TOWARDS THE DETERMINATION OF SUPERDEFORMATION IN ^{42}Ca*

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The Coulomb excitation experiment to study electromagnetic structure of low-lying states in ^{42}Ca with a focus on a possible superdeformation in this nucleus was performed at the Laboratori Nazionali di Legnaro in Italy. Preliminary values of the determined quadrupole deformation parameters for both the ground state band and the presumed superdeformed band are presented.

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1. Motivation

Detailed spectroscopy studies of superdeformed bands in the $A \approx 40$ region are important to understand these structures in the frame of shell model. The large shell gaps at nucleon numbers $N, Z = 16, 18, 20$, which were calculated for $\beta_2 \approx 0.4$–0.6, imply the existence of superdeformed rotational bands in these nuclei involving valence particles in both the *sd* and *pf* shells.

A recently observed rotational structure in ^{42}Ca [1] is similar to the previously identified superdeformed bands in several $A \approx 40$ nuclei such as ^{40}Ca [2], ^{36,38,40}Ar [3–6] and ^{44}Ti [7]. The low-spin behavior of these bands is distinctive when compared to SD bands in other mass regions — here, a considerable amount of decay intensity remains within the band, down to the excited 0^+ band-head. Another important feature is that the SD bands in light nuclei are linked to the spherical or low deformed states by intense discrete transitions. Multiple Coulomb excitation experiments are an excellent tool to complement spectroscopic information about these structures by measuring the $B(E2)$ values for both in-band and out-of-band transitions. In ^{40}Ca, large transitional quadrupole moments in bands built on the low-lying 0^+ states (where $0^+_{\rm gs}$ is spherical) suggested shape coexistence. These different structures could be interpreted as an effect of multiparticle — multihole excitations [8].

In the ^{42}Ca nucleus, lifetime measurements, performed using the Doppler shift attenuation method [9], indicated that the band built on the second 0^+ state (1837 keV) is characterized by a deformation smaller than the superdeformed band in ^{40}Ca. However, moments of inertia of these two bands were found to be very similar [1], which, in contrast, pointed to a rather similar magnitude of deformation of the highly deformed structures in ^{40}Ca and ^{42}Ca.

A support for the highly deformed character of the band in ^{42}Ca came also from the observation of its preferential feeding in the decay of the low energy component of the highly split GDR in ^{46}Ti [10].

2. Coulomb excitation of ^{42}Ca

In order to resolve the existing ambiguities concerning the magnitude of the deformation of the side rotational band in ^{42}Ca, a Coulomb excitation measurement has been performed to measure the $B(E2)$ values [11]. The experiment took place in February 2010 at the Laboratori Nazionali di Legnaro. The γ-ray spectrometer AGATA Demonstrator [12], coupled to the charged particle detection set-up DANTE [13], was used for the first time during the experiment.

A ^{42}Ca beam of 170 MeV energy bombarded a 1 mg/cm^2 ^{208}Pb target. Gamma rays from the Coulomb excited nuclei were measured in coincidence with back-scattered projectiles and detected by three position-sensitive heavy ion Micro-Channel Plate detectors forming the DANTE array that covered $\theta_{\rm LAB}$ range from 100° to 144°. The AGATA Demonstrator spectrometer consisting of three triple germanium clusters was used to measure γ-ray transitions in the energy range up to 3 MeV. Data acquisition for the AGATA array was fully digital, while the MCP detector signals were processed by analog electronics. The total γ-ray spectrum, Doppler corrected for the ^{42}Ca scattered projectile, in coincidence with one of the DANTE detectors is shown in Fig. 1.

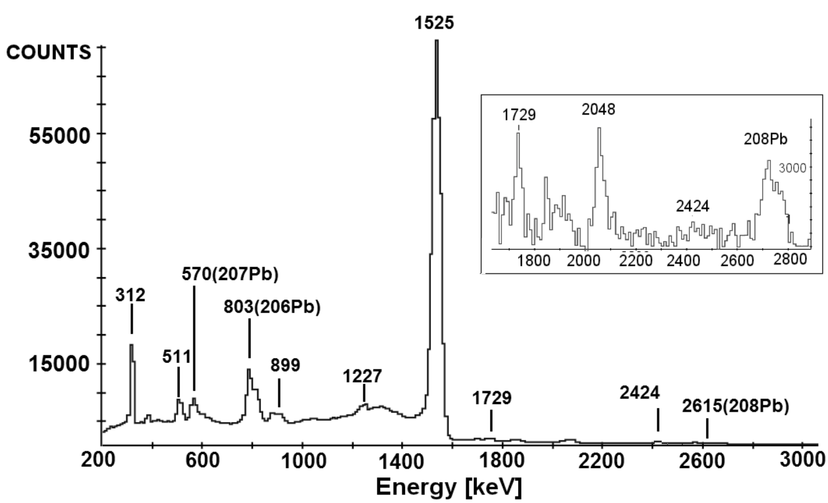

Fig. 1. Doppler-corrected γ-ray spectrum observed in the ^{42}Ca + ^{208}Pb Coulomb excitation experiment.

Transitions deexciting the highly deformed side band were observed, as well as γ rays decaying from the low-lying states in the yrast band. It was possible to detect Coulomb excited levels up to 4^+ in both the ground state and the highly deformed band (figure 2).

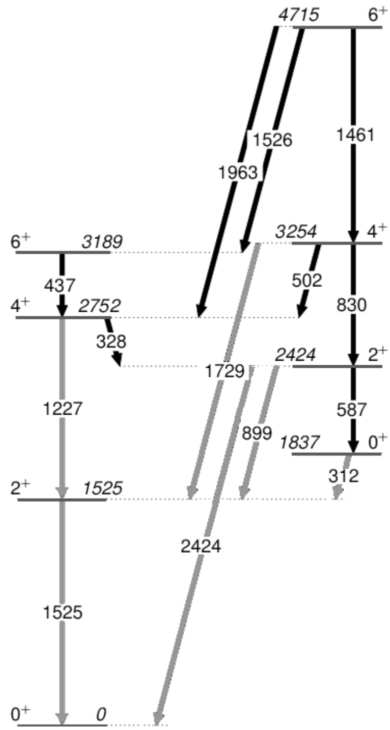

Fig. 2. The scheme of excited states in ^{42}Ca. Transitions observed in the current Coulomb excitation experiment are marked in gray.

Unexpectedly, two unknown γ lines of 2048 and 376 keV energies were also observed in this experiment. The 2048 keV transition was particularly strong. The properties, especially the Doppler corrected width of these γ rays, indicated that they could be emitted from the ^{42}Ca scattered projectile.

The calculations of transition probabilities performed using the GOSIA code [14] excluded possibility that the 2048 keV line is identical with the known 2048 keV transition connecting the 1^- and 0_2^+ states in ^{42}Ca. Observation of the 376 keV γ line, however, supported the scenario that both 376 and 2048 keV transitions could be related to a new state located at 2048 keV in ^{42}Ca and populated in the Coulomb excitation experiment. In such a case, the 2048 keV γ-ray would just deexcite this new level while the 376 keV γ transition would be a branch from the 2424 keV level. The first results from this work, including possibility of existence of an unknown level at 2048 keV, was presented in [11].

3. Confirmation of the low spin level scheme in ^{42}Ca

A dedicated fusion-evaporation experiment aiming at confirmation of the low spin level scheme in ^{42}Ca was performed at the Heavy Ion Laboratory, University of Warsaw, using the EAGLE spectrometer [15] in the configuration with 15 HPGe detectors in anti-Compton shielding. A ^{32}S beam of 80 MeV energy bombarded a thick 100 mg/cm^2 ^{12}C target. Significant production of ^{42}Ca was observed in the $2p$ reaction channel. In addition, states in ^{42}Ca, including the 2424 keV level, were populated in the beta decay of ^{42}Sc, a product of the pn channel. In the course of analysis it was possible to observe the 2424 and 899 keV transitions deexciting the 2424 keV state (figure 3). In the γ–γ matrices, however, there was no sign of the 376 keV transition in coincidence with the 2048 keV γ-ray. To conclude, there is no additional γ-decay branch from the 2424 keV energy level.

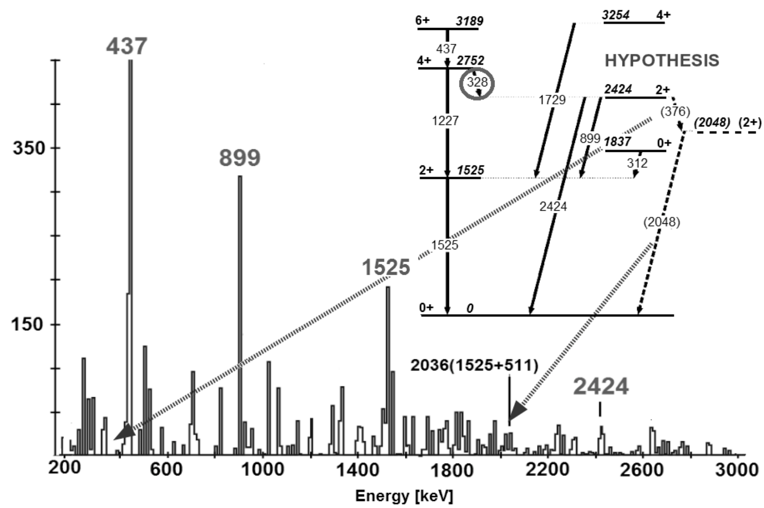

Fig. 3. A γ–γ matrix projection with 328 keV gamma energy gate. There is no indication of 376 or 2048 keV transitions deexciting of the 2424 keV level in ^{42}Ca.

At this point, the only plausible explanation of the presence of the 376 and 2048 keV transitions in the COULEX spectrum seemed to be sub-barrier transfer reactions. Indeed, it was noticed that in ^{43}Ca, which might be a product of the sub-barrier ^{208}Pb(^{42}Ca,^{43}Ca)^{207}Pb transfer reaction, there is a $J^{\pi} = 3/2^{-}$ state at 2046 keV with a sizable neutron single particle strength. This state decays via a 2046 keV transition which, due to a slight mismatch between the kinematics of the transfer process with respect to Coulomb excitation, might have been observed as a 2048 keV line. Similarly, the 376 keV line might correspond to the lowest excited state in ^{43}Ca at 374 keV which is fed in the decay of the 2046 keV excitation.

To examine the possibility of such a scenario, the reaction cross section to populate the 2046 keV state in ^{43}Ca in the one neutron transfer process was calculated using the FRESCO code [16] and compared with the cross section obtained from the Coulomb excitation formalism and experimental yields [17]. It turned out that the observed intensity of the 2048 keV transition can be explained in the frame of one neutron sub-barrier transfer theory.

4. Results — quadrupole deformation parameters of ^{42}Ca

The least squares fitting code GOSIA was used to determine $E2$ reduced matrix elements in ^{42}Ca from the Coulomb excitation experiment performed in LNL di Legnaro. Taking into account known spectroscopic data related to electromagnetic matrix elements, such as branching ratios, lifetimes of excited states, $E2/M1$ mixing ratios, previously measured matrix elements, the GOSIA code was used to fit a set of $E2$ reduced matrix elements to the experimentally measured γ-ray yields.

Based on the obtained set of $E2$ matrix elements and using the Quadrupole Sum Rules method [17, 18], the overall deformation parameters of the lowest 0^+, 2^+ states in both ground state and side bands, as well as that of 4_1^+ in ^{42}Ca were extracted. The calculated $\sqrt{\langle\beta^2\rangle}$ quadrupole deformation parameter values are shown in figure 4.

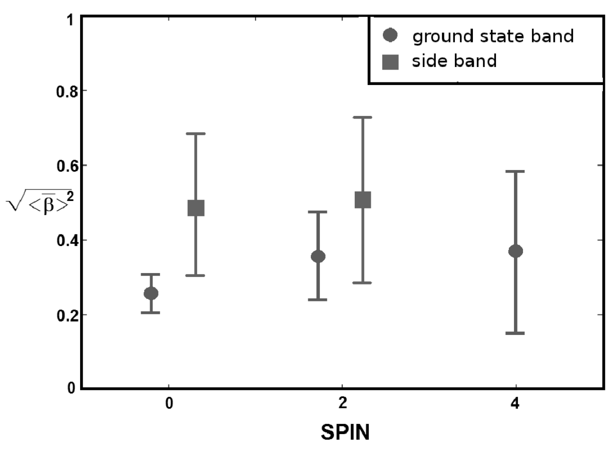

Fig. 4. Preliminary values of the overall quadrupole deformation parameters $\sqrt{\langle\beta^2\rangle}$ calculated for the 0^+, 2^+ states in both ground state and side bands, as well as that of the 4_1^+ state in ^{42}Ca.

The Quadrupole Sum Rules method approach is based on the fact that the electric multipole transition operator is a spherical tensor. Thus, zero-coupled products of such an operator that are rotationally invariant can be formed. In the intrinsic frame of the nucleus, the components of the $E2$ operator can be parametrized by the Q — the overall deformation parameter and δ — the triaxiality parameter. The lowest order rotationally invariant product, Q, brings information on the overall deformation of the individual state $|i\rangle$. In the laboratory frame it can be expressed by the $E2$ matrix elements which couple the state $|i\rangle$ with all other states that can be reached via a single $E2$ transition

$$\frac{1}{\sqrt{5}}\left\langle Q^2\right\rangle = \frac{1}{\sqrt{2I_i+1}}\sum_t \langle i\|E2\|t\rangle\langle t\|E2\|f\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_f & I_t \end{Bmatrix}, \qquad (1)$$

where I is the spin, $|i\rangle$ — the initial state, $|f\rangle$ — the final state, $|t\rangle$ — the intermediate state,

$$\begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_f & I_t \end{Bmatrix} \qquad (2)$$

is a Wigner's $6j$ symbol.

The Q parameter that describes the charge distribution of the nucleus in the individual nuclear state, can be related to the Bohr deformation parameter β [19] (r_0 is a nuclear radius, A — mass number, Z — atomic number):

$$\left\langle Q^2\right\rangle = \left[\frac{3}{4\pi}Z\left(r_0\sqrt[3]{A}\right)^2\right]^2\left\langle \beta^2\right\rangle . \qquad (3)$$

To determine the overall deformation for the excited 0_2^+ state, one needs to take into account the couplings of this state to all 2^+ states, while determination of the deformation of 2^+ and 4^+ levels requires us to take into account contributions from all matrix elements of transitions between the state in question and those that may be reached from it by a single $E2$ transition. It should be noted, for example, that it was possible to determine the $\langle 2_2^+\|E2\|0_2^+\rangle$ matrix element in the present analysis from the intensity balance, even though the $2_2^+ \to 0_2^+$ transition was not observed.

The relatively large $\sqrt{\langle\beta^2\rangle}$ values determined for the 2_2^+ and 0_2^+ states at 2424 keV and at 1837 keV, respectively, strongly support a highly deformed character of the side rotational band. Our results indicate also non-spherical shape of the ground state.

Further analysis, which will provide a more precise information on electromagnetic properties of the highly deformed band, is in progress.

5. Summary

Coulomb excitation of low-lying levels in ^{42}Ca was observed up to the 4^+ states in both the ground state band and the deformed side band built on the 0_2^+.

Additionally, two relatively strong γ-ray transitions with energies of 376 and 2048 keV were identified in the spectrum. A dedicated experiment to study the low-energy part of ^{42}Ca level scheme, together with FRESCO reaction cross section calculations, suggest that these lines originate from the sub-barrier one neutron transfer reaction ^{208}Pb(^{42}Ca,^{43}Ca)^{207}Pb.

Preliminary results of the COULEX analysis, provided the information on electromagnetic properties of the states in the side-deformed band in ^{42}Ca by determination of the $B(E2)$ values. Deformation parameters for the 0_1^+, 2_1^+, 4_1^+ (ground state band) and 0_2^+, 2_2^+ (side band) indicate the existence of superdeformation in ^{42}Ca, although the uncertainties are quite large. The analysis aimed at reducing these uncertainties is in progress.

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