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Lifetime measurements in ^{80}Br and a new region for observation of chiral electromagnetic selection rules

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ABSTRACT

Level lifetimes for the candidate chiral doublet bands of ^{80}Br were extracted by means of the Doppler-shift attenuation method. The absolute transition probabilities derived from the lifetimes agree well with the $M1$ and $E2$ chiral electromagnetic selection rules, and are well reproduced by the triaxial particle rotor model calculations. Such good agreements among the experimental data, selection rules of chiral doublet bands and theoretical calculations are rare and outstanding in researches of nuclear chirality. Besides odd-odd Cs isotopes, odd-odd Br isotopes in the $A \approx 80$ mass region represent another territory that exhibits the ideal selection rules expected for chiral doublet bands.

1. Introduction

Chirality is a quite common phenomenon in the branches of science like chemistry, biology and high energy physics. The chirality in nuclei has been originally predicted in Ref. [1], and extensively investigated over the past two decades from both the experimental and theoretical standpoints. The rotational motion of triaxial nuclei attains a chiral character where the angular momenta of the valence protons and neutrons, and the core are mutually perpendicular, and therefore result in the formation of left- and right-handed orientations. The experimental signal of nuclear chirality is the appearance of doublet bands with the same parities and nearly degenerate energies, which are called chiral doublet bands [1]. Up to now, a number of chiral doublet bands have been reported in the $A \approx 80$, 100, 130, and 190 mass regions ([2–10] and references therein).

At the beginning of the experimental exploration of chirality in nuclei, the main sign to identify chiral doublet bands was the existence of nearly degenerate states with the same parities. It is well known that the electromagnetic transition probabilities carry more stringent information on the intrinsic structure than excitation energies. The chiral doublet bands were expected to exhibit the following electromagnetic selection rules [11–13]. (i) The electromagnetic transition probabilities $B(M1)$ and $B(E2)$ values for

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Table 1
The present measured lifetimes τ and the previous lifetime results in Ref. [39], as well as the measured branching ratios (BR) and DCO ratios for the transitions of chiral doublet bands in ^{80}Br.

I_i^π ($\hbar$)	τ[a] (ps)	τ[b] (ps)	E_γ (keV)	BR	DCO ratio[c]
Band 1					
9^+	$0.38^{+0.07}_{-0.05}$		525.6	0.94(0.09)	0.56(0.06)
			693.1	0.06(0.01)	0.93(0.14)
10^+	$0.66^{+0.13}_{-0.11}$	$1.1^{+0.4}_{-0.3}$	447.1	0.53(0.05)	0.52(0.05)
			972.6	0.47(0.05)	1.04(0.11)
11^+	$0.22^{+0.02}_{-0.02}$	$0.5^{+0.2}_{-0.2}$	668.9	0.79(0.07)	0.53(0.06)
			1116.0	0.21(0.02)	0.94(0.10)
12^+	$0.17^{+0.04}_{-0.03}$	$0.9^{+0.3}_{-0.2}$	264.8	0.14(0.02)	
			687.8	0.10(0.01)	
			1356.0	0.76(0.07)	0.90(0.12)
13^+	< 0.16		713.3	0.46(0.07)	0.64(0.07)
			1401.1	0.46(0.07)	
$(14)^+$			793.1	0.11(0.03)	
			1507.8	0.89(0.14)	
$(15)^+$			743.4	0.39(0.04)	
			1537.2	0.61(0.07)	
Band 2					
9^+	$0.37^{+0.08}_{-0.08}$		918.8	0.64(0.06)	0.49(0.06)
			1086.3	0.36(0.03)	0.97(0.10)
10^+	$0.27^{+0.07}_{-0.06}$		467.4	0.25(0.02)	
			860.7	0.75(0.07)	0.43(0.05)
11^+	$0.26^{+0.06}_{-0.05}$		679.2	0.71(0.11)	
			1091.8	0.06(0.01)	
			1146.3	0.23(0.03)	0.97(0.21)
12^+	< 0.24		531.5	0.11(0.02)	
			955.3	0.62(0.08)	0.57(0.06)
			1209.6	0.27(0.04)	

[a] The present lifetimes.
[b] Previous lifetimes in Ref. [39].
[c] DCO ratio obtained by using stretched E2 transitions as gating transitions.

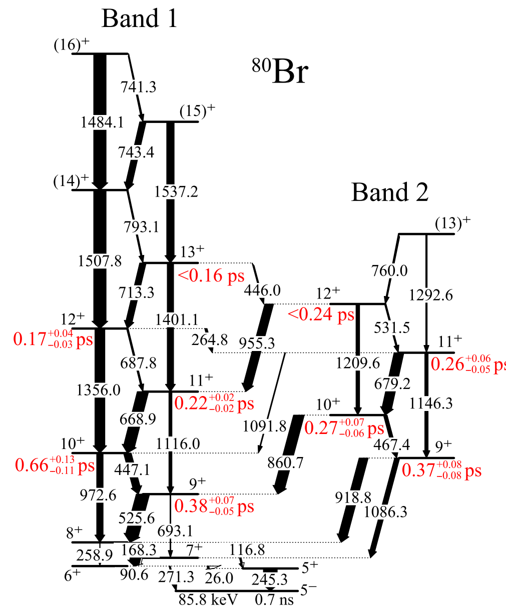

Fig. 1. Candidate chiral doublet bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration in ^{80}Br observed in the experiment. The arrow widths are proportional to the branching ratios (except for the very weak 446.0, 741.3, 760.0 and 1292.6 keV transitions). The sum of transition intensities depopulating the given level is normalized to unity. The lifetime of levels is given in red under the spins of the corresponding levels.

the doublet bands should be almost identical. (ii) The $B(M1)$ exhibit odd-even staggering, and the phase of staggering for in-band and interband $B(M1)$ should be opposite. (iii) The interband $E2$ transitions should vanish at the high spin regime. Recently, several chiral doublet bands have been tested by the absolute transition probabilities obtained from the lifetime measurements [14–25]. It was found that only the candidate chiral doublet bands in odd-odd Cs isotopes (^{124,126,128,130}Cs) [18–21] completely fulfill the above selection rules.

The $A \approx 80$ mass region is a new region of chirality [26–30] compared to the $A \approx 100$, 130, and 190 mass regions. In the $A \approx 80$ mass region, the nucleus ^{80}Br was firstly reported as a candidate chiral nucleus [26]. It opens up a new mass region and configuration that chiral nuclei can be established. However, candidate chiral doublet bands in ^{80}Br were suggested only by their behaviors on energy spectra and the ratios of transition probabilities. Therefore, it is essential to obtain the absolute transition probabilities of the chiral doublet bands in ^{80}Br by precise lifetime measurements, in order to test whether it fulfills the chiral electromagnetic selection rules.

2. Experiment

The experiments were carried out at the MP tandem accelerator of the Max-Planck-Institut für Kernphysik Heidelberg and employed a 35 MeV ^{7}Li beam to populate high-spin states of ^{80}Br with the ^{76}Ge(^{7}Li, 3n) reaction. Two experiments were performed: one with a thin target consisting of 0.2 mg/cm^2 ^{76}Ge on a 0.05 mg/cm^2 carbon backing, and the other with a relatively thick target consisting of 0.6 mg/cm^2 ^{76}Ge on a 2.5 mg/cm^2 gold backing. The thickness of the second backing was chosen such that the recoil nuclei are completely stopped, thus enabling the determination of level lifetimes using the Doppler-shift-attenuation method (DSAM). Emitted γ rays were measured with six EUROBALL CLUSTER detectors [31] positioned at ±40°, ±90°, and ±140° relative to the beam direction. In each of the experiment about 7 × 10^8 coincidence events of fold two or higher were recorded. Transition intensities used to obtain branching ratios were extracted using the symmetric matrix from the first experiment. The analysis of directional correlations of coincident γ rays emitted from oriented states (DCO) was applied to deduce the multipole order of the γ rays and to assign spins to the emitting states. The DCO ratios referred to a stretched quadrupole gate obtained for the present geometry are 1.0 for stretched quadrupole transitions and 0.5 for the pure stretched dipoles. The branching ratios and DCO ratios are listed in Table 1. Three asymmetric matrices were constructed in the second experiment to perform the lineshape analysis using DSAM. More details on the experiments can be found in Ref. [32].

The analysis of experimental lineshapes was carried out using an updated version of the computer code LINESHAPE for DSAM [33]. The code was used to generate 10000 Monte Carlo simulations for the velocity history of recoiling nuclei traversing the backed target in time steps of 0.01 ps with recoil velocities of the order of 0.7% c following the used reaction in the present work. Electronic stopping powers were taken from Ziegler's tabulation with low-energy modifications [34]. A χ^2 minimization for the observed Doppler shifted lineshapes was then carried out using the level lifetimes, side-feeding lifetimes, background and contaminant peaks (i.e., FWHM and intensity) as input parameters. Experimental uncertainties in the extracted lifetimes were determined based on the behavior of the χ^2 fit in the vicinity of the minimum [33,35–37]. More details on the fitting method can be found in Refs. [33,35,38]. Furthermore, the present lifetime measurements for the respective $17/2^-$ and $25/2^-_2$ levels in ^{79}Br provide a good comparison of results measured using the modified DSAM code (i.e., 0.60±0.04 and 0.17±0.02 ps) [33] and the old code (i.e., 0.59±0.10 and 0.18±0.01 ps) reported in the Ref. [32].

3. Results and discussions

The candidate chiral doublet bands in ^{80}Br [26] are shown in Fig. 1, labeled as bands 1 and 2. The present investigation focused

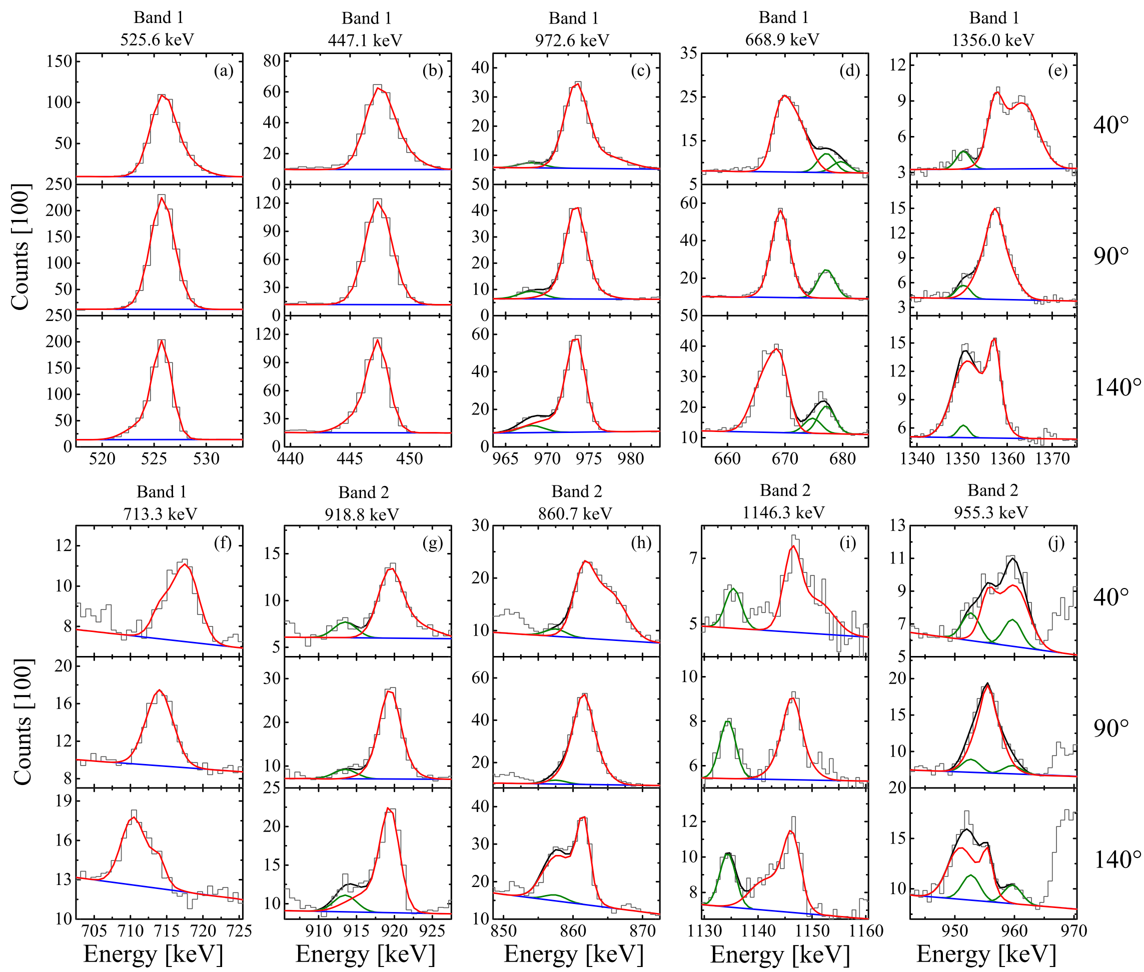

Fig. 2. Doppler broadened lineshapes of γ-transitions calculated at angles of $\pm 40°$, $\pm 90°$ and $\pm 140°$ with respect to the beam direction have been shown in red line. The contamination peaks have been presented in green. Black line shows fit to the experimental data plotted in gray. Blue line represents the background.

primarily on the lifetime measurements of states in the two bands. Experimental data and line shape fits at forward, transverse and backward angles are displayed in Fig. 2. The extracted lifetimes are listed in Table 1 and are marked with red in Fig. 1 for the corresponding states. Systematic errors in the stopping power values are not included in the quoted errors and may be as large as 15% [24]. Prior to this work, lifetimes of 10^+, 11^+ and 12^+ states belonging to band 1 had been measured in Ref. [39], which are also tabulated in Table 1. Following the comparison of results tabulated in Table 1, it can be suggested that the larger statistical magnitude in the present measurements has resulted in a significant amount of reduction of errors (factor of 3-10) which is within an agreement of 2 sigma level.

The absolute transition probabilities $B(E2)$ and $B(M1)$ of bands 1 and 2 were extracted and displayed in Fig. 3. The $B(M1)$ values were obtained by assuming pure $M1$ multipolarity, since the extracted DCO ratio of $M1$ transitions (see Table 1) is very close to that of the pure stretched dipoles. It can be seen from Fig. 3 (a) and (b) that the $B(E2)$ and $B(M1)$ values are very similar for bands 1 and 2, and the in-band $B(M1)$ values exhibit odd-even staggering with spin. In addition, as shown in Fig. 3 (b) and (c), the $B(M1)_{\text{out}}$ values also show odd-even staggering but have the opposite phase compared to the in-band ones. These features are consistent with the chiral electromagnetic selection rules mentioned in the introduction, and give strong support for these bands to be chiral doublet bands. Similar experimental features were also observed in ^{76}Br, which were reported in Ref. [40]. Therefore, one can conclude that, besides odd-odd Cs isotopes, odd-odd Br isotopes in the $A \approx 80$ mass region also represent another territory that exhibits the ideal selection rules expected for chiral doublet bands.

In order to have a better understanding of the experimental results, a comparison of the presently measured transition probabilities has been made in Fig. 3, with the calculations reported in Ref. [26] employing the triaxial particle rotor model (TPRM) coupled with two quasiparticles [41–44]. The calculations are observed to well reproduce the absolute transition probabilities which can be seen in Fig. 3. It indicates that the calculations achieve a good description for the rotational mode of ^{80}Br. Further the discussion in Ref. [26] points to the chiral vibration pattern for the observed chiral doublet bands in ^{80}Br, which is suggested by the analysis of the probability distributions of the angular momentum. Therefore, the combinations of the experimental and calculated results manifest that chirality vibration follows the chiral electromagnetic selection rules. On investigating further, it is found that the different chiral isotopes have different characteristics for the transition probabilities. In Cs isotopes, the chiral doublet bands in ^{124,126,128,130}Cs [18–21] are found to satisfy the complete selection rules of chirality and maintain energy differences around 200 keV within the observed spin interval. As typical examples, the chiral doublet bands in ^{124,130}Cs were suggested to correspond to chiral vibration [44,45], i.e., a rapid conversion between the left-handed and right-handed configurations [23]. Similarly, in the case of present ^{80}Br nucleus, with the observed energy differences around 350 keV and satisfying the selection rules of chirality, chiral vibration still can be exhibited. By contrast, in ^{134}Pr, the measured

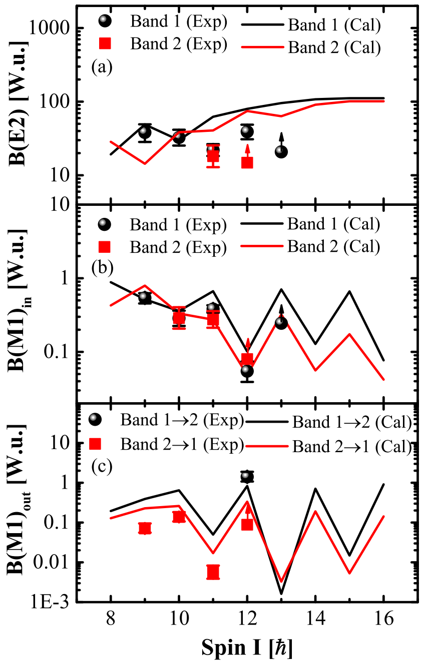

Fig. 3. Comparisons of experimentally measured and theoretically calculated electromagnetic transition probabilities in bands 1 and 2. The $B(E2)$ and $B(M1)$ values for the in-band transitions are shown in panels (a) and (b), respectively. For interband transitions, $B(M1)_{out}$ values are shown in panel (c).

electromagnetic properties are inconsistent with electromagnetic selection rules of chirality [22], although the energy differences are smaller than those of doublet bands in ^{80}Br. ^{134}Pr was suggested to have a possible dynamical character with the deformation parameters of chiral doublet bands fluctuating [46]. Thus, based on the above discussion, it is concluded that the measurement of absolute transition probabilities is the most effective method to distinguish chiral vibration and dynamic chirality. Further, more experimental investigations are still needed to find the well-established chiral configurations (static chirality), satisfying electromagnetic selection rules and degenerate energies in a certain spin range (as predicted in Ref. [12]).

4. Summary

In summary, the level lifetimes are measured using the Doppler-shift attenuation method for the candidate chiral doublet bands in ^{80}Br. The absolute transition probabilities obtained from the lifetime results agree well with the electromagnetic selection rules of chiral doublet bands, and are well reproduced by the previous TPRM calculations. Such good agreements among the experimental data, chiral selection rules and theoretical calculations are rare and outstanding in researches of nuclear chirality, proving the chirality in ^{80}Br. Further investigations of chiral nuclei indicate that the measurement of absolute transition probabilities is the most effective method to distinguish chiral vibration and dynamic chirality. More experimental investigations are still needed to find the static chirality, satisfying electromagnetic selection rules and with quite degenerate energies in a certain spin range.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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