The structure of the deformed nucleus $^{103}_{42}$Mo$_{61}$

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Abstract. The lifetimes of the three lowest excited members of the rotational ground-state band of $^{103}$Mo at 102.6, 241.1 and 433.2 keV as well as of the levels at 353.8 and 456.1 keV have been determined through a measurement of the delayed coincidences between $\beta$ particles from the decay of the parent $^{103}$Nb and the $\gamma$ rays which depopulate the levels. A plastic and a BaF$_2$ detector have been used for the $\beta$ and $\gamma$ rays, respectively, in these experiments at the fission product separator JOSEF. The results for all three band members evince that this nucleus has a sizeable deformation, with a value of $\beta_q=0.34(1)$. This value is larger than that of the neighbouring even-even Mo isotopes which indicates an odd-even effect. On the other hand it confirms the observation that the Mo nuclei are in general less strongly deformed than their Sr and Zr isotones. Particle-rotor model calculations with the Nilsson parameters $\kappa=0.084$, $\mu=0.28$ provide a good description of the ground-state band and of a side band based on the 346.5 keV level, including the new lifetimes. This substantiates the Nilsson orbital assignments of $[411]3/2^+$ and $[532]5/2^-$ for these two bands, respectively, where the sideband is strongly affected by a $[541]3/2^-$ admixture. There is evidence for an additional band based on the 641.1 keV level for which the assignment $[422]3/2^+$ is proposed.

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1. Introduction

The nucleus $^{103}$Mo is a member of the region of deformed neutron-rich isotopes at $A \sim 100$. A rotational ground-state band (g.s. band) $^1[1, 2]$ has been identified, and the deformation of this nucleus has been determined $^3$ to $\beta_q=0.3(1)$ from the lifetime of the first excited state at 102.6 keV. These findings for $^{103}$Mo are in accordance with the general observation that ground-state deformation sets in at $N=60$ in this nuclear region and that $\beta_q$ reaches values of 0.3–0.4. It should be noted that the isotope $^{101}$Mo with 59 neutrons seems still to be $^4$ spherical.

There is a Z dependence of the strength of the deformation in the $A \sim 100$ region: the values of $\beta_q$ $^5$ of $^{103}$Mo and $^{104}$Mo amount to 0.28(1) and 0.33(1), respectively, whereas the corresponding isotones $^{98}$Sr, $^{100}$Zr $^6$ and $^{100}$Sr $^7$, $^{102}$Zr $^8$ have larger values, namely $\beta_q=0.37(1)$, 0.34(1) and 0.38(1), 0.38(2). This Z dependence may be caused by the pattern of the shell model orbitals around the doubly submagic $^{96}$Zr and differences in the deformation-driving proton-neutron interactions. In fact, the properties of the even-even isotopes both of Mo and of Sr, Zr have been accounted for in the $N_p$, $N_n$ scheme $^9$, however, only when different magic numbers were used for $N \leq 59$ and $N > 60$. It is of interest to see whether this Z dependence of the deformation of the even-even isotopes is also present in the odd-mass nuclei or whether it is overcome through an increase of the deformation in the odd Mo isotopes by the effect of the unpaired neutron.

The odd-mass nuclei in the $A \sim 100$ region of deformation provide an attractive testing ground for models of rotational nuclei like the particle-rotor model which are routinely used for the classical regions of deformation. For a successful application of such models at $A \sim 100$ the values of the model parameters, in particular of the Nilsson parameters $\kappa$ and $\mu$ $^10$, have to be known. A difficulty for the determination of these model parameters is the fact that the available experimental information for a comparison with calculations is rather restricted. This is so since the $A \sim 100$ nuclei lie far from stability and can only be produced in nuclear fission. Because of the general problems in studying these short-lived nuclei, the precise knowledge about electromagnetic transition probabilities is especially valuable for the test of model calculations.

Therefore and in order to check how the deformation of $^{103}$Mo compares with that of the even-even neighbours, a new measurement of level lifetimes has been performed at the fission-product separator JOSEF $^11$. A technique to measure lifetimes in the ps range using the fast timing properties of BaF$_2$ crystals and plastic scintillators,
which has been introduced recently [12, 13] into β decay studies, has been applied. It is expected to give much higher precision for the half-life of the 102.6 keV state in 103Mo than the previous determination [3] with Ge detectors which resulted in $t_{1/2}(102.6 \text{ keV}) = 0.45(15) \text{ ns}$. A further goal of the new experiment was the determination of the lifetimes of other levels in 103Mo. If the interpretation [1, 2] of the lowest levels of this nucleus as a rotational band based on the [411] $3/2^+$ Nilsson configuration is correct, then the half-life of the second excited state of the g.s. band at 241.1 keV can be extrapolated from that of the 102.6 keV level to about 100 ps and that of the next higher level at 433.2 keV to about 25 ps. Such values are accessible with the new technique. A confirmation of these predictions would provide compelling evidence for the above interpretation. Moreover, any additional information on lifetimes of low lying levels will help to determine the values of the Nilsson parameters for the $A \sim 100$ region of deformation.

2. Experimental setup and data analysis

The new β-γ-γ triple coincidence technique consists of a measurement of the time interval between the β-decay of the parent and the γ transition which depopulates the level of interest, e.g. the first excited member of the g.s. band. A plastic scintillator and a BaF$_2$ crystal are used as β detector and γ detector, respectively. The experimental setup at JOSEF has been described in [5, 6, 14]. The plastic detector consisted of a sheet of 4 mm thickness and 3 cm diameter of NE111A, and the BaF$_2$ crystal had the shape of a truncated cone of 3 cm and 2 cm base and top diameter, respectively. A time resolution of 150 ps was obtained at $E_\gamma \approx 1 \text{ MeV}$ for the plastic-BaF$_2$ coincidence with the use of dynode timing.

The lifetime of the first excited state in 103Mo was measured via the delay between the β particles from the decay of 102Nb and the γ rays of 102.6 keV, see Fig. 1. Since the decay scheme of 103Nb is complex and since the beam of JOSEF contained several fission products, the β-gated BaF$_2$ spectrum did not show individual lines. Therefore, a Ge detector was operated in coincidence with the plastic and BaF$_2$ scintillators [12–14]. Only if a gate was set on an appropriately chosen γ ray in the Ge spectrum which is in coincidence with the γ ray of interest, the β- and γ-gated BaF$_2$ spectrum became pure enough to determine the β-γ-time distribution for an individual γ transition. In the case of the first excited state this Ge gate has been set on the 538.5 keV transition, see insert in Fig. 1. Compton background has been subtracted for both the Ge and the BaF$_2$ spectra.

From the slope of the time distribution in Fig. 1a, we have obtained a value of 440(20) ps for the half-life of the 102.6 keV level. The uncertainty of 20 ps takes into consideration the statistical contribution as well as an estimated systematic uncertainty, which resulted from the fitting procedure. A second independent measurement has been performed which led to a value of $t_{1/2}(102.6 \text{ keV}) = 430(20) \text{ ps}$. The average of $t_{1/2}(102.6 \text{ keV}) = 435(14) \text{ ps}$ is used in the following. This result agrees well with the published value [3] of 0.45(15) ns, but is an order of magnitude more precise.

The β-γ-t distribution for the 102.6 keV–251.2 keV cascade (here and in the following the γ ray mentioned first and second in each cascade has been detected with the BaF$_2$ and Ge detector, respectively) contains two components, see Fig. 1b. The lifetime which corresponds to the observed slope is in the ns range and is, thus, longer than $t_{1/2}(102.6 \text{ keV})$. This lifetime can, in principle, correspond to any level between the one which is fed in β decay and the 102.6 keV state, or even represent the sum of several lifetimes. But since the 353.8 keV level is strongly fed