Electromagnetic transitions and α decay of the ^{223}Pa nucleus

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Actinides with $N\sim 132$ present the best explored region of pear shape nuclei. Still almost no spectroscopic information is available for the heaviest elements, $Z=91-98$, which are predicted to be octupole instable. The lack of data for the latter nuclei results from the high fission probability encountered in the heavy-ion reactions used to populate them. In order to overcome this handicap, an α-decay tagging technique was used to identify γ rays in ^{223}Pa produced through the ^{208}Pb(^{19}F,4n) reaction. A new value of 4.9(4) ms for the half-life of ^{223}Pa was obtained as a by-product. [S0556-2813(99)00711-6]

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It has been recognized for some time that in a certain region of the nuclear chart nuclei are subject to deformations ($\lambda=3$ or higher odd-λ deformations) which do not conserve the intrinsic parity. Signatures of reflection-asymmetric shapes are the occurence of alternating parity bands, parity doublets, and $E1$ transitions which are usually enhanced roughly by two orders of magnitude as compared to $E1$ transitions in reflection-symmetric nuclei.

Actinides nuclei with $N\sim 132$ form the first and best explored region of pear shape nuclei. Theoretically [1] the candidates for octupole deformation are in an area delimited by proton numbers $Z=86$ and 98 and neutron numbers $N=130$ and 140. Experimentally, whereas the onset of stable octupole correlation effects has been the subject of several studies [2–4] and a large amount of work has been devoted to the Rn, Ra, Ac, Th nuclei [5,6], no spectroscopic investigation has been made so far for $Z\geqslant 92$ nuclei with the exception of a recent study of ^{226}U which suggests an octupole nature of this nucleus [7]. The lack of high-spin data for such nuclei arises from the high fission probability encountered in heavy-ion-induced reactions used to populate them.

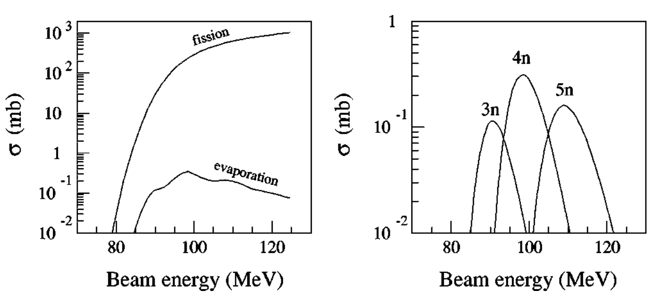

FIG. 1. Cross sections in the ^{208}Pb+^{19}F reaction. The fusion-fission cross section is compared to the fusion-evaporation cross sections for the *xn* and *pxn* exit channels on the left-hand side and cross sections for neutron evaporation are shown on the right-hand side.

As far as experimental evidence is concerned, the situation in the Pa isotopes ($Z=91$) is slightly different. ^{229}Pa was long considered as the archetype of ground-state octupole deformation [8], but the results of more recent investigations [9,10] conflict with the previous finding. The question of the presence of strong octupole correlations in ^{229}Pa is still being discussed [6,11,12]. For ^{231}Pa, which lies at the border of the accepted region for reflection asymmety, the level scheme [13] does not show any evidence for a stable octupole deformation, but suggests rather an octupole shape susceptibility of the nucleus. In order to check on the existence of reflection asymmetric shapes in the light Pa nuclei, a spectroscopic study of ^{223}Pa ($N=132$) was undertaken. Two reasons underline the choice of this nucleus. First, ^{223}Pa may be produced with a cross section large enough in view of modern γ-ray mulidetector arrays. Second this nucleus is predicted to be a good example of octupole instability [14].

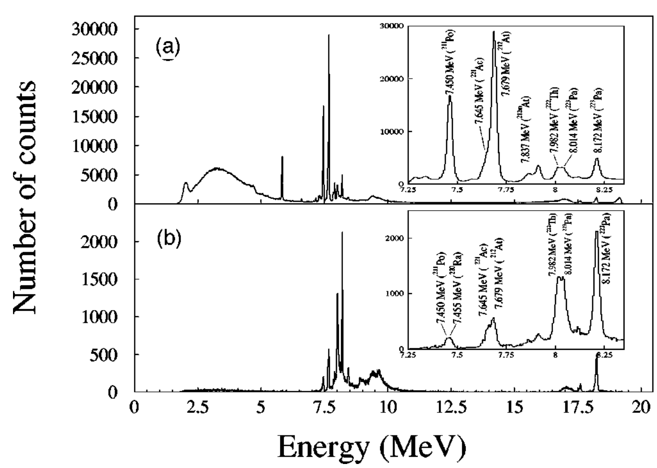

FIG. 2. Spectrum of all events registered with the Si-strip detector set in the focal plane of RITU (a) and spectrum of α particles occurring up to 20 ms after the arrival of recoiling ions (b). The α-decay region of interest is expanded in the inserts.

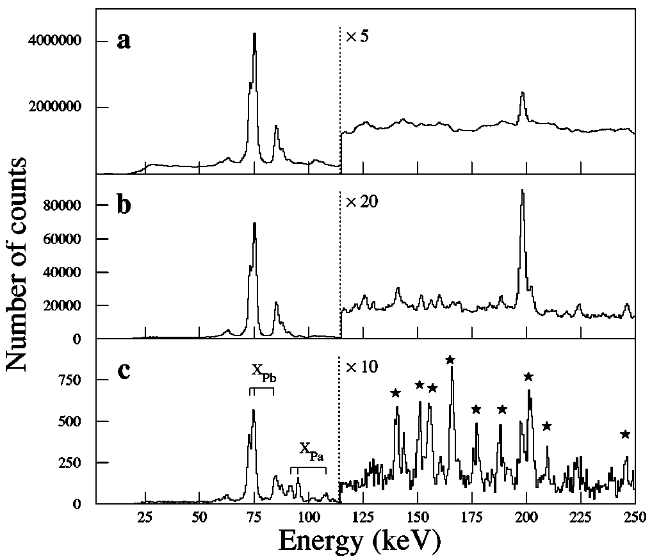

FIG. 3. Spectrum of the photons detected in JUROSPHERE (a), the photons detected in coincidence with an event in RITU (b) and photons in coincidence with both a recoiling ion and one of the two α-decay lines from ^{223}Pa (c). The peaks marked by stars are the strongest γ lines attributed to electromagnetic transitions in ^{223}Pa.

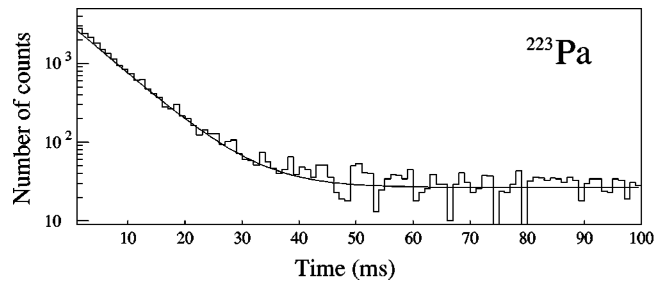

FIG. 4. Time spectrum of the α decay of ^{223}Pa. Events correspond to the 8.172 MeV α decay and yield a value of $T_{1/2}=(4.9\pm0.5)$ ms.

Calculations yield two close-lying band heads with $\Omega=5/2$ and 3/2, the quantum number Ω being the projection of the single-particle angular momentum onto the symmetry axis of the nucleus. Octupole barriers for these configurations are predicted to be among the largest ($\sim$ 1 MeV) in the odd-A actinides with $86\leqslant Z\leqslant 91$.

The ^{223}Pa nucleus was produced by the ^{208}Pb(^{19}F,4n) reaction with a 500 μg cm^{-2} ^{208}Pb target at the cyclotron of the University of Jyväskylä. Statistical calculations with the code HIVAP [15] show that 99 MeV is the optimal bombarding energy and that the evaporation process for the *xn* and *pxn* exit channels ($\sim$100 μb) is three orders of magnitude weaker than the fission cross section (see Fig. 1). In order to overcome this handicap, γ rays in ^{223}Pa were identified by using an α-decay tagging technique detailed below.

Prompt γ rays were collected by the JUROSPHERE array [16] consisting in the present experiment of 13 EUROGAM I [17] and 10 TESSA [18] Compton-suppressed germanium detectors. The RITU (Recoil Ion Transport Unit) device [19] separated magnetically the recoiling ions from the fission products and focalized them on a silicon detector set in the focal plane. The ions recoiled from the target to the silicon detector in a low pressure gas leading to an average charge state for the ions and increasing thereby the recoil detection efficiency. The silicon detector was composed of eight vertical strips, each of them being sensitive to the deposited energy, the position and the time of the ion arrival. The implantation of a recoil ion led to an (E_1, x_1, y_1, t_1) event. After implantation, the α decay of the nucleus gave an (E_2, x_1, y_2, t_2) event. The recoiling ions corresponding to ^{223}Pa were selected by the delay coincidence method: two events are selected, the first one corresponding to a recoiling ion, the second one to a subsequent α decay whose energy corresponds to one of the ^{223}Pa decay transitions within a time window equal to three times the half-life of the isotopes and with a $|y_2\text{-}y_1|$ value less than 1.2 mm. The events detected by RITU are shown in the upper part of Fig. 2 and the α particles in delayed coincidences with the recoiling ions in the lower part of the same figure. Figure 3 illustrates the selectivity of the α-decay tagging technique. It shows all the electromagnetic transitions detected by JUROSHERE (a), the ones in prompt coincidences with an event in RITU (b) and those in coincidence with both a recoiling ion and one of the two α-decay lines from ^{223}Pa (c).

γ transitions have been identified in ^{223}Pa. The corresponding lines are labeled by stars in Fig. 3(c) and their energies and intensities are given in Table I. The line at 197 keV is most probably a contaminant arising from the Coulomb excitation of ^{19}F. The statistics of γ-γ-RITU events was unfortunately insufficient to allow to build up a level scheme for ^{223}Pa.

The experiment yields also as a by-product a new value for the half-life of ^{223}Pa. The average value obtained from

TABLE I. Gamma rays in ^{223}Pa.

γ energies	Relative intensities	γ energies	Relative intensities
140.4	66(7)	187.8	46(7)
150.8	60(7)	201.7	89(6)
155.3	96(7)	208.9	33(5)
165.8	100(7)	245.3	24(4)
177.1	49(6)		

TABLE II. Half-life measurements.

Alpha emitter	Half-lives (ms) Present work	Half-lives (ms) Other works	References
^{212}At	306(15)	314(2)	[21]
^{212m}At	125(17)	119(3)	[21]
^{222}Th	4.2(5)	4(1)	[22]
		2.8(3)	[23]
^{223}Pa	4.9(4)	6.5(10)	[20]

both the 8014(5) and 8172(5) keV α decays is $T_{1/2}=(4.9\pm0.4)$ ms (see Fig. 4). This value differs from an earlier result, $T_{1/2}=(6.5\pm1.0)$ ms [20]. Confidence in our new value ensues from the agreement between half-life values obtained for other nuclei and previous results as shown in Table II. Moreover, the relative intensities for the two α decays, $(33\pm2)\%$ for the 8.014 MeV α line and $(67\pm2)\%$ for the 8.172 MeV α line differ also from the previous values, $(55\pm5)\%$ and $(45\pm5)\%$, respectively.

A nucleus with a high atomic number ($Z=91$) has been studied in a region where strong octupole correlations are expected. The nucleus ^{223}Pa was produced with a weak cross section through a fusion-evaporation reaction and the characteristics of the α decay of the evaporation residue has been used to select the γ rays corresponding to its electromagnetic transitions. Such transitions have been observed, but the experiment could not lead to the construction of a level scheme. This nucleus could be studied in more detail with a more efficient γ-multidetector array coupled to a device allowing the separation of the evaporation residues from the high background arising mainly from fission.

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