^+, quadrupole vibration of the ^{48}Ca core.

4 Conclusions

The structure of ^{47}Ca was studied in the EXILL experimental campaign at ILL, using the cold-neutron-capture reaction ^{46}Ca(n,γ) on a rare ^{46}Ca target. High-resolution γ-ray spectroscopy was performed by means of a composite array of HPGe detectors and 3 new decay branches and 9 new γ rays were identified and assigned to ^{47}Ca. The experimental results will be interpreted by a microscopic theoretical model, based on the Skyrme effective interaction, which describes hole-core coupled states in nuclei close to doubly-magic systems. Preliminary calculations show already a qualitative agreement between data and theory for the ground state and the first-excited state in this nucleus. The model described here will be further extended to enlarge the model space, in order to take into account more complicated configurations, and to include the description of open-shell nuclei within the quasiparticle formalism.

References

[1] R. F. Garcia Ruiz *et al.,* Nature Physics **12**, 594 (2016).
[2] D. Steppenbeck *et al.*, Nature **502**, 207 (2013).
[3] F. Wienholtz *et al.,* Nature **498**, 346 (2013).
[4] D. Montanari *et al.,* Phys. Rev. C **85**, 044301 (2012).
[5] G. Hagen *et al.,* Phys. Rev. Lett. **109**, 032502 (2012).
[6] J.D. Holt *et al.,* Phys. Rev. C **90**, 024312 (2014).
[7] B. A. Brown and W. A. Richter, Phys. Rev. C **58**, 2099 (1998).
[8] D. Montanari *et al.,* Phys. Lett. B **697**, 288 (2011).
[9] A. Bohr, B.R. Mottelson, Nuclear Structure, vols. I and II, W.A. Benjamin, 1975.
[10] G. F. Bertsch, P. F. Bortignon, and R. A. Broglia, Rev. Mod. Phys. **55**, 287 (1983).
[11] H. L. Crawford *et al.,* Phys. Rev. C **95**, 064317 (2017).
[12] M. Brenna, *PhD thesis*, A microscopic particle-vibration coupling approach for atomic nuclei, 2014.
[13] I. Hamamoto, Physics Reports **10**, 63 (1974).
[14] D. Lacroix, 2009 International Joliot-Curie School (EJC2009).
[15] G. Colò, P. F. Bortignon, and G. Bocchi, Phys. Rev. C **95**, 034303 (2017).
[16] G. Bocchi *et al.*, Phys. Lett. B. **760**, 273 (2016).
[17] M. Jentschel *et al.,* J. Instrum. **12**, P11003 (2017).
[18] J. Simpson *et al.,* Acta Phys. Hung., New Ser. Heavy Ion Phys. **11** 159, (2000).
[19] C. Rossi Alvarez, Nucl. Phys. News **3**, 3 (1993).
[20] C. Müller *et al.*, J. Nucl. Med. **55**, 1658 (2014).
[21] Experimental Nuclear Reaction Data (EXFOR), http://www.nndc.bnl.gov/exfor/.
[22] Evaluated Nuclear Structure Data File (NNDC), http://www.nndc.bnl.gov.
[23] N. Cieplicka-Oryńczak *et al.*, Acta Phys. Pol. B **48**, 557 (2017).
[24] N. Cieplicka-Oryńczak *et al.*, Phys. Rev. C **93**, 054302 (2016).
[25] N. Cieplicka-Oryńczak *et al.*, Phys. Rev. C **93**, 014311 (2016).
[26] G. Colò, L. Cao, N. Van Giai and L. Capelli, Comput. Phys. Commun. **184**, 142 (2016).
[27] G. Colò, H. Sagawa and P. F. Bortignon, Phys. Rev. C **82**, 064307 (2010).
[28] J. Rowe, J. Math. Phys. **10**, 1774 (1969).