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Transition strengths and signature inversion in odd-odd ^{74}Br

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Lifetimes of states in ^{74}Br produced by the ^{60}Ni(^{16}O,np) reaction at 50 MeV have been measured by using the recoil-distance method. From these experiments several reduced transition strengths for the low energy states have also been determined. The results show that the alternating pattern in the $B(M1)$ strengths of the yrast positive parity band is preserved across the signature inversion region. [S0556-2813(99)04004-2]

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I. INTRODUCTION

The structure of nuclei in the $A\approx 80$ mass region presents a rich variety of different phenomena. Large deformation, shape-coexistence effect, and sudden shape change due to variation of a few nucleons are well established aspects from the study of nuclei in this mass zone. Among the features exhibited by the rotational spectra of nuclei in this mass region the signature inversion deserves a special attention. This kind of perturbation of the rotational bands has been found and investigated for the first time in the structure of ^{76}Br [1,2], where an anomaly was observed in the level staggering of the energy difference

$$\Theta_I = \frac{E(I)-E(I-1)}{2I}, \tag{1.1}$$

where $E(I)$ is the energy of the state of spin I. This effect was interpreted in terms of a two-quasiparticle-plus-rotor model as a change of phase of the level staggering above the 9^+ state, whose spin value $I=9\hbar$ equals that corresponding to the maximum alignment of the odd proton and neutron (being both of $g_{9/2}$ parentage). Below this state both the rotation and the realignment of the intrinsic spin contribute to the total angular momentum. Above this state, the increase in angular momentum comes mainly from rotation.

Currently the signature is considered as a quantum number associated with a 180° rotation of a deformed nucleus around a principal axis. A rotational band whose bandhead is J (the total angular momentum of the intrinsic quasiparticles) consists of levels $I=J,\ J+1,\ J+2,\ \ldots$, and splits into two different bands with $I=J$ (mod 2) and $I=J+1$ (mod 2) according to the signature. The action of the Coriolis force in the rotating systems in general is to decrease the energy of the $I=J$ (mod 2) states with respect to the others, and for this reason the $I=J$ receives the name of favored band and the $I=J+1$ the unfavored partner. The energy shift between both bands at a given rotational frequency $\hbar\omega$ is called the signature splitting and is characterized by a level staggering, which is observed by looking at the energy difference calculated according to Eq. (1.1). By following the evolution of this couple of bands as a function of spin or angular frequency one may observe that sometimes the favored and unfavored bands cross each other, producing the so-called signature inversion phenomenon.

In odd-A nuclei this effect is present after the band crossing takes effect and its relation to the appearance of triaxial shapes is discussed in the literature [3–5]. On the other hand, in the doubly-odd nuclei the signature inversion takes place at relatively low angular momentum, before the band crossing takes effect, and it is known as anomalous signature inversion [6].

Several attempts to interpret the low-spin signature inversion in odd-odd nuclei have been undertaken by several authors. They analyze several effects that might produce the band crossing with different signature such as: (i) the triaxial nuclear shape [7]; (ii) different dynamical symmetries of the interacting boson-fermion model [8]; and (iii) the residual proton-neutron interaction [9]. In spite of these efforts, the essential mechanism for the signature inversion is still an open question and for this reason it attracted the attention of several groups.

As a result of this interest, at present it is known that besides the $A\simeq 80$ nuclei many others, in different mass regions, also exhibit this particular behavior. For instance, we can mention the systematic studies for $A=120$–140 [10] and $A=160$–170 [11]. However, such studies are mostly restricted to determinations of decay schemes, which for the first time allowed to follow systematically the evolution of this effect as a function of angular frequency, mass region, etc.

Certainly, the information about electromagnetic properties is very useful to elucidate this phenomenon. For instance, the knowledge of the ratio $B(M1)/B(E2)$ of electromagnetic transition probabilities between members of bands with different signature is of interest. In particular, it becomes even more important to measure the individual values of $B(M1)$ of interband transitions and of $B(E2)$ of innerband transitions that some theoretical works predicted to be sensitive to the interpretation of this effect.

In the present paper we shall focus our attention on the odd-odd ^{74}Br nuclide. The level scheme of this nucleus has been determined by García Bermúdez *et al.* [2]. These data

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exhibited a change of phase in the level staggering above the $I^{\pi}=9^{(+)}$ state, characteristic of the signature inversion phenomenon. Subsequent studies performed by Neumann *et al.* [12] and Holcomb *et al.* [13] yielded further information about the structure of this nucleus up to high-spin states and also provided experimental values of several lifetimes.

It is the aim of this work to improve the knowledge of the odd-odd ^{74}Br nucleus by measuring electromagnetic transition probabilities in the region where the inversion of signature takes place. Therefore, we measured the lifetimes of γ transitions deexciting levels of the positive-parity band in the proximity of the $I^{\pi}=9^{(+)}$ state.

II. EXPERIMENTAL TECHNIQUES

The energies of the γ rays of interest lie below 400 keV, and lifetimes of about one picosecond or bigger are expected. Therefore the recoil-distance method (RDM) was used.

High-spin states in ^{74}Br were populated by the reaction ^{60}Ni(^{16}O,pn) at 50 MeV energy produced at the Buenos Aires TANDAR accelerator. The lifetimes were measured by RDM using a plunger device which was described elsewhere [14]. The target to stopper distance was varied by means of a micrometer screw and was monitored at small values (<50 μm) by measuring the electric capacity. The distance was determined by using an inductive gauge [15] covering a range of linear displacement of 0–1000 μm with an overall accuracy of about 1 μm. For larger distances, a standard micrometer screw was used. The target was a self-supporting stretched foil enriched to 99.7% in ^{60}Ni with a thickness of 1 mg/cm^2, and the stopper consisted of a stretched 10 mg/cm^2 Au foil.

Two HPGe detectors placed at 0° and 150° relative to the beam direction were used to measure the γ ray singles spectra for different target-stopper distances. A recoil velocity value $v/c=1.3\%$ was obtained from the energy separation between the shifted and unshifted peaks produced by strong transitions. An experiment covering the distance range of 1–15000 μm and measuring 28 different positions at different intervals was performed.

III. LIFETIME MEASUREMENT

In what follows, a discussion of the lifetime measurements of positive- and negative-parity bands in ^{74}Br is presented. The analysis proceeds from the highest-energy level towards the ground state. At each level the contributions of all previous γ rays, as well as side feedings, have been taken into account. The side-feeding time was estimated to be of the order of 0.5 ps. This result is consistent with determinations reported by Heese *et al.* [16].

The analysis of the positive-parity band starts with the study of the $9^{(+)}$ state (see Fig. 1), which decays by the 348 and 504 keV transitions. The information about the feeding transitions to this level, which allows us to determine the lifetime of the 348 keV γ ray, was obtained from the previous work of Holcomb *et al.* [13]. In turn, the study of the negative-parity band was started at the (7^-) state. In both these bands, we measured all the transitions down the band which present a clear stopped peak at least in one of the detectors and were not perturbed with any contaminating peak. The singles spectra which display the evolution of the γ-ray intensities, as a function of different target-stopper distances, are shown in Fig. 2. Several decay curves of the analyzed transitions are shown in Fig. 3. It is worth mention-

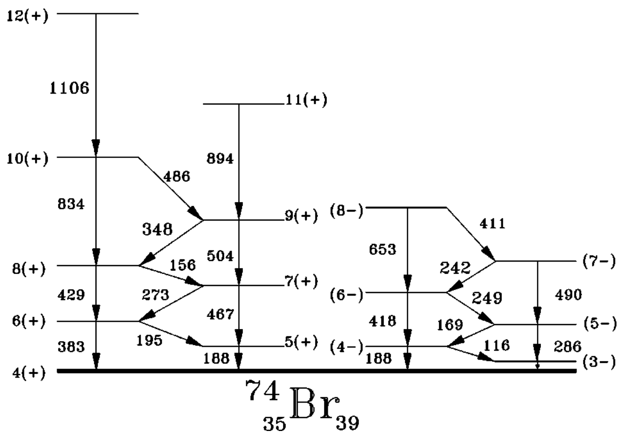

FIG. 1. A partial decay scheme of ^{74}Br.

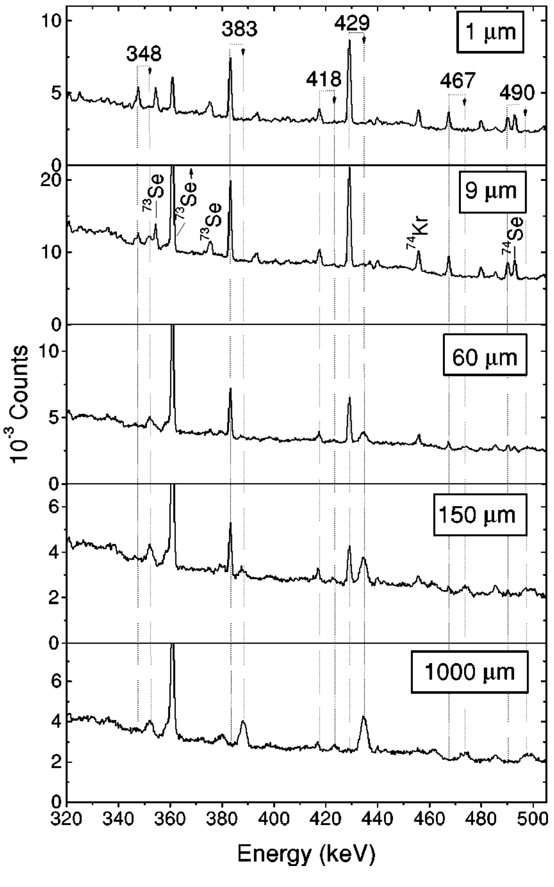

FIG. 2. The evolution of the γ-ray intensities, as a function of the indicated target-stopper distances, is shown for the 320–500 keV energy region. The spectrum labeled by 1 μm shows with dotted lines the unshifted and shifted γ-ray energy for most of the transitions in ^{74}Br. In turn in the spectrum labeled by 9 μm transitions from several other reaction channels are indicated. The arrow shows the γ ray originating from the decay of the nucleus indicated.

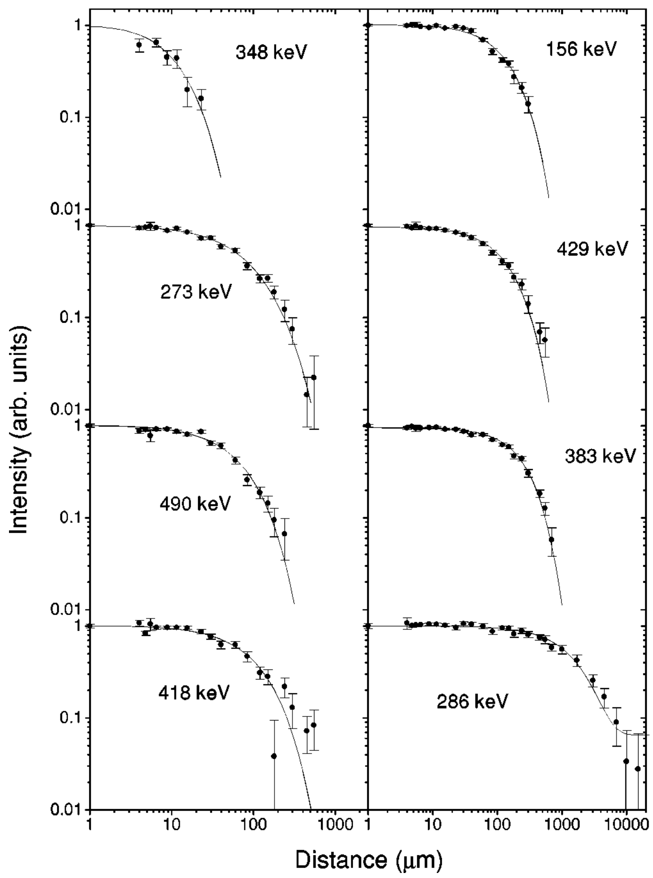

FIG. 3. Decay curves of the indicated γ rays in ^{74}Br. The best-fit curves to the data points are also shown.

ing that the errors of the lifetimes reported in this paper were estimated by taking into account not only the statistical error for each particular γ ray but also by including the contribution of the errors in the lifetimes and intensities of the γ ray feeding the levels of interest.

The ten lifetimes measured in the present work are listed in Table I, where they are compared with previously accepted values reported in Ref. [13]. These accepted values were obtained from the measurement performed in the latter work and from the study of Neumann *et al.* [12] which has been only published in a conference proceedings. As can be observed in Table I the present and previous results are rather similar, therefore, we calculated the average values quoted in the last column of this table.

TABLE I. Measured lifetimes compared with previous values. The error in the last digit is given in parentheses.

$I_i^\pi \rightarrow I_f^\pi$	E_γ [keV]	τ [ps]	τ^a [ps]	τ^b [ps]	τ^c [ps]
$9^{(+)}\rightarrow 8^{(+)}$	348	2.4 (5)			2.4 (5)
$8^{(+)}\rightarrow 7^{(+)}$	156	38 (7)	34 (3)	23 (7)	32 (3)
$8^{(+)}\rightarrow 6^{(+)}$	429	33 (3)			
$7^{(+)}\rightarrow 6^{(+)}$	273	16 (3)	14 (3)	13 (2)	14 (2)
$7^{(+)}\rightarrow 5^{(+)}$	467	11 (3)			
$6^{(+)}\rightarrow 4^{(+)}$	383	51 (5)		68 (8)	56 (4)
$(7^-)\rightarrow(6^-)$	242	17 (2)	18 (1)	17 (1)	18 (1)
$(7^-)\rightarrow(5^-)$	490	18 (1)			
$(6^-)\rightarrow(4^-)$	418	27 (4)			27 (4)
$(5^-)\rightarrow(3^-)$	286	400 (50)			400 (50)

[a] Average of the level lifetimes.

[b] Values taken from Ref. [13].

[c] Average values.

The measured branching ratios are given in Table II, together with results of previous works [13,17], and average values are reported in column five. The averages of lifetimes and branching ratios were used to determine the $E2$ transition strengths $B(E2)$ for the $\Delta I=2$ decays. The transition quadrupole moments Q_t were calculated from the $B(E2)$ strengths given in column six by using the rotational model formula and, subsequently, by assuming axial symmetry the corresponding β_2 values were inferred.

The moments Q_t of the $I^\pi=9^{(+)}$, (6^-), and (5^-) states are reported for the first time. As it has been already pointed out in Ref. [13], Table II shows that the deformation parameter β_2 for the positive-parity band fluctuates around 0.35–0.41, indicating a very strong deformation. A similar strong deformation is also suggested for the negative-parity band by the corresponding β_2 values, which lie in the range 0.29–0.41.

Table III reports the measured $B(M1)$ values for the positive- and negative-parity bands compared with previous results. The mixing ratio parameters necessary to calculate the transition strengths were assumed as in the work of Ref. [13]. In the latter work, the mixing ratio from the A_2 and A_4 values were obtained from a previous work [2] and for those transitions whose angular distributions are not known a value of $\delta=0.2$ was assumed. The $B(M1)$ strength values reported in Table III for the $I^\pi=8^{(+)}$, $7^{(+)}$, and $6^{(+)}$ states are comparable with the previous values of Ref. [13], and those for the $I^\pi=9^{(+)}$, (7^-), (6^-), and (5^-) states were measured for the first time in the present work.

Figure 4 shows the $B(M1)$ strengths for $\Delta I=1$ transitions measured in the present work, up to the angular momentum of $9\hbar$. The strengths plotted for states above this level, namely the $I=10$, 11, and 12 which entail shorter lifetimes, were taken from the previous Doppler-shift attenuation experiment [13].

IV. DISCUSSION

Signature inversions in odd-odd nuclei have been found systematically in regions of mass number $A\simeq 80$, 130, and 160. Although several explanations have been proposed to interpret this phenomenon, it is still not well understood. Therefore, as emphasized in the Introduction, measurements of transition strengths become particularly important because the electric quadrupole moments are sensitive to the deformation, and the magnetic moments reflect the change in the intrinsic structure of the valence nucleons. This information could shed some light on the nature of the signature inversion phenomena.

In general the $B(M1)$ strengths are inferred from the measurement of the $B(M1)/B(E2)$ ratios because this only involves the measurement of the branching ratios. To extract the $B(M1)$ value it is assumed that the mixing ratio is small and that the $B(E2)$ value changes slowly within the rotational band. Then, the alternation of the $B(M1)/B(E2)$ ra-

TABLE II. Branching ratio $BR(\%)$, $B(E2)$ transition strength, quadrupole moment Q_t, and axial deformation β_2 for the $\Delta I=2$ transitions. The error in the last digit is given in parentheses.

I^π	$BR(\%)$ Present work	Ref. [13]	Ref. [17]	Average	$B(E2)$ $[e^2\,\mathrm{fm}^4]$	[W.u.]	Q_t [eb]	β_2 [a]
$9^{(+)}$	17 (4)		20 (2)	19 (2)	1988^{+520}_{-340}	108^{+30}_{-20}	3.1^{+4}_{-3}	0.41
$8^{(+)}$	71 (2)	82 (1)	74 (2)	79 (1)	1387^{+140}_{-120}	75^{+8}_{-6}	2.9(1)	0.38
$7^{(+)}$	32 (2)	33 (1)	32 (3)	33 (1)	866^{+140}_{-110}	47^{+8}_{-6}	2.7(2)	0.35
$6^{(+)}$	37 (2)	36 (1)	25 (2)	34 (1)	600^{+50}_{-40}	33^{+2}_{-3}	3.1(1)	0.40
(7^-)		57 (1)	53 (5)	57 (1)	915^{+50}_{-50}	50^{+2}_{-3}	2.2(1)	0.29
(6^-)		65 (2)[b]	59 (4)	64 (2)	1517^{+260}_{-200}	82^{+14}_{-10}	3.2^{+3}_{-2}	0.41
(5^-)	26 (4)	37 (2)[b]	34 (3)	35 (2)	380^{+50}_{-40}	21^{+2}_{-3}	2.1(1)	0.29

[a] Assuming axial symmetry.

[b] Estimated errors.

tios observed as a function of the spin is mostly attributed to an alternation of the $B(M1)$ strengths. The assumption of the constancy of $B(E2)$ is not always true and certainly a better way is to obtain the $B(M1)$ strength directly from the lifetime measurement.

The present experiment measured ten lifetimes and determined several reduced transition strengths. In particular, we measured the 348 keV transition that deexcites the $I^\pi=9^{(+)}$ state, which lies in the proximity of the signature inversion region. The $B(M1)$ strength reported in the present work for the 348 keV transition, 0.44(12), is consistent with the value 0.48(12) inferred by Holcomb *et al.* [13] by assuming that the quadrupole moments are constant above and below the $9^{(+)}$ state.

The present $B(M1)$ strength measurement, together with previous values reported in the mass 80 region, are shown in Fig. 4. The crossing between bands of different signature also occur at the angular momentum region of $I^\pi=9^+-10^+$, shown as dashed lines in Fig. 4, for the ^{82}Y [18] and ^{78}Rb [19] pair of nuclei. As is apparent from the figure the $B(M1)$ strength at spin below $9\hbar$ fluctuates around 0.1–0.2. Above the angular momentum of $9\hbar$, corresponding to the maximum alignment of the two odd particles in the $g_{9/2}$ shell, it is observed a sudden increase in the $B(M1)$ value of almost a factor of four. At about the same spin a similar behavior is also exhibited by the $B(E2)$ values, whose rates are enhanced by large factors above the single-particle estimates indicating the onset of a deformed rotational band.

TABLE III. $B(M1)$ transition strengths for $\Delta I=1$ transitions in ^{74}Br. The error in the last digit is given in parentheses.

$I_i^\pi \rightarrow I_f^\pi$	E_γ [keV]	$B(M1)[\mu_N^2]$ Present work	Ref. [13]
$9^{(+)}\rightarrow 8^{(+)}$	348	0.44 (12)	0.48 (12)[a]
$8^{(+)}\rightarrow 7^{(+)}$	156	0.10 (1)	0.12 (4)
$7^{(+)}\rightarrow 6^{(+)}$	273	0.13 (3)	0.14 (2)
$6^{(+)}\rightarrow 5^{(+)}$	195	0.086 (6)	0.07 (1)
$(7^-)\rightarrow(6^-)$	242	0.093 (6)	
$(6^-)\rightarrow(5^-)$	249	0.05 (1)	
$(5^-)\rightarrow(4^-)$	169	0.018 (3)	

[a] Assumed value, see text.

Above this region, as mentioned before, it is observed a considerable increase in the $B(M1)$ strength, but the fact that the $B(M1)$ value is large for transitions from odd spin compared with transitions that deexcite even to odd spin is

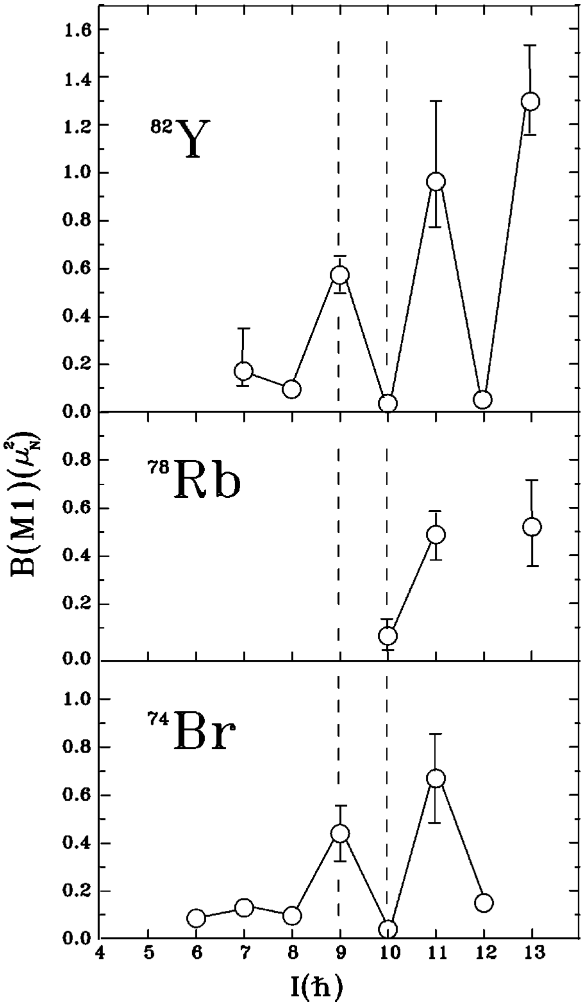

FIG. 4. Graph of the $B(M1)$ strengths as a function of the spin of the initial state for the yrast positive-parity bands in ^{82}Y, ^{78}Rb, and ^{74}Br. Error bars not shown are smaller than the symbol size. The dashed lines indicate the angular momentum region in which the signature inversion takes place.

preserved along the known spin region as is shown in Fig. 4.

The signature inversion is more clearly observed in the energy level sequence as a band crossing effect, rather than being reflected in the $B(M1)$ strength evolution. Let us finish the present report pointing out that this is the second work in the mass 80 region which reports measurements of the electric and magnetic transition strengths across the signature inversion zone. Certainly, more experimental effort will help to clarify this phenomenon.

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