LIFETIME MEASUREMENTS OF SHORT LIVED STATES IN ^{69}As*

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Lifetimes of high-spin states in ^{69}As have been measured using Doppler shift attenuation technique with the GASP and RFD set-up. The nucleus of interest was populated in the ^{40}Ca(^{32}S, $3p$)^{69}As reaction at beam energy of 95 MeV. Extracted lifetimes for the $33/2^+$ state at 7897 keV and $37/2^+$ state at 9820 keV are 72 (-45, $+55$) fs and 25(-25, $+50$) fs, respectively. The transition quadrupole moment resulting from the measurement can serve as a test of the TRS calculations.

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1. Introduction

The nucleus ^{69}As lies close to the $N = Z$ line, between doubly magic ^{56}Ni and strongly deformed ^{76}Sr isotopes. Species in that region exhibit shape instability that is manifested by a presence of rotational bands associated with moderate elongation $\beta \sim 0.3$ and significant degree of triaxiality.

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Coexistence of the prolate and oblate shapes is here a typical phenomenon. Measurements of excited states lifetimes can provide information on the nuclear deformation and other properties of collective structures, however, relevant data on electromagnetic properties of such bands at high spins are largely missing.

2. Experimental set-up

To investigate experimentally the evolution of nuclear deformation in the $A \sim 70$, $N \sim Z$ region, we have performed a measurement of excited-state lifetimes, in a femtosecond range, with the GASP and RFD detection system at LNL INFN. A 95-MeV ^{32}S pulsed beam from the Tandem XTU accelerator was focused on a 0.8 mg/cm^2 ^{40}Ca target. Such reaction led to the compound nucleus ^{72}Kr and, after the evaporation process, final nuclei were produced, including ^{69}As. In order to avoid fast oxidation of the target material, it was covered with a 10 μg/cm^2 carbon layer, from both sides.

Evaporation residues were detected by the segmented Recoil Filter Detector (RFD) [1] in coincidence with γ rays measured with the GASP germanium detector array. A trigger condition required at least two gamma rays and the recoiling nucleus in prompt coincidence. Each segment of RFD provides information on the time of flight with respect to the beam pulse signal and the direction of every individual evaporation residuum, thus allowing for precise Doppler correction of γ-ray energies. This feature allows to perform line shape analysis and is helpful in determination of excited states lifetimes if they are comparable to or shorter than the transit time of the recoil through the target — in our case, these times are in a femtosecond range.

Gamma lines corresponding to very fast transitions emitted inside the target are broadened and exhibit an angle-dependent tail due to a difference between the measured velocity of the recoil and its velocity at the emission — this difference is caused by the straggling of the recoil in the target and depends on the time at which the decay occurs. Thus, the γ-line shape is related to the excited state lifetime τ.

3. Results for ^{69}As

For the lifetime extraction, collected γ–γ-recoil coincidence data were sorted into γ–γ-angle cubes, using the GASPware software package developed in Legnaro. In the analysis, conditions were placed on the time of flight to select γ rays originating only from evaporation residues. Event-by-event Doppler correction has been applied to the data, under the assumption that the γ rays were emitted after the nucleus left the target. As seen in the

γ–γ-recoil coincidence spectra (Fig. 2), the applied correction is appropriate for the 1305 and 2093 keV transitions in ^{69}As, resulting in sharp lines at these energies. In contrast, the 1529 and 1930 keV lines, which are the consecutive transitions in the "band 3" (Fig. 1) known from previous studies [2], are not properly corrected what indicates that the corresponding γ rays were emitted, while the recoiling nucleus was still travelling inside the target. Moreover, these lines do not show any trace of the sharp component.

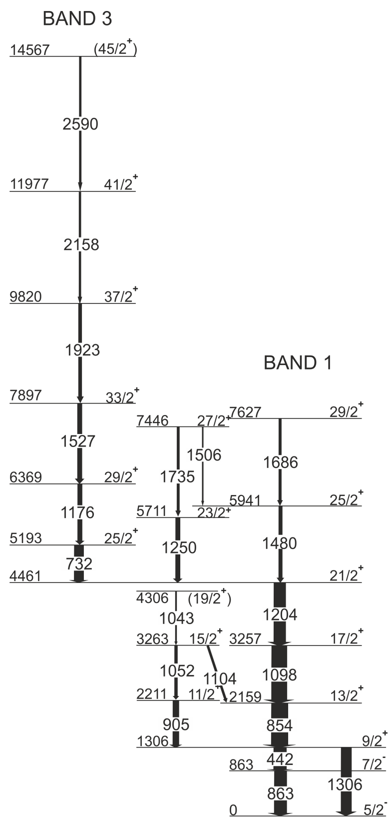

Fig. 1. Partial ^{69}As level scheme.

Complete analysis of the data, taking into account all angles of detection (*i.e.*, 35°, 60°, 72°, 90°, 108°, 120° and 145°), allowed to extract the cumulative lifetime for the $33/2^+$ state at 7897 keV and for the $37/2^+$ state at 9820 keV. A minimization procedure was applied in which the γ-ray spectra at different angles were taken as input, while level lifetime τ and γ-ray energy were considered as fitted parameters. Two-dimensional χ^2 maps were calculated.

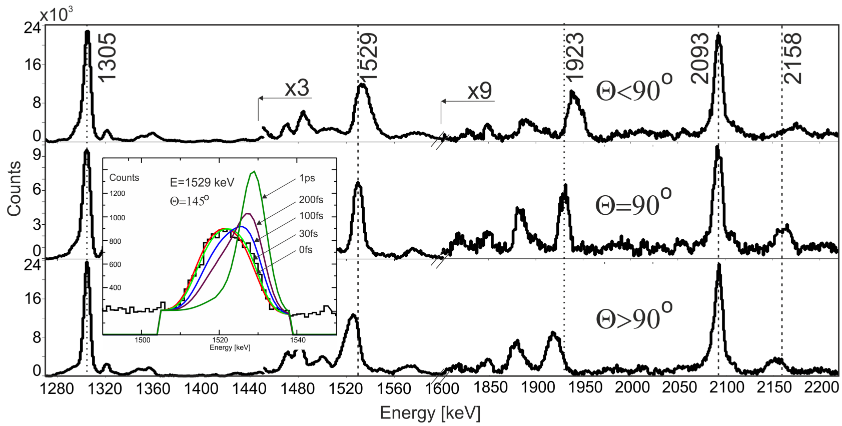

Fig. 2. Double-γ coincidence spectra gated by the ^{69}As transitions, registered at forward (upper panel), 90 degree (middle) and backward (lowest) angles with respect to the beam axis. The 1529 keV, 1930 keV and 2158 keV lines corresponding to the consecutive γ-transitions exhibit tails due to very short level lifetimes ($\tau < 50$ fs). For comparison, the sharp γ-lines at 1305 keV and 2093 keV resulting from the levels with longer lifetimes are indicated. Lineshapes calculated for several values of τ indicate that the lifetime of $33/2^+$ state is of the order of tenth fs.

For the 1529 keV line, χ^2 map is shown in Fig. 3 as a result of the simultaneous fit to the spectra collected at all angles of detection. It shows the minimum at the lifetime of 72 (-45, $+55$) fs for the 7897 keV state. Figure 4 displays experimental and calculated line shapes for the 1529 keV transition for the values obtained in the χ^2 minimum.

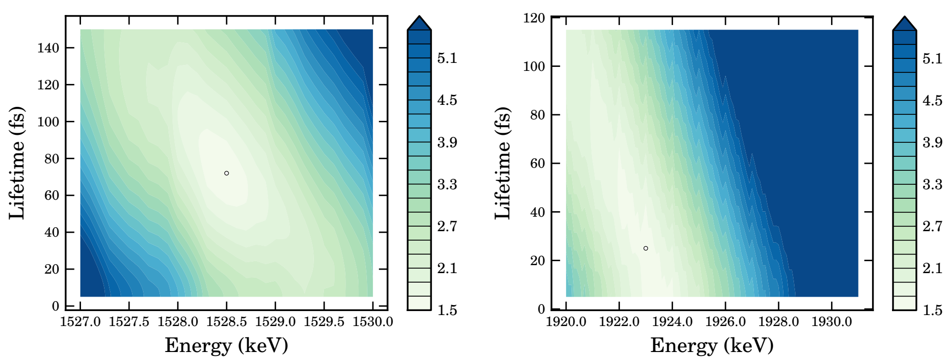

Fig. 3. Left panel: χ^2 map for the 1529 keV transition deexciting the $I^\pi = 33/2^+$ state at 7897 keV. Simultaneous fit to the all angles of detection. Minimum at $E = 1528.5$ keV and $\tau = 72$ (-45, $+55$) fs. Right panel: χ^2 map for the 1923 keV transition feeding the $I^\pi = 33/2^+$ state at 7897 keV. Simultaneous fit to the spectra registered at 35° and 145°. Minimum at $E = 1923$ keV and $\tau = 25$ (-25, $+50$) fs.

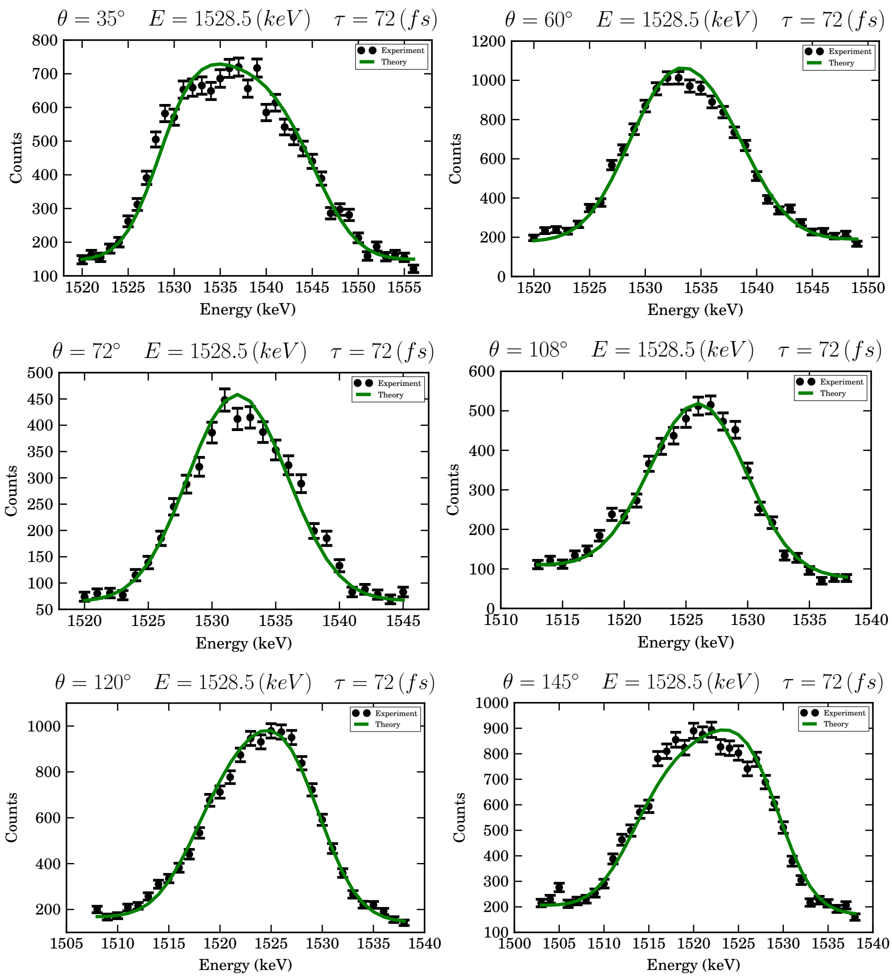

Fig. 4. Comparison between experimental and calculated line shape for the 1529 keV line seen at all angles of detection. Experimental spectrum obtained by placing gates on 732 and 1176 keV lines. Fit for the χ^2 minimum parameters value.

The same procedure was applied to shape analysis of the 1923 keV γ-ray line originating from the $37/2^+$ state at 9820 keV. As a result, lifetime of 25(−25, +50) fs for that $37/2^+$ state was extracted. The results of the fit and the experimental spectrum are presented in Figs. 3, right panel and 5.

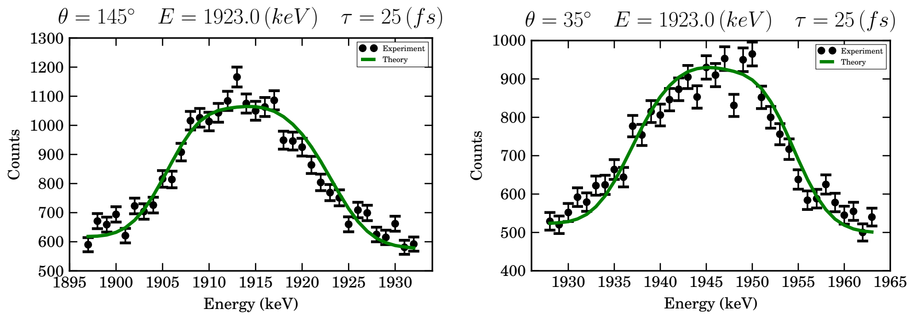

Fig. 5. Comparison between calculated and experimental line shape for the 1923 keV transition detected at 35° and 145°. Experimental spectra were obtained by placing gates on selected ^{69}As transitions, *i.e.*, 863, 442, 1306, 854, 1098, 1204, 732 and 1176 keV.

4. Discussion

The measured states lifetimes can be used to extract transition quadrupole moments, Q_t, which, in turn, can be related to nuclear deformation. The transition probability T [s^{-1}] for a band member of a spin I is described by the expression [3]

$$T(\mathrm{E2}, I \to I-2) = 1.22 \times 10^9 E_\gamma^5\,[\mathrm{MeV}] B(\mathrm{E2})\,\left[e^2\mathrm{fm}^4\right] , \tag{1}$$

where the reduced transition probability $B(\mathrm{E2})$ is given by

$$B(\mathrm{E2}, I \to I-2) = \frac{15}{32\pi} e^2 Q_\mathrm{t}^2 \frac{(I-1-K)(I-1+K)(I-K)(I+K)}{(I-1)(2I-1)I(2I+1)} . \tag{2}$$

The K value is the projection of the total spin I onto the symmetry axis of the deformed nucleus.

From the extracted lifetimes, we could calculate Q_t for the $33/2^+$ state: Q_t $(K = 3/2) = 1.98(-0.5, +1.25)$ eb, and the lower limit for the $37/2^+$ state: $Q_\mathrm{t} > 1.1$ eb. (We assumed that the states of "band 3" with spins between $29/2^+$ and $45/2^+$ are associated with a rotating nucleus having a stable prolate deformation — this assumption has partly been justified by the TRS calculations as described later in the paper.) Our results offer an unique opportunity for testing predictions of various micro- and macroscopic theoretical models that are used to interpret the variety of collective bands known in this part of the nuclear chart. Total Routhian Surface calculations (TRS) [4] were performed for the ^{69}As nucleus. In these calculations, one proton occupying $g_{9/2}$ orbit was blocked. At low rotational frequency (ω), the potential energy surface shows existence of a non-collective oblate minimum ($\beta \sim 0.3$, $\gamma \sim 50$), and, also, a prolate-deformed collective minimum with $\beta \sim 0.4$ and $\gamma \sim -20$. (The oblate-deformed minimum is the deepest one.) The prolate-deformed structure exists up to very high rotational frequency ($\omega = 1.5$), and, when comparing its energy-spin dependence, could correspond to the experimentally known "band 3" in ^{69}As. However, the transition quadrupole moment of this calculated collective band, $Q_{\rm t} = 3.62$ eb, exceeds significantly the experimental "band 3" value of 1.98 (-0.5, $+1.25$) eb, what makes the assignment less certain.

Another feature that is apparent in the TRS calculations regards evolution of the deepest minimum at high angular velocity: when ω reaches a value of 0.9, the absolute minimum moves from non-collective oblate to another prolate-deformed collective structure with $\beta \sim 0.25$ and $\gamma \sim 20$. The excitation energy is in the range of 6905 keV to 13284 keV. This sequence of collective prolate-deformed states, with spins from $33/2^+$ to $45/2^+$, reproduces quite well not only the experimental "band 3" energies, but also the transition quadrupole moment associated with the calculated sequence. $Q_{\rm t} \sim 1.5$ eb, agrees with experiment (although, one should be aware of the prolate shape approximation made for the experimental $Q_{\rm t}$ extraction).

In conclusion, excited states lifetimes in the femtosecond range were assessed by measuring γ-recoil coincidences with the GASP germanium array and the Recoil Filter Detector. Analysis of the 1529 keV γ-line shape allowed to extract the lifetime of 72 (-45, $+55$) fs for the $I^\pi = 33/2^+$ state at 7897 keV and the resulting transition quadrupole moment is $Q_{\rm t}(K = 3/2) = 1.98\,(-0.5, +1.25)$ eb; it also provided the lower limit 1.1 eb for $Q_{\rm t}$ of the $37/2^+$ state. TRS calculations predict in ^{69}As two positive parity collective structures which might be associated with the experimental "band 3". Our result regarding transition quadrupole moment allowed to constrain the assignment: the "band 3" seems to be associated with the yrast prolate-deformed structure with rather moderate deformation $\beta \sim 0.25$.

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REFERENCES

[1] W. Męczyński *et al.*, *Nucl. Instrum. Methods* **A580**, 1310 (2007).

[2] I. Stefanescu *et al.*, *Phys. Rev.* **C70**, 044304 (2004).

[3] H. Morinaga, T. Yamazaki, *In-beam Gamma-ray Spectroscopy*, North-Holland, Amsterdam 1976.

[4] F.R. Xu, W. Satuła, R. Wyss, *Nucl. Phys.* **A669**, 119 (2000).