RECENT STUDIES OF ODD-A, NEUTRON-RICH Pr ISOTOPES*

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Delayed conversion-electron and γ-ray spectroscopy of $A = 151$ nuclei has been performed at the Lohengrin mass spectrometer of the ILL Grenoble. A previously reported 35.1-keV isomer of ^{151}Pr has been determined to decay by an $E1$ transition and its half-life of 50(8) μs measured for the first time. These data has been complemented by high-fold γ-ray coincidence data collected with the EUROGAM-II and GAMMASPHERE arrays of anti-Compton spectrometers to search for medium-spin excitations in these nuclei. The long half life of this isomer and the lack of intraband $E1$ transitions show an absence of strong octupole correlations in the observed states of ^{151}Pr.

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1. Introduction

Strong octupole correlations have been observed in lanthanide nuclei around the neutron number $N = 88$. These modes are generated by Nilsson orbitals originating from the spherical $\pi h_{11/2} \leftrightarrow d_{5/2}$ and $\nu i_{13/2} \leftrightarrow f_{7/2}$ states.

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In odd-A nuclei, one signature of such correlations is almost-degenerate parity-doublet bands, connected by fast $E1$ decays. The determination of $E1$ transition rates is, therefore, an indirect method of probing octupole correlations. In general, $E1$ transition rates for heavy nuclei are in the range of 10^{-4} to 10^{-7} Weisskopf Units (W.U.). For nuclei exhibiting octupole deformation this can increase to 10^{-2} to 10^{-3} W.U. [1]. Despite numerous studies in this region, our knowledge on this subject is far from complete. For example, it is not yet clear how the octupole couplings are affected by the strong static quadrupole deformation, which suddenly appears beyond neutron number $N = 90$, and how far the softness to octupole modes extends. It is of interest to study the Pr isotopes, especially at higher neutron number, to follow the evolution of octupole correlations with increasing neutron number and quadrupole deformation. In a recent paper [2], an extensive level scheme, containing a parity-doublet band, has been reported for ^{151}Pr, which is in contradiction to recent data on ^{149}Pr, where no evidence of octupole correlations was observed. Furthermore, several microscopic ground-state deformation calculations predict no static octupole deformation [3, 4] in the even–even neighbors of this nucleus. The neutron-rich Pr nuclei have been studied using triple-γ coincidences, obtained when ^{248}Cm and ^{252}Cf sources were placed inside the EUROGAM-II and GAMMASPHERE detector arrays, respectively. The decay of a 35.1-keV isomeric state, previously reported for ^{151}Pr [8], has been studied by γ-ray and conversion-electron spectroscopy to give a more complete picture of this nucleus. The experimental results have been compared to quasi-particle-rotor model (QPRM) calculations using a reflection-symmetric core.

2. Experimental procedure

Delayed γ rays and conversion electrons from mass 151 fission fragments were observed using the Lohengrin mass spectrometer at the high-flux reactor of the Institut Laue–Langevin, Grenoble. The fission fragments were produced by thermal neutron induced fission of an $0.870\,\mathrm{mg/cm^2}$, $7\times0.5\,\mathrm{cm}$ ^{241}Am target which mostly fissions following two neutron captures. The target was subjected to a neutron flux of $5\times10^{14}\,n\,\mathrm{s^{-1}\,cm^{-2}}$. The Lohengrin mass spectrometer was used to select nuclei recoiling from the target, according to their A/q and kinetic E/q ratios. The flight time of $A = 151$ nuclei through the spectrometer was around $2.6\,\mu$s. The fission fragments were detected in an ionization chamber divided into two regions separated by a Frisch grid and stopped in the mylar foil placed at the end of the chamber. Two liquid–nitrogen cooled Si(Li) conversion-electron detectors, $3\times2\,\mathrm{cm}^2$ each, $\sim15\%$ efficient, were placed a few mm behind the mylar foil. Conversion electrons down to 10 keV were observed. Delayed γ rays were detected by two Clover Ge detectors placed perpendicularly to the beam. The absolute efficiency for γ-ray detection was 21% for photons of 100 keV and 3% for the ones of 1 MeV, the energy resolution was 2.2 keV at 1.3 MeV.

Any γ rays or electrons arriving up to 40 μs after the arrival of an ion were recorded for off-line analysis. More details concerning the experimental setup are given in [5, 6, 7].

3. Experimental results

Fig. 1 shows background-subtracted delayed, 35.1(2)-keV γ rays measured in the Ge detectors up to 15 μs after the arrival of an $A = 151$ ion, in agreement with the results reported in [8], where this isomeric state was assigned to an excited state of ^{151}Pr, based on the β-decay half life of its parent. The γ-ray background was obtained from ion-γ events recorded in a 15-μs period towards the end of the ion-γ coincidence window.

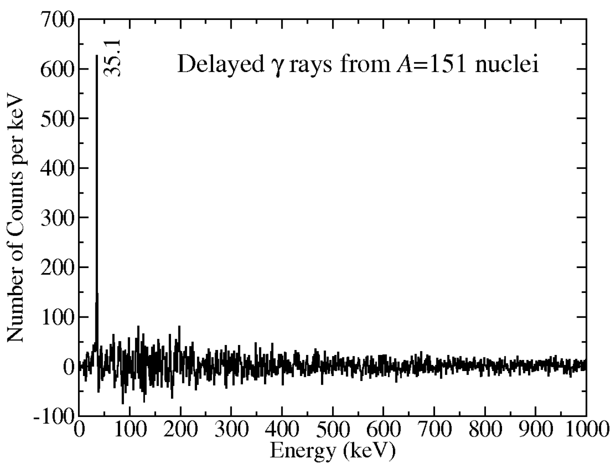

Fig. 1. Delayed γ rays, detected by the Ge detectors at Lohengrin up to 15 μs after the arrival of an $A = 151$ ion.

Background-subtracted delayed conversion-electrons and γ rays measured in the Si(Li) detectors up to 15 μs after the arrival of an $A = 151$ ion, are shown in Fig. 2. A comparison of electron and γ-ray intensities in Fig. 2 gives conversion coefficients of $\alpha_{\mathrm{L}} = 0.6(2)$ and $\alpha_{\mathrm{M}} = 0.11(4)$ for the 35.1-keV transition. Such conversion coefficients are compatible only with an $E1$ transition.

The halflife of this new isomer in the ^{151}Pr has been determined to be 50(8) μs, as shown in Fig. 3.

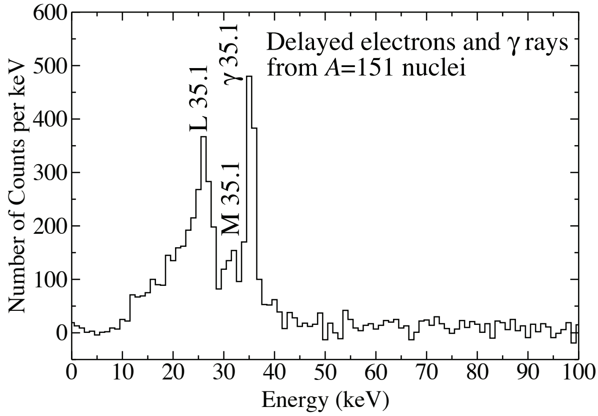

Fig. 2. Conversion electron spectrum of the $A = 151$ mass chain in delayed coincidence with the fission fragments up to 15 μs after the arrival of an $A = 151$ ion.

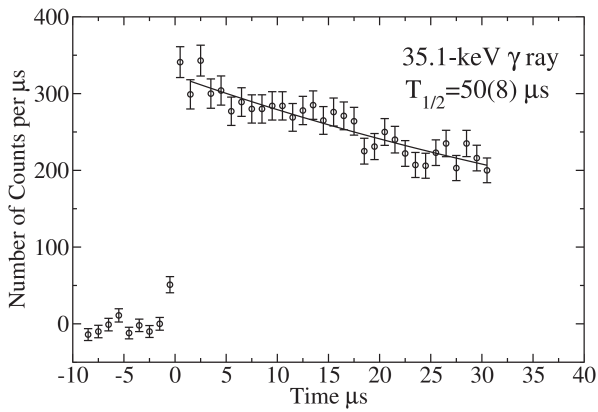

Fig. 3. Time spectrum of the 35.1 keV γ rays in coincidence with $A = 151$ ions.

A new band, which has been proposed to contain stretched $E2$ transitions has been observed in the spontaneous-fission data. More details on these results are presented in [9]. Combing the results of the delayed γ-ray and electron measurement with the results obtained from the prompt-γ results allowed the level scheme presented in Fig. 4 to be obtained. The experimental level scheme is compared to QPRM calculations, of the same type as those used in [5]. More details on the calculations can also be found in [9]. A comparison with the calculations allows the bandhead to be determined to have a dominant $3/2^-[541]$ configuration. The lowest-lying postive-parity quasi-particle states have dominant $1/2^+[420]$ and $3/2^+[422]$ configurations. Without more experimental information, or more detailed calculations we are unable to determine which of these is the isomeric state.

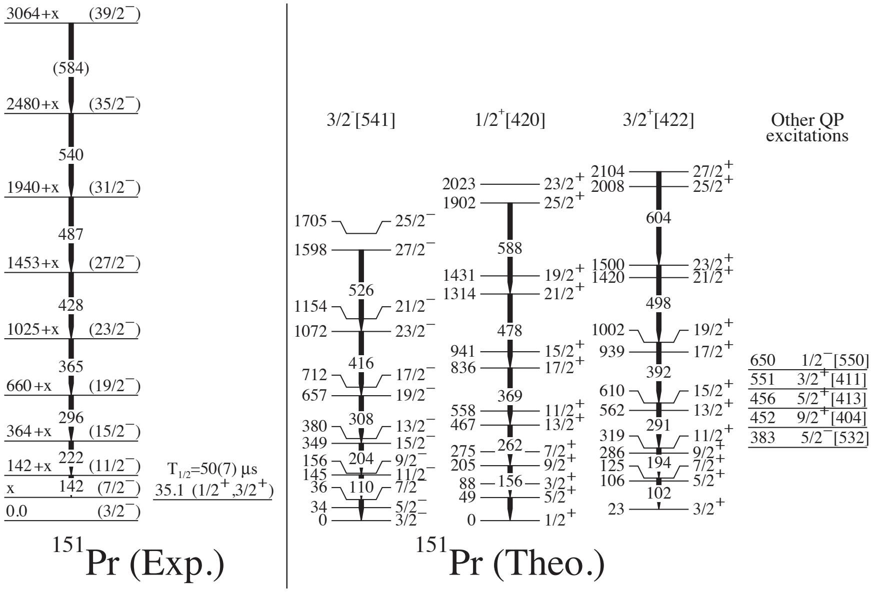

Fig. 4. Comparison of experimentally measured and calculated partial decay scheme of ^{151}Pr.

The levels of the bands of ^{151}Pr do not decay by any observed interband $E1$ decays and the 35.1-keV isomeric state of this nucleus has a low $B(E1)$ value of $6.3(10) \times 10^{-8}$ W.U. Therefore, we can conclude that there is no evidence of any octupole collectivity in the states studied of ^{151}Pr. The results of the present work on ^{151,153}Pr are in agreement with our recent study of the deformed $N = 93$, 94 Nd and Sm isotones [1], where it was concluded that the isomeric one- or two-quasiparticle excitations are mostly responsible for the dipole moments of these states. Octupole correlations seem to be absent from these isomeric states. The absence of octupole correlations here can be related to increasing quadrupole deformation beyond $N = 90$. Quadrupole deformation is known to break the $(2j+1)$ degeneracy of spherical shell-model states and these states generally fan out in energy, with the energy splitting increasing with the quadrupole deformation. The unique-parity orbitals follow undeviated trajectories, in a given harmonic oscillator shell, whereas natural-parity orbitals can be involved in orbital crossings which can further separate states with the same spherical shell-model state origin. Simplistically, increasing quadrupole deformation should correspond to a general decrease in the strength of octupole collectivity. The situation is not so simple, however, as hexadecapole deformation is also present in the neutron-rich $A = 150$ region. This deformation multipole has the effect of quenching the energy splitting of the unique-parity Nilsson orbitals, as well as mixing $\Delta N = 2$ orbitals.

4. Conclusions

A delayed 35.1-keV transition in ^{151}Pr has been determined to be $E1$ in multipolarity from conversion-electron measurements. A half life of 50(8) μs was determined for this transition. Based on GAMMASPHERE and EUROGAM-II data a new rotational band has been assigned to this nucleus. The decay sequence of these bands is well reproduced using a QPRM calculations and allows the ground-state band to be assigned a $3/2^-[541]$ configuration and the isomeric state either a $1/2^+[420]$ or a $3/2^+[422]$ configuration. The slow $E1$ isomeric transition and the non-observation of interband $E1$ transitions for ^{151}Pr show an absence of octupole correlations for these states. These results are in agreement with our recent measurements on Nd and Sm nuclei with $N > 92$, where no evidence of octupole correlations was observed in the states [5]. An explanation why strong octupole correlations are not present can be put forward in terms of an absence of octupole-generating orbits close to the Fermi surface in these nuclei, due to increasing quadrupole deformation.

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