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Short Note

In-beam γ-ray spectroscopy of ^{42}Ca

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Abstract. High-spin states of the ^{42}Ca nucleus, populated in the 68 MeV ^{18}O + ^{30}Si reaction, have been studied in a γ-γ-recoil coincidence experiment. The level scheme of ^{42}Ca has been extended up to 13.7 MeV. An elaborate decay pattern with various paths, together with high-quality DCO and polarization information assigns spins and parities for almost all observed levels. The sequence of non-yrast positive-parity states is discussed and compared with highly deformed bands in ^{36}Ar and ^{40}Ca.

PACS. 21.60.Cs Shell model – 23.20.Lv Gamma transitions and level energies – 27.40.+z $39 \leq A \leq 58$

The excitations observed in the $f_{7/2}$-shell nuclei reveal properties attributed not only to the spherical shapes but also characteristic of nuclear deformation, and thus provide unique opportunities to investigate single-particle and collective modes in the same nucleus. The deformed structure can result from a coherent motion of many valence nucleons. The best example of such a structure is the yrast rotational-like band in ^{48}Cr with the deformation parameter $\beta = 0.28$ at low spin [1]. Different nature characterizes very regular rotational bands of unnatural-parity states, identified first in the light odd-A ^{43}Ca, ^{45}Sc and ^{45}Ti nuclei [2,3] and recently observed in many other nuclei, for example the odd-odd ^{46}V nucleus [4] and the even-even ^{44}Ca nucleus [5]. In the shell model, the properties of this band are described by the additional cross-shell excitations occurring when one of the core particles is promoted to the $f_{7/2}$ orbital. The highly deformed states can also be formed in these nuclei. They arise from multiparticle-multihole excitations of the core. Theoretical calculations performed for several even-even calcium and titanium isotopes [6] predicted the existence of low-lying rotational bands with deformation parameters up to $\beta = 0.56$ for the 8-particle 8-hole configuration in the ^{40}Ca nucleus. Superdeformed bands have been recently observed in the structure of the ^{36}Ar [7] and ^{40}Ca nuclei [8]. The rotational-like bands have also been identified in ^{38}Ar [9], although their collective character has not yet been experimentally proven. The ^{42}Ca nucleus, having only two valence neutrons outside the doubly closed ^{40}Ca core, is also a good candidate in which to study the interplay between single-particle and deformed structures. Furthermore, the highly deformed bands are expected to lie low in energy, as their band heads, the $I^{\pi} = 0^{+}$ states of 6p-4h and 4p-2h configurations [10], occur in ^{42}Ca at 1837 keV and 3300 keV, respectively.

Encouraged by the successful studies of nuclei in the closest vicinity of ^{40}Ca mentioned above, we investigated the structure of high-spin states in ^{42}Ca. Our in-beam experiment was performed with the VIVITRON accelerator at IReS Strasbourg. The experimental set-up contained the high-efficiency EUROBALL IV germanium detector array in coincidence with the Recoil Filter Detector (RFD) [11]. The main purpose of using the RFD in this experiment was to reduce a large Doppler broadening of the observed γ-lines, which is caused by high recoil velocity ($v/c = 2.8\%$). The ^{42}Ca nuclei were populated in the (^{18}O, α2n) reaction with a pulsed beam of 68 MeV ^{18}O ions bombarding a metallic, 800 μg/cm^2 thick ^{30}Si target [12]. A thorough analysis of γ-γ- and γ-γ-γ-recoil coincidences, together with DCO ratios and γ-polarization information, provided the high-spin level scheme of the ^{42}Ca nucleus as presented in fig. 1.

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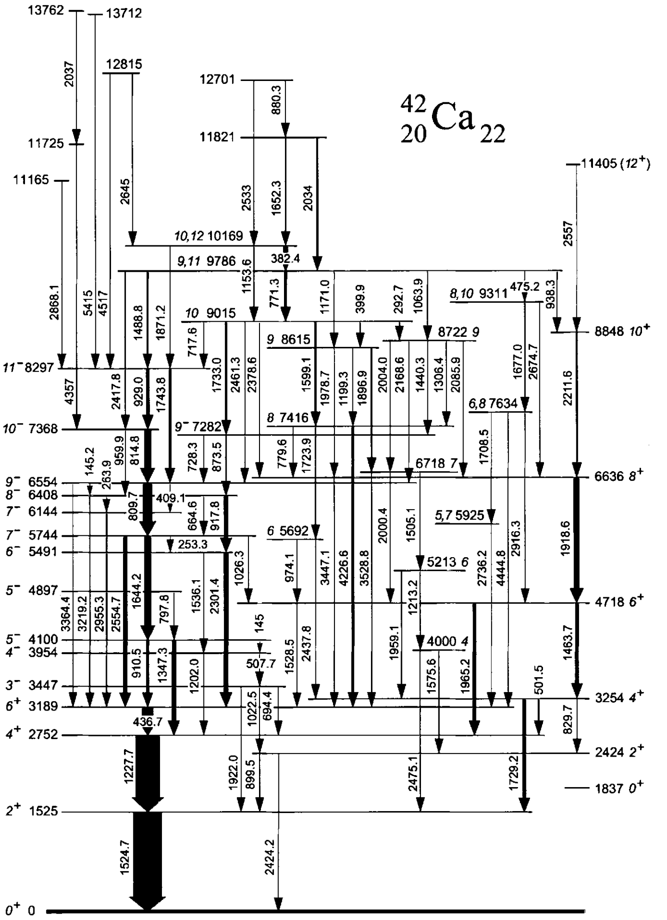

Fig. 1. Level scheme of the ^{42}Ca nucleus as observed in our experiment except for the 0^+ state at 1837 keV discussed in [10].

High-spin states in ^{42}Ca were extensively studied in the late 1970s [13,14]. Essentially, the yrast excitations up to the 8296 keV level were known from these investigations. However, the experimental techniques available at that time did not allow details of the decay pattern to be observed, which consequently caused a misplacement of some γ-rays. The efficiency of the γ-ray detection system used in our experiment, and the good quality of γ-γ-recoil coincidence spectra, extended the ^{42}Ca level scheme up to 13.8 MeV and revealed a very complicated decay mode of almost all yrast and non-yrast states.

The spin assignments shown in fig. 1 are based on DCO information. Events from detectors of chosen geometry were sorted into γ-γ-recoil matrices. The experimental DCO factors were extracted from the coincidence spectra gated on known $E2$ transitions, whereas for the weak γ-rays the summed spectra were used. The detailed analysis of the experimental DCO ratios and the fact that depopulation of each state branches into several decay paths eliminate some of the spin values and uniquely determine spin for almost all observed levels. In fig. 2, we collect experimental $R^{\mathrm{exp}}_{\mathrm{DCO}}$ ratios for selected γ-transitions depopulating the new 11821 keV level via various decay paths. These paths include several γ-rays unknown until now. For comparison, the theoretical DCO ratios were calcu-

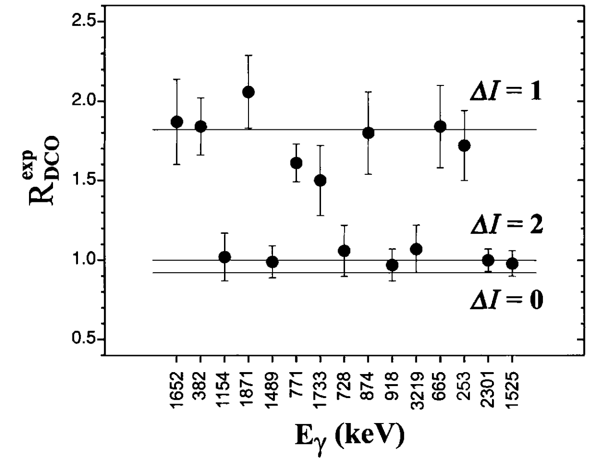

Fig. 2. Experimental DCO ratios for selected γ-cascades depopulating the 11821 keV level. Solid lines give the $R^{\mathrm{th}}_{\mathrm{DCO}}$ values calculated for $\Delta I = 1$, $\Delta I = 2$ and $\Delta I = 0$ transitions observed in $E2$-gated DCO spectra.

lated [15] for the geometry used in our experiment. Assuming the pure character of the γ-transitions involved, the calculated $R^{\mathrm{th}}_{\mathrm{DCO}}$ values are 1.82 and 0.92 for the $(11 \to 10, 10 \to 8)$ and $(11 \to 11, 11 \to 9)$ spin sequences, respectively. For the two $\Delta I = 2$ quadrupole transitions, the theoretical DCO ratio is $R^{\mathrm{th}}_{\mathrm{DCO}} = 1.0$.

An example of a γ-γ-recoil coincidence spectrum with a gate on the 382.4 keV transition is presented in fig. 3. It documents the placement of the level depopulated by this γ-ray as the excitation at 10169 keV which is much higher in energy than proposed before [14]. All coincidence relations indicate that the 382.4 keV γ-ray feeds the 9786 keV level, showing at the same time its complex decay.

Although in the shell model the ^{42}Ca nucleus, with only two valence neutrons outside the ^{40}Ca core, invokes a rather simple structure, the theoretical interpretation of the observed excitations is not possible without advanced calculations. Nonetheless, a qualitative description of some excitations can be attempted. The nature of the three yrast positive-parity states at 1525, 2752 and 3189 keV is rather evident. They represent the excitations of two neutrons in the $f_{7/2}$-shell. The negative-parity yrast sequence up to the $I^{\pi} = 11^-$ level at 8297 keV can be understood as a coupling of the valence neutrons to the lowest particle-hole excitations of the ^{40}Ca core. The 8297 keV state has the maximum aligned spin for the $(\pi d^{-1}_{3/2} f_{7/2} \nu f^2_{7/2})$ configuration. The 7282 and 9015 keV levels are most likely members of the same multiplet, whereas the interpretation of the structure of higher-lying states is not straightforward. The new levels at 11725, 12815 and 13712 keV decay via very high-energy γ-transitions of 4357, 4517 and 5415 keV to the 7368 keV ($I^{\pi} = 10^-$) and 8297 keV ($I^{\pi} = 11^-$) states, the two highest-spin excitations of the $(d^{-1}_{3/2} f^3_{7/2})$ configuration. Similarly, the high-energy decay of the well-separated levels above the $I^{\pi} = 31/2^+$ band-terminating state was observed in ^{45}Sc [3]. The theoretical description of these

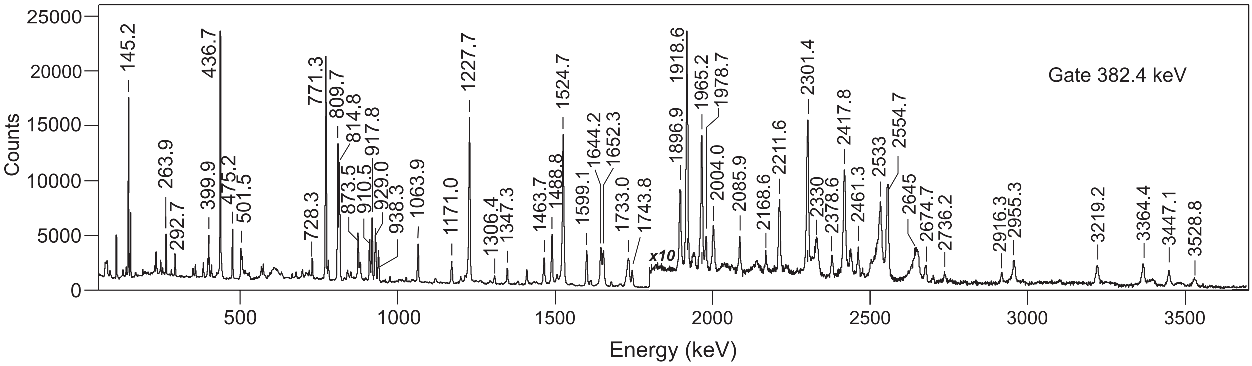

Fig. 3. Coincidence γ-γ-recoil spectrum gated on the 382.4 keV transition depopulating the 10169 keV level. One notes the very good energy resolution of all γ-lines. Broad lines at 2533 and 2645 keV are due to very short lifetimes of the highly excited states.

states required a promotion of particles across the energy gap to the next $f_{5/2}$ orbital [16].

The non-yrast positive-parity states, shown to the furthest right in fig. 1, form a regular rotational-like band. The highest excitation in this sequence is the level at 11405 keV depopulated by a weak transition of 2557 keV. Although neither its spin nor parity could be established, for further considerations we arbitrarily assign its spin as $I^\pi = 12^+$. The collective character of the 4^+, 6^+ and 8^+ levels at 3254, 4718 and 6635 keV has been proven by the measured enhancement of the in-band $E2$ transitions depopulating these states [17]. The determination of the lifetime for the 10^+ 8848 keV level is discarded because of the strong feeding from the longer-living 9786 keV state. Whereas, the 2557 keV transition from the (12^+) state at 11405 keV exhibits a broad line shape which points to a lifetime below 40 fs [18]. However, the exact value cannot be deduced due to unknown feeding. It can be noted that the level spacing observed in this sequence of ^{42}Ca is very similar to that of the superdeformed band in ^{40}Ca. Consequently, the $J^{(1)}$ kinematic moment of inertia extracted for the positive-parity band in ^{42}Ca shows similar, smooth behaviour as observed for the highly deformed band in ^{40}Ca. In fig. 4, the $J^{(1)}$ values for the ^{42}Ca band are compared to the moment of inertia for the superdeformed bands of ^{36}Ar [7] and ^{40}Ca [8].

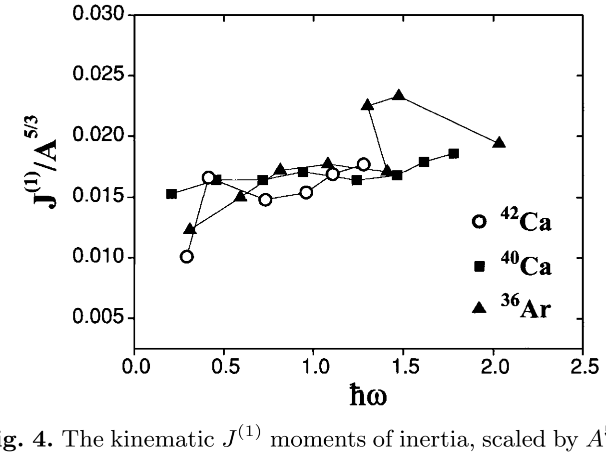

Fig. 4. The kinematic $J^{(1)}$ moments of inertia, scaled by $A^{5/3}$, as a function of rotational frequency for non-yrast positive-parity states in ^{42}Ca and for superdeformed bands in ^{40}Ca [8] and ^{36}Ar [7].

In summary, we have performed detailed investigations of the ^{42}Ca nucleus to a rather high excitation, both in spin and energy, beyond the 11^- terminating state, applying a precise gamma-recoil technique (EB + RFD) with DCO and polarization measurements. The positive-parity regular sequence of states observed up to (presumably) $I^\pi = 12^+$ is interpreted in terms of the highly deformed band built on the 6p-4h configuration, similar to the 8p-8h band observed in ^{40}Ca.

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