REFINEMENT OF THE ^{42}Ca LEVEL SCHEME. PRELIMINARY RESULTS FROM THE FIRST AGATA DEMONSTRATOR EXPERIMENT*

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The Coulomb excitation experiment to study electromagnetic properties of low-lying states in ^{42}Ca with a focus on a presumably superdeformed band was performed at the Laboratori Nazionali di Legnaro in Italy using the γ-ray spectrometer AGATA Demonstrator coupled to the DANTE charged particle detector array. First results are presented, including the refinement of the ^{42}Ca level scheme.

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1. Introduction

In the ^{42}Ca nucleus a rotational structure has been observed [1], which is similar to the previously identified superdeformed bands in several $A \approx 40$ nuclei such as ^{40}Ca [2], ^{36,38}Ar [3, 4, 5]. Large transitional quadrupole moments in bands built on the low-lying 0^+ states in ^{40}Ca suggested shape coexistence in this nucleus, which could be interpreted as an effect of multiparticle–multihole deformed excitations [6].

Lifetime measurements performed for the ^{42}Ca nucleus using the Doppler shift attenuation method [7] indicate a smaller deformation of the band built on the second 0^+ state (1837 keV) than in the case of the superdeformed band in ^{40}Ca. On the other hand, moments of inertia of these two bands were found to be very similar [1]. Another argument for the highly deformed character of this band was the observation of its preferential feeding by the decay of the low energy component of the highly split GDR in ^{46}Ti [8].

2. Coulomb excitation of ^{42}Ca

In order to resolve the existing ambiguities concerning the deformation of the presumably superdeformed band, a Coulomb excitation measurement has been performed to extract the $B(E2)$ values in ^{42}Ca. The experiment took place in February 2010 at the Laboratori Nazionali di Legnaro. For this measurement, the γ-ray spectrometer AGATA Demonstrator [9] coupled to the charged particle detection set-up DANTE [10] was used for the first time.

A ^{42}Ca beam of 170 MeV energy bombarded a 1 mg/cm^2 target of ^{208}Pb. Gamma rays from the Coulomb excited nuclei were measured in coincidence with back-scattered projectiles, detected by three position-sensitive heavy ion micro-channel plate detectors forming the DANTE array that covered θ 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 of the AGATA array was fully digital, while MCP detectors signals were processed by analog electronics. The readout of DANTE was synchronized and merged with the AGATA acquisition system using the AGAVA interface.

Transitions deexciting the highly deformed band were observed, as well as γ rays depopulating low-lying states in the yrast band. In both the ground state band and the highly deformed band it was possible to Coulomb excite levels of spin up to 4^+. Doppler correction was performed based on the information of particle scattering angle provided by MCP detectors. In Fig. 1 the total γ-ray spectrum in coincidence with one of the DANTE detectors is shown. In addition to the γ lines coming from known low energy states in ^{42}Ca, γ rays depopulating the Coulomb excited states of lead target and aluminum holder nuclei are visible. These lines are significantly broadened since the Doppler correction was performed for the ^{42}Ca scattered projectile.

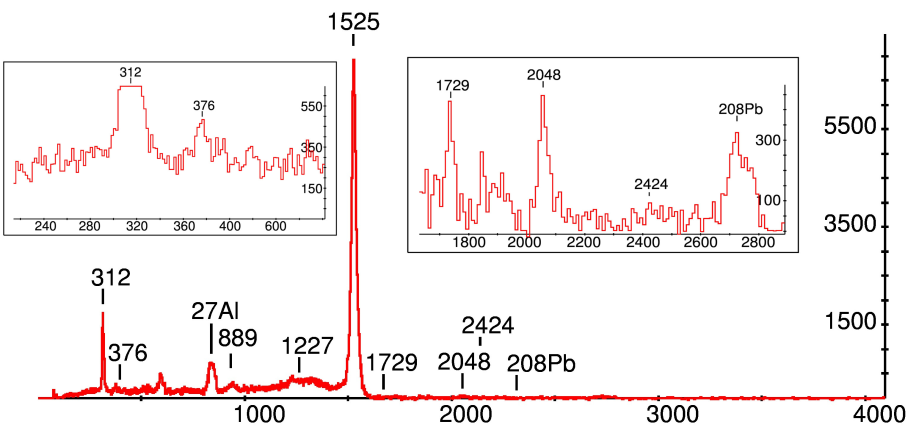

Fig. 1. Doppler-corrected γ-ray spectrum observed in the ^{42}Ca + ^{208}Pb Coulomb excitation experiment. The insets present 376 keV and 2048 keV γ-ray transitions, discussed in the text.

Moreover, a very strong 2048 keV γ-ray transition is clearly visible. Its width indicates that this line comes from the ^{42}Ca scattered projectiles. A γ ray of such an energy is known in the ^{42}Ca level scheme as an $E1$ transition from the 1^- state at 3885 keV [7] — the known level scheme of ^{42}Ca is presented on the left-hand side of Fig. 2. The most probable way to Coulomb excite the 1^- state is via combination of $E2$ and $E3$ transitions: $0_1^+ \rightarrow 2_1^+ \otimes 2_1^+ \rightarrow 1^-$. A simulation performed using the GOSIA code [11] has shown that to reproduce the observed yield of the 2048 keV transition, a large $B(E3; 2_1^+ \rightarrow 1^-) \sim 10^6$ W.u. is required. Such an enormous $B(E3; 2_1^+ \rightarrow 1^-)$ value means that the 2048 keV line observed in the present experiment cannot be identical with the one that is known to originate from the 1^- state at 3885 keV.

An alternative assignment of the 3885 keV state as 3^-, suggested by the studies of transfer reactions [7], implies one-step Coulomb excitation of this level via an $E3$ transition directly from the ground state. This interpretation cannot be supported by the data collected in present experiment because of two reasons. Firstly, in such a case the selection rules would require the existence of a 2360 keV $E1$ transition from the 3^- to the 2_1^+ state in the yrast band. There is no evidence for such a γ line in the collected γ-ray spectra. Secondly, if one assumes that the 3^- state at 3885 keV could be excited via the following combination of transitions: $0_1^+ \rightarrow 2_1^+ \otimes 2_1^+ \rightarrow 0_2^+ \otimes 0_2^+ \rightarrow 3^-$, it is impossible to reproduce the observed intensity of the 2048 keV γ line. This case is presented in the right-hand side of Fig. 2 while the results of the appropriate simulations using the GOSIA code to calculate $B(E\lambda)$ values required to reproduce the observed yield of the 2048 keV transition are presented in Table I.

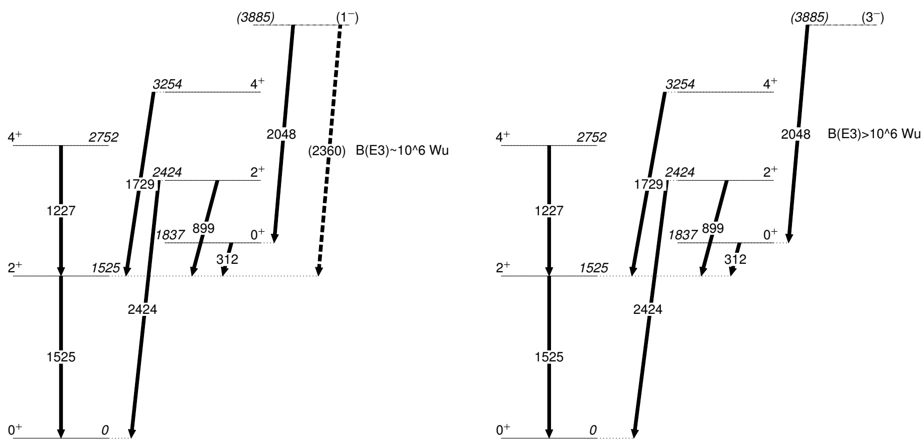

Fig. 2. The level scheme of ^{42}Ca observed in the present experiment with tentatively assigned 1^- state (left-hand side) and 3^- state (right-hand side) at the energy of 3885 keV. In the case of 1^- state excitation of this level proceeds via non-observed 2360 keV $E3$ γ transition.

TABLE I

All possible assignments of the new level with $B(E\lambda)$ values required to reproduce the observed intensity of 2048 keV transition, calculated using the GOSIA code [11].

E_{level} [keV]	E_{gamma} [keV]	J^{π}_{level}	λ	$B(E\lambda)$ [W.u.]
3885	2048	1^-	3	$\sim 10^6$
3885	2360	3^-	3	$>10^6$
3573	2048	1^-	3	$>10^6$
3573	2048	3^-	3	$>10^6$
3573	2048	2^+	2	400
3573	2048	4^+	2	200
2048	2048	3^-	3	350
2048	2048	2^+	2	1

Since the energy of the observed gamma ray does not fit to any other transition in the known level scheme of ^{42}Ca, one has to consider that an unknown state was populated in this measurement. For example, assuming a two-step Coulomb excitation process, a level lying 2048 keV above the 2_1^+, *i.e.*, at 3573 keV, could be populated via excitation from the 2_1^+ state. There are four possible spin and parity assignments that should be taken into consideration: 1^-, 3^-, 2^+ and 4^+.

If this new level had spin-parity of 1^- or 3^- (left-hand side of Fig. 3.), the excitation could be achieved only via an $E3$ transition of 2048 keV energy from the 2_1^+ state. Otherwise, the assignment 2^+ or 4^+ implies that it could be excited via combination of $E2$ transitions: $0_1^+ \rightarrow 2_1^+ \bigotimes 2_1^+ \rightarrow 2^+/4^+$. Both 2^+ and 4^+ cases are shown on the right-hand side of Fig. 3.

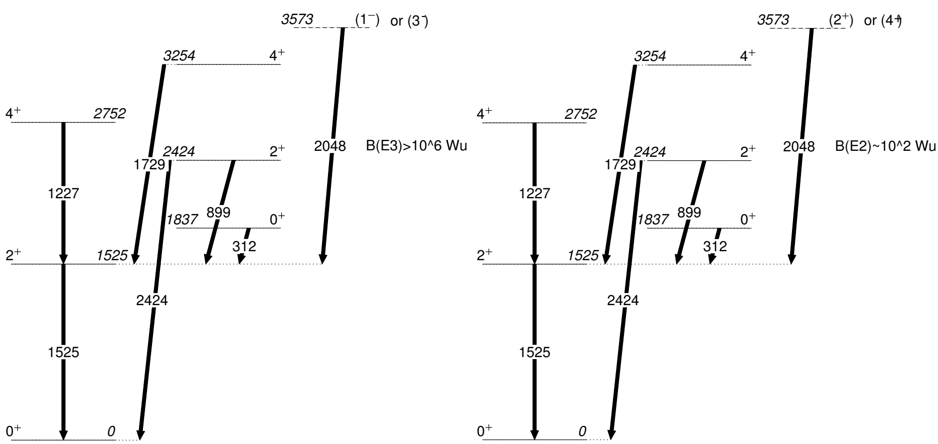

Fig. 3. The level scheme of ^{42}Ca observed in the present experiment with tentatively assigned 1^- or 3^- state (left-hand side) and 2^+ or 4^+ state (right-hand side) at the energy of 3573 keV.

It is worth noting that a possible coupling of 2_3^+ to the ground state would only reduce the 2048 keV line yield — the direct decay to the ground state would be favored due to a large energy difference between the two decay paths and, in consequence, even higher $B(E2; 2_1^+ \rightarrow 2_3^+)$ would be necessary to reproduce the 2048 keV yield in spite of some increase of the population of the 1^- state in the one-step process.

While the two-step Coulomb excitation process, required to populate a hypothetical level at 3573 keV, is unlikely in view of the arguments presented above, one should consider another scenario by assuming that an unknown level is excited directly from the ground state. In such a case, the observed 2048 keV γ ray would be related to deexcitation of the 3^- or 2^+ state lying at the energy of 2048 keV. The existence of such a level is supported by the fact that a 376 keV γ line is present in the spectrum. This transition fits to the energy difference between the 2_2^+ state at 2424 keV and the newly located state at 2048 keV (Fig. 4).

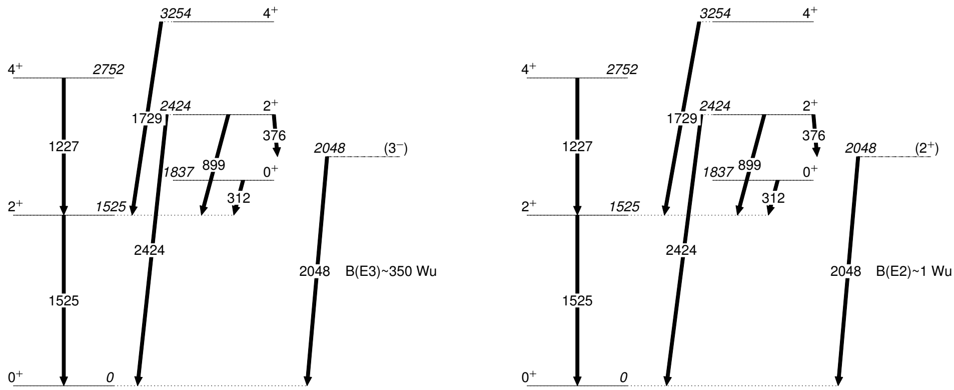

Fig. 4. The level scheme of ^{42}Ca observed in the present experiment with tentatively assigned 3^- state (left-hand side) and 2^+ state (right-hand side) at the energy of 2048 keV.

In the present experiment there is no sign of a 523 keV γ line, which could be expected between the level at 2048 keV and 2_1^+ state if the interpretation of the 2048 keV level as 3^- was adopted. The remaining possibility, *i.e.*, assignment of 2^+, is the most favorable. In such a case only 1 W.u. is required to reproduce the observed intensity of the 2048 keV line according to the calculation performed using the GOSIA code.

3. Summary

Coulomb excitation of low-lying levels in ^{42}Ca was observed up to 4^+ states in both the ground state band and the highly deformed band. A new strong gamma-ray transition at the energy of 2048 keV was identified in the spectrum. The calculations of various transition probabilities performed using the GOSIA code exclude the attribution of the 2048 keV line to the known level scheme of ^{42}Ca. The most probable scenario is that this line originates from a new state located at 2048 keV and populated in the Coulomb excitation process.

Further analysis, which will provide information on electromagnetic properties of the highly deformed band by determination of $B(E2)$ values, is in progress.

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REFERENCES

[1] M. Lach *et al.*, *Eur. Phys. J.* **A6**, 309 (2003).
[2] E. Ideguchi *et al.*, *Phys. Rev. Lett.* **87**, 222501 (2001).
[3] C.E. Svensson *et al.*, *Phys. Rev. Lett.* **85**, 2693 (2000).
[4] C.E. Svensson *et al.*, *Phys. Rev.* **C63**, 061301(R) (2001).
[5] D. Rudolph *et al.*, *Phys. Rev.* **C65**, 034305 (2002).
[6] J.L. Wood *et al.*, *Phys. Rep.* **215**, 101 (1992).
[7] B. Singh, J.A. Cameron, *Nucl. Data Sheets* **92**, 1 (2001).
[8] M. Kmiecik *et al.*, *Acta Phys. Pol. B* **36**, 1169 (2005).
[9] Ed. J. Simpson, J. Nyberg, W. Korten, AGATA Technical Design Report, Internal Report, 2008, `http://www-win.gsi.de/agata/publications.htm`
[10] J.J. Valiente-Dobón *et al.*, *Acta Phys. Pol. B* **37**, 225 (2006); A. Gadea *et al.*, *NIM*, in press.
[11] T. Czosnyka *et al.*, *Bull. Am. Phys. Soc.* **28**, 745 (1983) `www.slcj.uw.edu.pl/gosia`