

Fig. 1 The candidate chiral nuclei in nuclear chart. The squares and circles represent the stable nuclides and candidate chiral nuclei, respectively. The red circles represent the candidate chiral nuclei reported by Chinese researchers. Lines are drawn for the magic numbers.

Since this original work in 1997 [1], chiral symmetry in atomic nuclei has attracted significant attention and become one of the hot topics in current nuclear physics frontiers.

Several experimental signatures have been suggested as the fingerprints of chiral doublet bands [1–4]. Besides the nearly degenerate levels, similar spin alignments, moment of inertia and electromagnetic transition probabilities are demanded for claiming the same single particle configuration and deformation. The energy staggering parameter $S(I) = [E(I) - E(I - 1)] / (2I)$ should possess a smooth dependence with spin since the particle and hole angular momenta are both approximately perpendicular to the core rotation. Due to chiral symmetry restoration in the laboratory frame, there are phase consequences for the chiral wavefunctions resulting in $M1$ and $E2$ selection rules which can manifest as the odd–even staggering of $B(M1)$, and the vanishing of interband $E2$ transitions at high spin region.

So far, such chiral doublet bands have been experimentally reported in the $A \approx 80, 100, 130$, and 190 mass regions of the nuclear chart (see Refs. [5–13]). Thereinto, Chinese researchers have made the important contributions and studied experimentally a lot of candidate chiral nuclei, i.e., ^{74}As [14], ^{76}Br [15], ^{78}Br [16], ^{80}Br [17, 18], ^{82}Br [19], ^{81}Kr [20], ^{84}Rb [21], ^{106}Mo [22], ^{110}Ru [22], ^{112}Ru [22], ^{98}Tc [23], ^{104}Ag [24], ^{106}Ag [25, 26], ^{107}Ag [27, 28], ^{110}Ag [29], ^{109}In [30], ^{123}I [31], ^{126}I [32], ^{126}Cs [33, 34], ^{130}Cs [35, 36], ^{131}Ba [37], ^{128}La [38], and ^{138}Pm [39]. The distribution of the candidate chiral nuclei in the nuclear chart is shown in Fig. 1.

In this review, we will focus on the experimental progress regarding nuclear chirality reported by Chinese researchers. An overview of experimental setups is given

in Section 2. Experimental information on chiral doublet bands in the $A \approx 80, 100$, and 130 mass regions is presented and discussed in Section 3. The lifetime measurements for chiral doublet bands, and simultaneous breaking of chirality and other symmetries are discussed and given in Sections 4 and 5, respectively. Finally, a brief summary and perspective are presented in Section 6.

2 Experimental setups

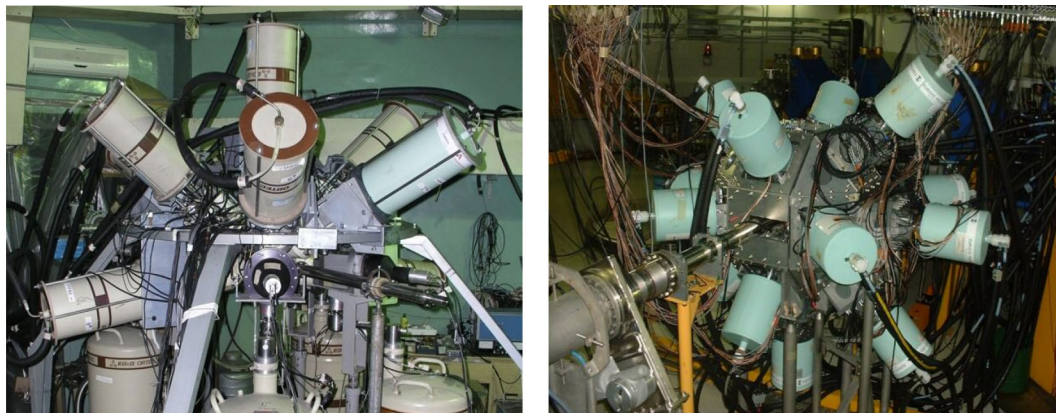
In this paper, 23 candidate chiral nuclei reported by Chinese researchers are reviewed. These candidate chiral nuclei together with the corresponding reactions, laboratories and detector arrays are summarized in Table 1. As shown in Table 1, most of the experiments were carried out by employing the Ge-Clover detector arrays at the China Institute of Atomic Energy (CIAE) and iThemba LABS.

Experimental studies on the nuclear chirality in ^{76}Br [15], ^{84}Rb [21], ^{98}Tc [23], $^{104,106,107,110}\text{Ag}$ [24–29], ^{109}In [30], ^{126}I [32], ^{130}Cs [35, 36], ^{128}La [38] and ^{138}Pm [39] were performed at CIAE. The detector array in CIAE consisted of several Compton-suppressed high-purity germanium (HPGe) detectors, two low-energy photon spectrometer (LEPS) detectors, and one Clover detector. Photograph of the detector arrays in CIAE is given in the left panel of Fig. 2.

Experimental works focused on chiral nuclei in the $A \approx 80$ mass region, including ^{74}As [14], $^{78,80,82}\text{Br}$ [16, 17, 19] and ^{81}Kr [20], were carried out by employing the AFRODITE array in iThemba LABS. The AFRODITE array composed of eight Compton-suppressed Clover detectors. The Clover detector can be used to measure

Table 1 Candidate nuclei reported by Chinese researchers.

Nuclei	Reaction	Lab.	Detection array
^{74}As [14]	$^{74}\text{Ge}(\alpha, 1p3n)$	iThemba LABS	AFRODITE (8 Clovers & 2 LEPS)
^{76}Br [15]	$^{68}\text{Zn}(^{12}\text{C}, 1p3n)$	CIAE	9 HPGe & 1 LEPS
^{78}Br [16]	$^{70}\text{Zn}(^{12}\text{C}, 1p3n)$	iThemba LABS	AFRODITE (8 Clovers & DIAMANT)
^{80}Br [17]	$^{76}\text{Ge}(^{11}\text{B}, \alpha 3n)$	iThemba LABS	AFRODITE (8 Clovers)
^{82}Br [19]	$^{82}\text{Ge}(\alpha, 1p3n)$	iThemba LABS	AFRODITE (8 Clovers)
^{81}Kr [20]	$^{82}\text{Ge}(\alpha, 5n)$	iThemba LABS	AFRODITE (8 Clovers)
^{84}Rb [21]	$^{76}\text{Ge}(^{11}\text{B}, 3n)$	CIAE	6 HPGe & 1 Clover
^{106}Mo [22]	Spontaneous fission of ^{252}Cf	LBNL	Gammasphere
^{98}Tc [23]	$^{96}\text{Zr}(^6\text{Li}, 4n)$	CIAE	14 HPGe
^{110}Ru [22]	Spontaneous fission of ^{252}Cf	LBNL	Gammasphere
^{112}Ru [22]	Spontaneous fission of ^{252}Cf	LBNL	Gammasphere
^{104}Ag [24]	$^{97}\text{Mo}(^{11}\text{B}, 4n)$	CIAE	13 HPGe
^{106}Ag [25, 26]	$^{100}\text{Mo}(^{11}\text{B}, 5n)$	CIAE	15 HPGe
	$^{100}\text{Mo}(^{11}\text{B}, 5n)$	CIAE	10 HPGe & 1 Clover & 2 LEPS
^{107}Ag [27, 28]	$^{100}\text{Mo}(^{11}\text{B}, 4n)$	CIAE	10 HPGe & 1 Clover & 2 LEPS
	$^{100}\text{Mo}(^{11}\text{B}, 4n)$	CIAE	12 HPGe & 1 Clover
^{110}Ag [29]	$^{110}\text{Pd}(^7\text{Li}, \alpha 3n)$	CIAE	9 HPGe & 1 Clover & 2 LEPS
^{109}In [30]	$^{100}\text{Mo}(^{14}\text{N}, 5n)$	CIAE	9 HPGe & 1 Clover & 2 LEPS
^{123}I [31]	$^{116}\text{Cd}(^{14}\text{N}, \alpha 3n)$	Niels Bohr Institute	NORDBALL (19 HPGe&1 LEPS)
^{126}I [32]	$^{124}\text{Sn}(^7\text{Li}, 5n)$	CIAE	12 HPGe & 2 LEPS
	$^{116}\text{Cd}(^{14}\text{N}, 4n)$	IMP	10 HPGe & 1 LEPS
^{126}Cs [33, 34]	$^{116}\text{Cd}(^{14}\text{N}, 4n)$	Niels Bohr Institute	NORDBALL (19HPGe & 1 LEPS)
	$^{124}\text{Sn}(^{11}\text{B}, 5n)$	CIAE	14 HPGe
^{130}Cs [35, 36]	$^{122}\text{Sn}(^{13}\text{C}, 4n)$	Laboratori Nazionali di Legnaro	GALILEO (25 HPGe)
^{128}La [38]	$^{118}\text{Sn}(^{14}\text{N}, 4n)$	CIAE	14 HPGe & 2 LEPS
^{138}Pm [39]	$^{124}\text{Te}(^{19}\text{F}, 5n)$	CIAE	10 HPGe & 1 Clover & 1 LEPS

**Fig. 2** Photographs of the detection arrays in CIAE (left panel) and AFRODITE array in iThemba LABS (right panel).

the linear polarization of the γ -rays and identify whether the observed transitions are electric or magnetic characters. It is helpful to study the simultaneous breaking of the chiral and reflection symmetries. To reduce the contamination from the side products, the CsI particle detector arrays (Chessboard [40] or DIAMANT [41, 42]) were also used with the AFRODITE array by selecting the specific charge particle reaction channels. Photograph

of the AFRODITE array in iThemba LABS is given in right panel of Fig. 2.

The rest of the experiments were performed at the Institute of Modern Physics in Chinese Academy of Sciences, Niels Bohr Institute, Lawrence Berkeley National Laboratory, and Laboratori Nazionali di Legnaro. Note that, besides the fusion–evaporation reaction, fission reaction was also used to investigate nuclear

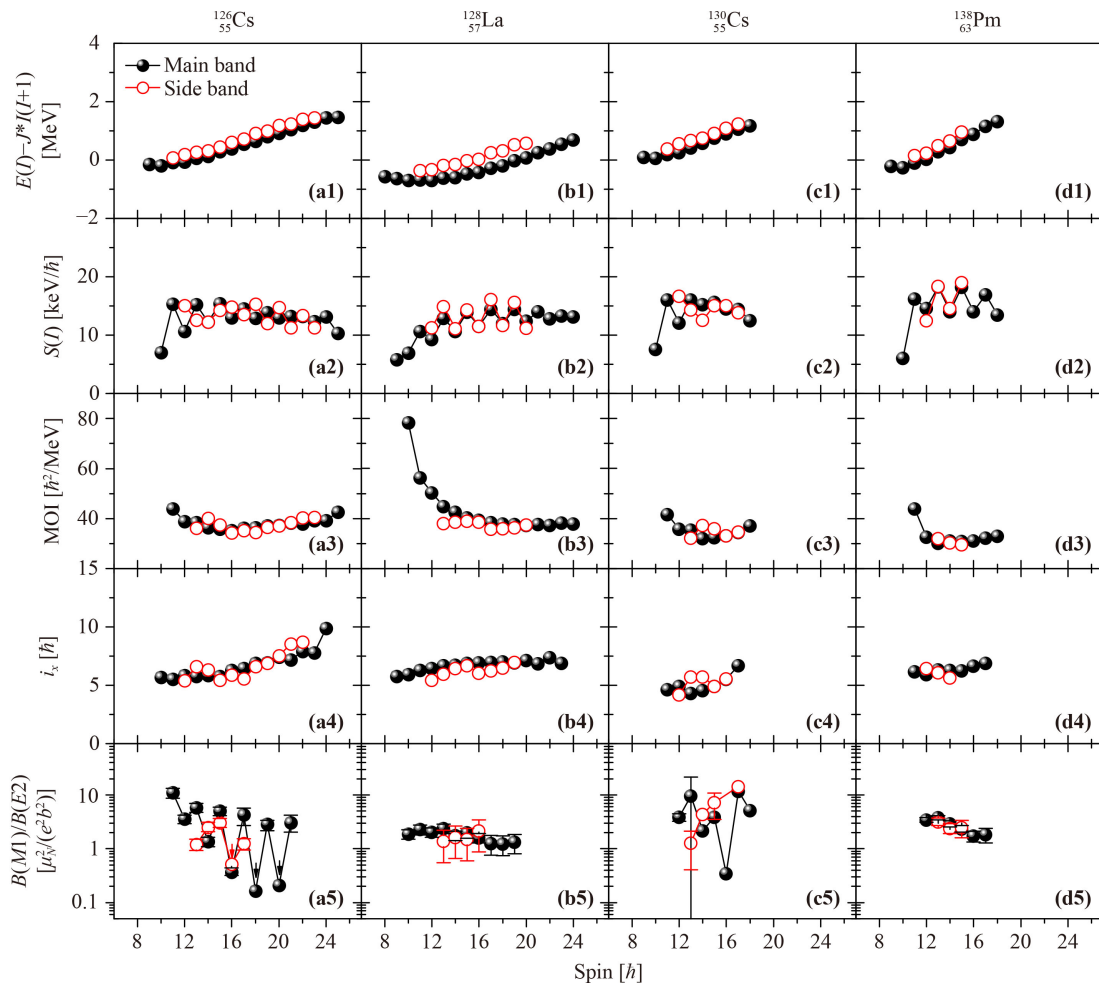


Fig. 3 The excitation energies relative to a rigid-rotor reference $E(I) - J * I(I + 1)$ (The J parameters are evaluated from the relation $J = 0.007 \times (\frac{158}{A})^{5/3}$ MeV), energy staggering parameter $S(I) = [E(I) - E(I - 1)] / (2I)$, kinematic moments of inertia (MOI), rotational alignments (i_x), and reduced transition probability ratios $B(M1)/B(E2)$ for the reported candidate chiral doublet bands with two quasiparticles configuration in ^{126}Cs [34], ^{128}La [38], ^{130}Cs [35, 36] and ^{138}Pm [39].

chirality. The soft chiral vibrational doublet bands based on γ bands were suggested in the even-even ^{106}Mo , $^{110,112}\text{Ru}$ nuclei by measuring the prompt γ -rays from the spontaneous fission of ^{252}Cf [22].

3 Chiral candidates in the nuclear chart

The first experimental evidence for chiral doublet bands was found in odd-odd $N = 75$ isotones in the $A \approx 130$ mass region [43]. Since then, chiral doublet bands have been also proposed in several $N = 71$ [33], $N = 73$ [44, 45] and $N = 77$ [45–48] isotones, revealing an island of chiral nuclei. There is no reason to consider the nuclei in $A \approx 130$ mass region as unique in terms of the underlying physics. Thus, it is necessary to search for chiral nuclei in other mass regions. As more experimental efforts continued to explore, new chiral nuclei have been found in the $A \approx 80$, 110 and 190 mass regions, as discussed in Refs. [8–13]. Chinese researchers mainly focus on the experimental studies for nuclear chirality in the $A \approx 80$,

110 and 130 mass regions. Next, we will discuss these mass regions in chronological order of discovery.

3.1 $A \approx 130$ mass region

Even-even nuclei with $A \approx 130$ are known to be γ -soft and under the influences of prolate driving by particle-like $h_{11/2}$ proton orbital and oblate driving by hole-like $h_{11/2}$ neutron orbital, the odd-odd nuclei with $A \approx 130$ are expected to have relatively stable triaxial shapes [34]. Thus the nuclei in the $A \approx 130$ mass region are nice candidates to occur chiral symmetry breaking.

The experimental groups in China performed continuous explorations on the chiral doublet bands in nuclei ^{126}Cs [33, 34], ^{123}I [31], ^{130}Cs [35, 36], ^{126}I [32], ^{128}La [38], ^{138}Pm [39] and ^{131}Ba [37]. The excitation energies relative to a rigid-rotor reference $E(I) - J * I(I + 1)$, energy staggering parameter $S(I) = [E(I) - E(I - 1)] / (2I)$, kinematic moments of inertia (MOI), rotational alignments i_x and reduced transition probability ratios $B(M1)/B(E2)$ for

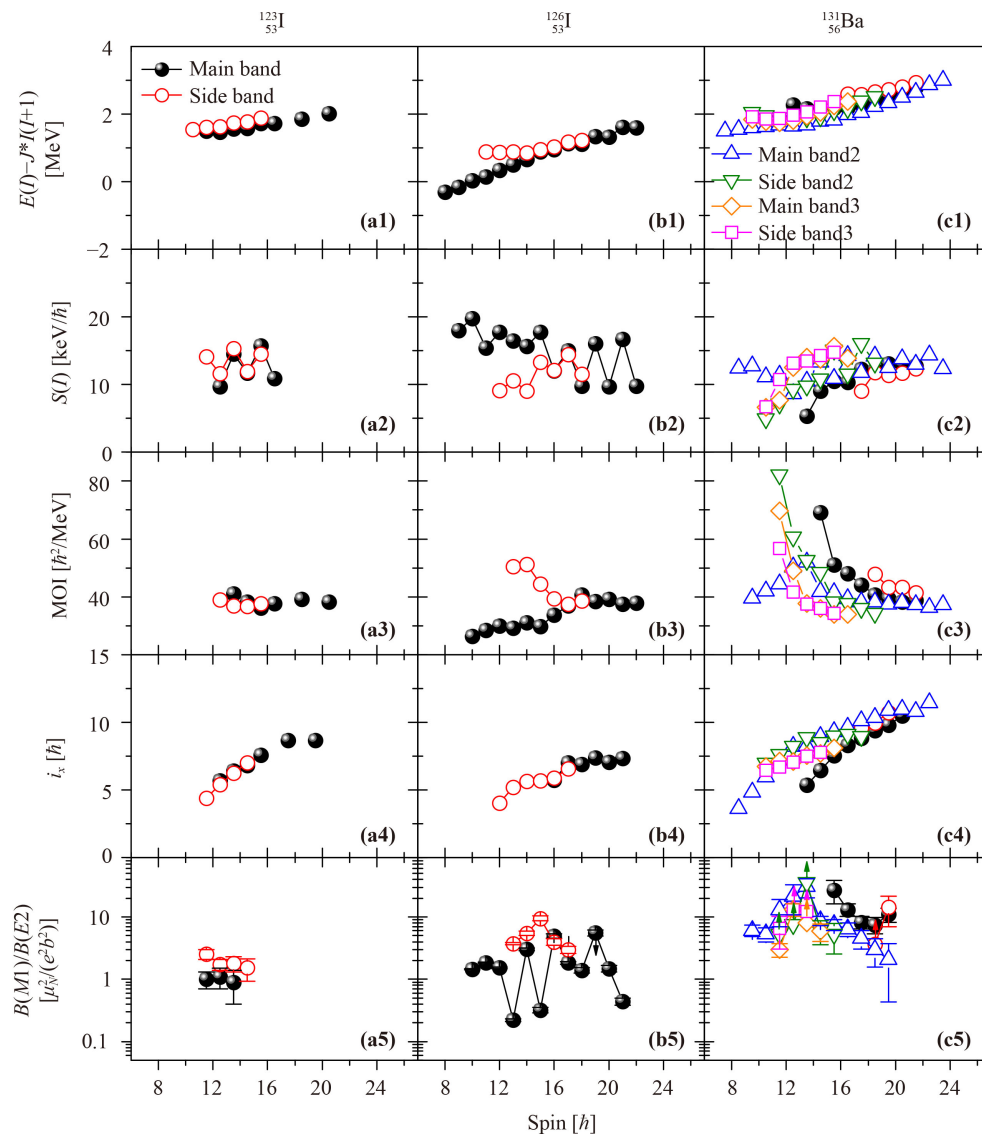


Fig. 4 Same as Fig. 3, but for candidate chiral doublet bands with three quasiparticles configuration in ^{123}I [31] and ^{131}Ba [37] and candidate chiral doublet bands with four quasiparticles configuration in ^{126}I [32].

candidate chiral doublet bands of these nuclei are shown in Figs. 3 and 4. These two figures show the data of the reported candidate chiral doublet bands with two quasiparticles and three/four quasiparticles configurations, respectively.

The first candidate chiral nucleus explored by experimental groups in China is ^{126}Cs . In 2002, one year after observing the first chiral evidence, the candidate for chiral doublet bands in ^{126}Cs was reported based on the similar energy spectra and identical parities of the two bands [33]. However, due to poor counting statistics, electromagnetic properties of the candidate chiral doublet bands were not discussed in Ref. [33]. Compared with the energy spectra, the electromagnetic transition probabilities carry more information on the intrinsic structure. In 2006, there was a wonderful story about the interpretation of chiral doublet bands. The transition

probabilities of nearly degenerate bands in ^{134}Pr , which had ever been considered as the best candidate for chiral bands, was extracted by lifetime measurements [49]. It showed the disagreement with the interpretation of static chirality. The risk of misinterpretation of nearly degenerate pair bands as chiral partners was argued on March 2006 [50]. At that moment when the interpretation of chirality was strongly doubted, Wang *et al.* [34] reported the extracted electromagnetic transition ratios for the doublet bands in ^{126}Cs on July 2006. As shown in Fig. 3(a), the $B(M1)/B(E2)$ values are similar for the doublet bands, and exhibit the evidently odd–even staggering. The features of observed electromagnetic transition agreed with criteria for chiral doublet bands [34]. Subsequently on October 2006, the absolute transition probabilities $B(E2)$ and $B(M1)$ of candidate chiral doublet bands in ^{128}Cs were extracted by lifetime measurements

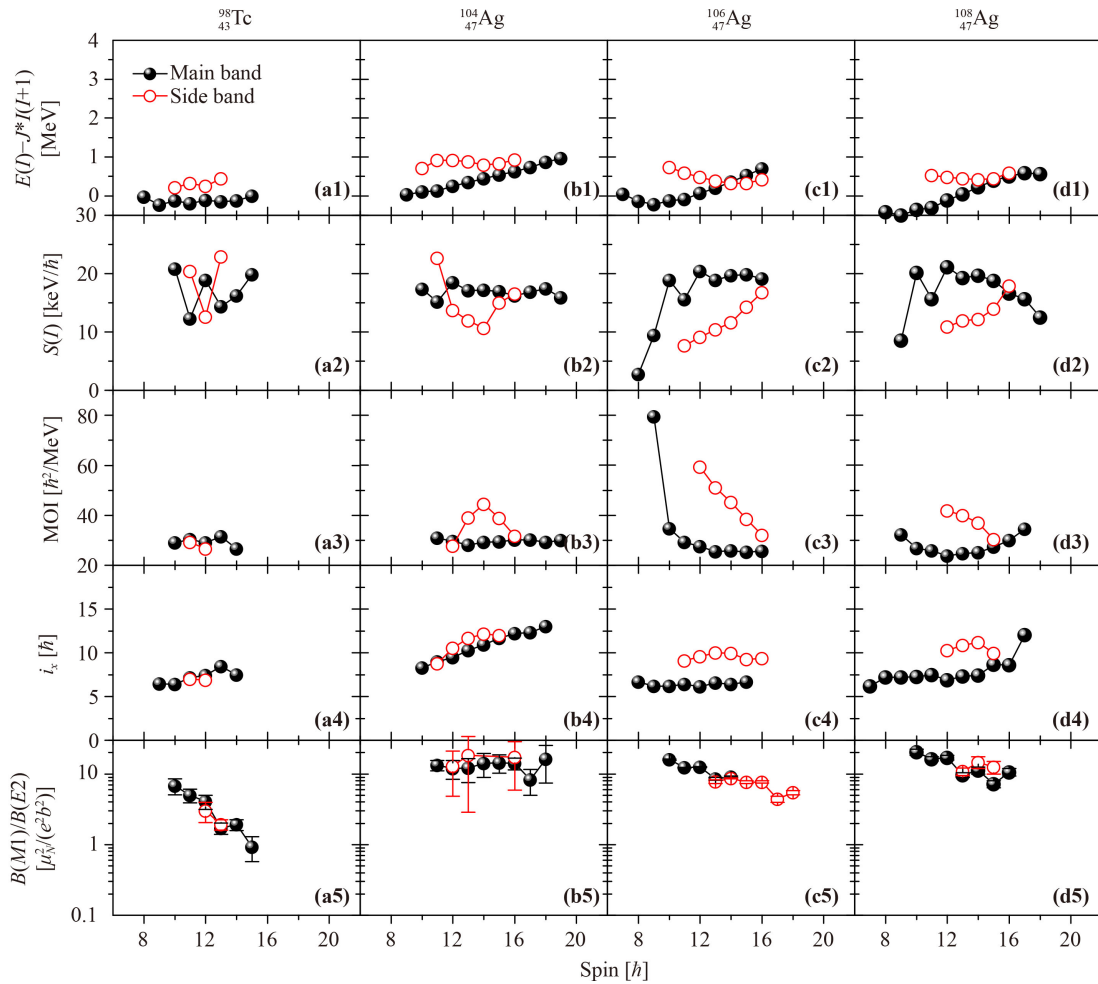


Fig. 5 Same as Fig. 3, but for candidate chiral doublet bands in ^{98}Tc [23], ^{104}Ag [24], ^{106}Ag [25], and ^{108}Ag [53].

and supported further the interpretation of chiral symmetry breaking [51].

In order to further explore the boundaries of $A \approx 130$ chiral island, high-spin states of ^{128}La [38] and ^{138}Pm [39] were studied by Jilin University group. Candidate chiral doublet bands based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration were identified by in-beam γ -ray spectroscopy techniques using the CIAE detector system. In addition, the level lifetimes in partner bands of ^{130}Cs were measured in CIAE, which supported the chiral interpretation in this nucleus [35, 36]. As shown in Figs. 3(b), (c), and (d), the nearly degenerate doublet bands in ^{128}La , ^{130}Cs , and ^{138}Pm have similar MOI, i_x and $B(M1)/B(E2)$ ratios. These features fit to the fingerprints of chiral doublet bands with the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration.

Besides the candidate chiral doublet bands with two quasiparticles configuration, candidate chiral doublet bands with three or four quasiparticles configuration have also been observed in several nuclei in the $A \approx 130$ mass region. Zhao *et al.* [31] observed a new band based on the $\pi g_{7/2} \otimes \nu h_{11/2}^2$ configuration in ^{123}I , which was suggested to be a chiral partner of the previously known

$\pi g_{7/2} \otimes \nu h_{11/2}^2$ band. Zheng *et al.* [32] extended the level scheme of ^{126}I and established five new bands. As shown in Fig. 4(b), the excitation energies of candidate chiral doublet bands in ^{126}I become nearly degenerate after spin 15 \hbar within an energy difference about 70 keV. Ref. [32] suggested the doublet bands have the same $\pi d_{5/2} \otimes \nu (h_{11/2})^3$ configuration after the band crossing and show the features of chirality. Recently, three nearly degenerate pairs of doublet bands were identified in ^{131}Ba [37]. Two of them, with positive-parity, were interpreted as pseudospin-chiral quartet bands with the configuration $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ in ^{131}Ba , which represented the first evidence of possible pseudospin-chiral quartet bands [37].

So far, candidate chiral doublet bands have been observed in more than thirty nuclei in $A \approx 130$ mass region. It is very interesting to further explore the boundary of $A \approx 130$ chiral island. Meantime, the coexistence of chirality and other phenomena such as pseudospin symmetry, octupole correlations and shape phase transition is expected to occur in this mass region.

3.2 $A \approx 100$ mass region

With regard to the search and study of chiral doublet bands, the nuclei in the mass region $A \approx 100$ are of much interest in that they often show evidence of triaxial shapes and have the necessary particle-hole orbitals near the Fermi surface. In 2004, Vaman *et al.* [52] reported the first case of the chiral nucleus ^{104}Rh in the $A \approx 110$ mass region. Subsequently, a series of chiral doublet bands have been observed in this mass region, making $A \approx 100$ mass region a new chiral region. Chinese researchers have also made important contributions to the experimental study of the chiral nuclei in the $A \approx 100$ mass region, especially in the extension of the boundary.

A pair of nearly degenerate negative-parity doublet bands based on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration were reported in ^{98}Tc [23], ^{104}Ag [24], and ^{106}Ag [25, 26]. In order to discuss the observed degenerate bands in these nuclei, the $E(I) - J^* I(I+1)$, $S(I)$, i_x , MOI and $B(M1)/B(E2)$ ratios for the doublet bands are plotted in Fig. 5 as a function of spin. As shown in Fig. 5, doublet bands in ^{98}Tc have rather close excitation energies, similar $S(I)$, i_x , MOI and $B(M1)/B(E2)$ ratios within the observed spin interval. These properties of the doublet bands in ^{98}Tc agree well with the expected chiral criteria [4]. The nearly degenerate bands in ^{104}Ag also show consistent behaviors with those expected from chiral doublet bands except that the MOI of the doublet bands show some difference [24]. However, the values of $S(I)$, i_x and MOI for the doublet bands in ^{106}Ag are quite different within the observed spin interval. These experimental observations show marked differences from the systematical expectation of chiral doublet bands. In fact, the interpretation for the doublet bands in ^{106}Ag has attracted considerable attention and a series of works, including the lifetime measurement, which will be discussed in the following section. Similar nearly degenerate negative-parity bands were also observed in ^{108}Ag . As shown in Fig. 5(d), all observed properties of ^{108}Ag have the very similar behavior to those of ^{106}Ag . Based on the observed experimental characters, Ref. [53] suggested the doublet bands in ^{108}Ag have the same single-particle configurations but different shapes. A further study involving g factor measurement might provide a chance to clarify the current interpretations in the odd-odd Ag isotopes.

Candidate chiral doublet bands were also reported by Chinese researchers in the odd- A nuclei of $A \approx 100$ mass region, i.e., ^{107}Ag [27, 28] and ^{109}In [30]. The experimental excitation energies, $S(I)$, MOI, i_x , and the $B(M1)/B(E2)$ ratios for the observed doublet bands in ^{107}Ag [28] are shown in Fig. 6(a). It is clear in Fig. 6(a) that the doublet bands in ^{107}Ag have very similar behaviors with each other. Besides, their $S(I)$ varies smoothly at lower spins and exhibits relatively small odd-even stagger at higher spins, and their $B(M1)/B(E2)$ ratios display staggers as

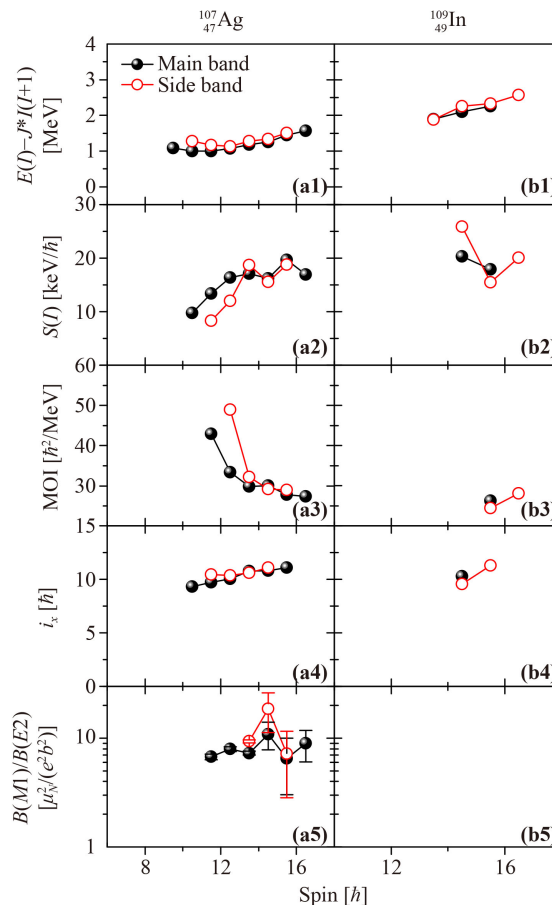


Fig. 6 Same as Fig. 3, but for candidate chiral doublet bands in ^{107}Ag [28] and ^{109}In [30].

a function of spin. These analysis may give the possible evidence of chirality existing in ^{107}Ag . For ^{109}In , a pair of negative-parity doublet bands based on the $\pi g_{9/2} \otimes \nu h_{11/2}(d_{5/2}, g_{7/2})$ configuration were observed in Ref. [30]. Their experimental characters were extracted and presented in Fig. 6(b). Due to the degeneracy in excitation energies and the similar behaviours between the doublet bands, Ref. [30] claimed that these bands may be candidates for chiral bands. It should be noted that the doublet bands in ^{107}Ag and ^{109}In also involve pseudospin orbits $d_{5/2}$ and $g_{7/2}$. Therefore, the possible coexistence of chiral and pseudospin symmetries is expected to be found in these nuclei in future experiments.

As mentioned above, a special type of chiral vibration bands was also suggested in this mass region. Zhu *et al.* [22] investigated the high-spin states in the neutron-rich even-even nuclei ^{106}Mo , ^{110}Ru and ^{112}Ru by measuring the prompt γ -rays from the spontaneous fission of ^{252}Cf . Similar nearly degenerate doublet bands were observed in these three nuclei. These bands were proposed to have the two quasi-neutron excitation configurations $\nu h_{11/2} \otimes \nu(g_{7/2}, d_{5/2})^{-1}$ [22]. We presented the experimental excitation energies, $S(I)$, MOI, i_x , and the $B(M1)/B(E2)$

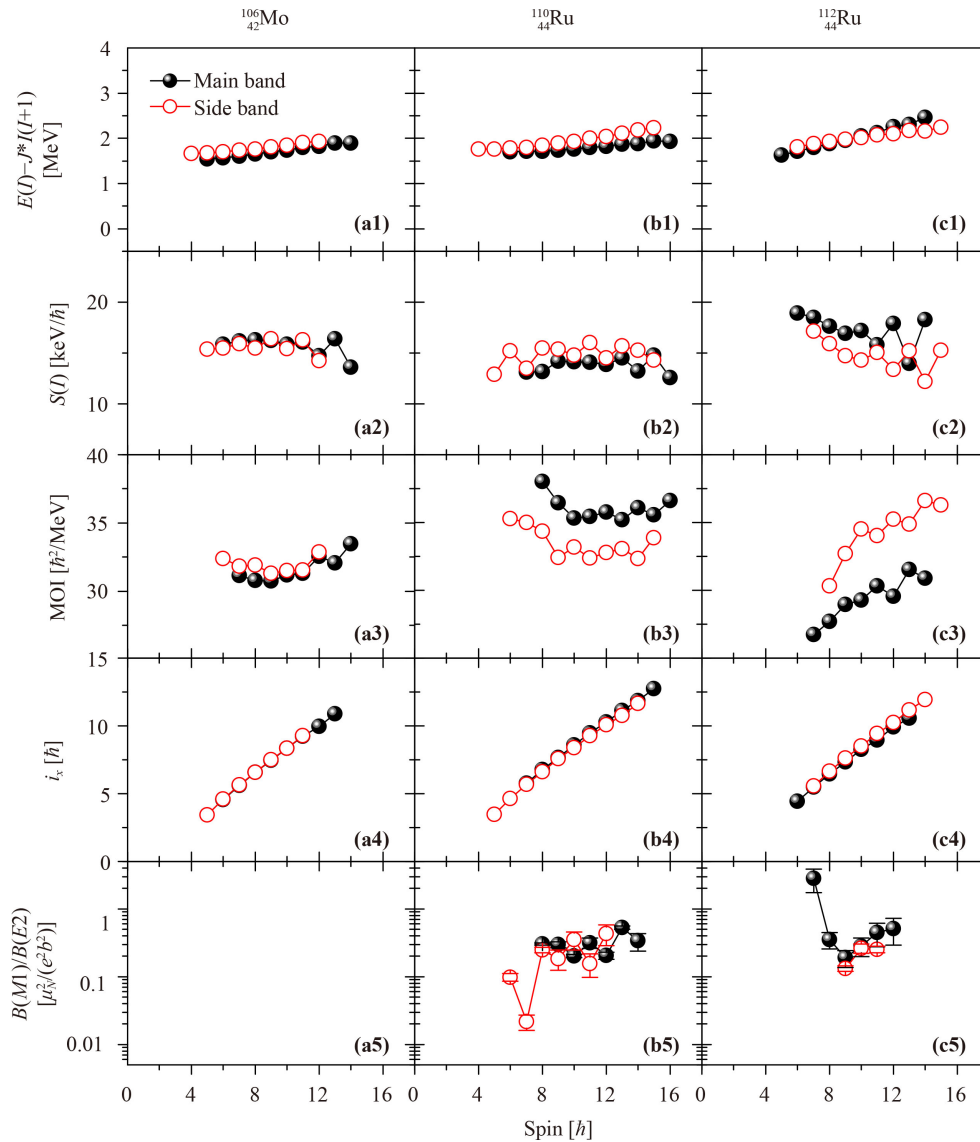


Fig. 7 Same as Fig. 3, but for candidate chiral doublet bands in ^{106}Mo , ^{110}Ru and ^{112}Ru [22].

for the doublet bands in ^{106}Mo , ^{110}Ru and ^{112}Ru in Fig. 7. As shown in Fig. 7, the excitation energy difference between the doublet bands in ^{106}Mo and ^{110}Ru is small and almost flat. However, a band crossover is observed in ^{112}Ru . The excitation energy difference for ^{112}Ru decreases with increasing spin, passing the $\Delta E = 0$ line and then crossing over to become negative. In addition, the $S(I)$ values for the doublet bands in ^{106}Mo , ^{110}Ru and ^{112}Ru show rather smooth patterns, these doublet bands also have the similar i_x and $B(M1)/B(E2)$ ratios. These features satisfy the criterion for chiral doublet bands. However, the MOI of doublet bands in ^{110}Ru and ^{112}Ru are quite different within the observed spin interval. Based on these experimental characters, the negative-parity doublet bands in ^{106}Mo , ^{110}Ru and ^{112}Ru are proposed as soft chiral vibrational doublet bands based on γ bands [22]. These work indicate that chirality as a

universal concept still exists in the neutron-rich region. However, due to the high-spin states of neutron-rich nuclei are hard to populate, the studies of chirality are very scarce and how the chiral properties manifest is an open question in the neutron-rich region. It is worth mentioning that the high-spin states in neutron-rich nucleus ^{116}In have been observed for the first time by using ^7Li -induced incomplete fusion reaction very recently and studied its possible chirality [54]. In Ref. [54], two nearly degenerate positive-parity doublet bands were observed in ^{116}In and tentatively interpreted as candidate chiral doublet bands with four quasi-particles configuration $\pi g_{9/2}^{-1} \otimes \nu(g_{7/2}/d_{5/2})h_{11/2}^2$. The possible chirality in ^{116}In indicates the existence of a new region of chirality in neutron-rich $A \approx 120$ mass region [54].

Besides the two-quasiparticle and three-quasiparticle configurations, a pair of doublet bands with the four-

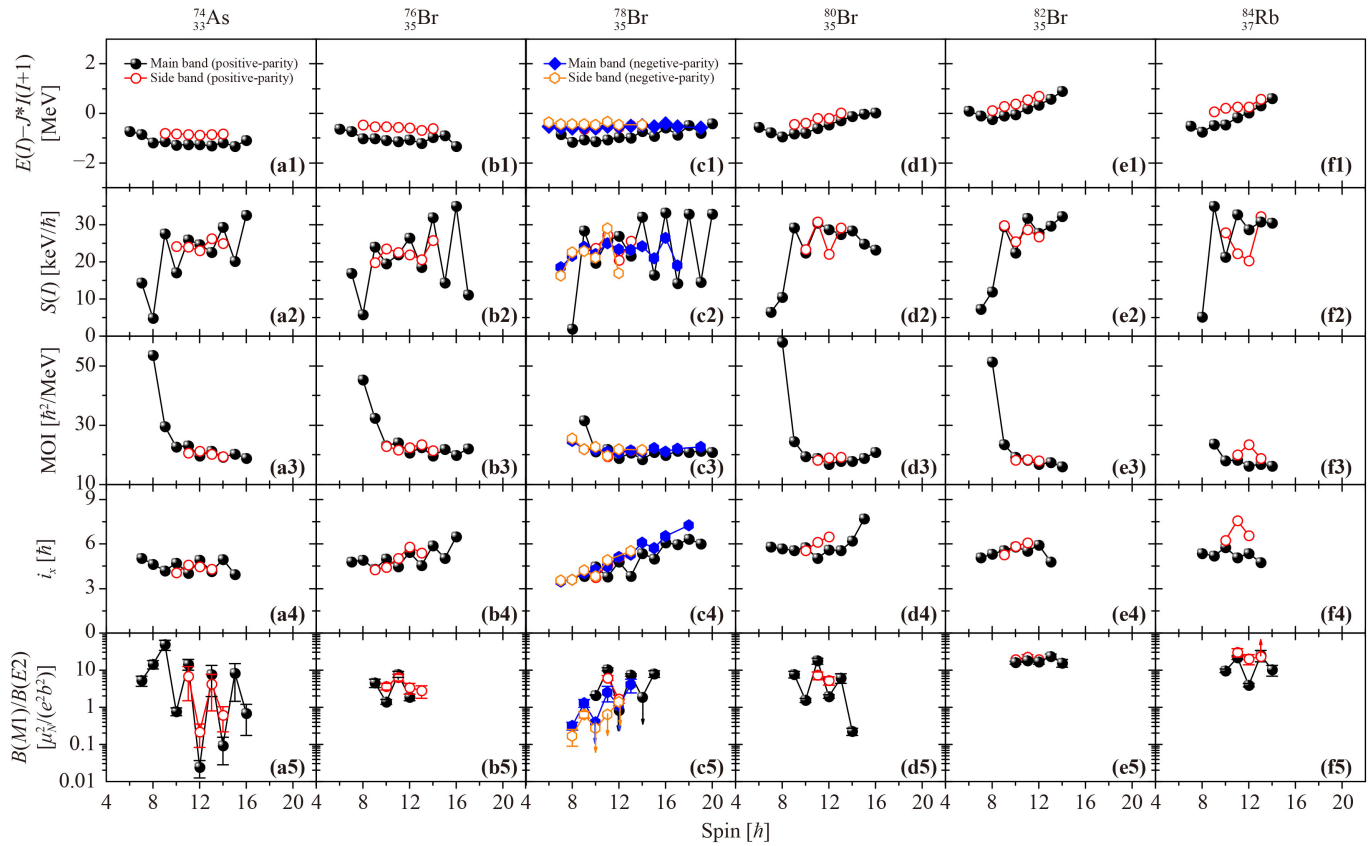


Fig. 8 Same as Fig. 3, but for candidate chiral doublet bands in ^{74}As [14], ^{76}Br [15], ^{78}Br [16], ^{80}Br [17], ^{82}Br [19] and ^{84}Rb [21].

quasiparticle $\pi g_{9/2} \otimes \nu h_{11/2}(d_{5/2}, g_{7/2})^2$ configuration have been reported in ^{110}Ag [29]. Based on the extracted experimental characters of the doublet bands, Ma *et al.* [29] found the properties of the doublet bands show the general agreement with the fingerprints of chiral rotation, and thus suggested the two negative-parity bands in ^{110}Ag to be candidates for chiral doublet bands. To further confirm this suggestion, more experimental results, especially the absolute $B(M1)$ and $B(E2)$ transition probabilities based on lifetime measurements, are desirable.

Chiral nuclei in the $A \approx 100$ mass region provide a unique opportunity to investigate the chiral geometry formed by asymmetric configuration of two-quasiparticle. Therefore, more candidate chiral doublet bands with lifetime and g factor measurements are highly expected.

3.3 $A \approx 80$ mass region

Chirality has also been predicted to exist in the $A \approx 80$ mass region, where chiral doublet bands can be formed with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration. Chinese researchers have made important contributions to the experimental exploration of the chiral nuclei in this mass region. So far, seven candidate chiral nuclei (^{74}As [14], ^{76}Br [15],

^{78}Br [16], ^{80}Br [17], ^{82}Br [19], ^{81}Kr [20] and ^{84}Rb [21]) have been reported in this mass region. Compared to the $A \approx 130$ and 110 mass regions, the $A \approx 80$ mass region is the lightest territory for the study of the chirality in nuclei.

In 2011, candidate chiral doublet bands was observed in ^{80}Br [17], which provided the first example for chirality in the $A \approx 80$ mass region, and gave a new chiral configuration $\pi g_{9/2} \otimes \nu g_{9/2}$. Up to now, in Br isotopes, the similar positive-parity chiral doublet bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration were found in ^{76}Br [15], ^{78}Br [16] and ^{82}Br [19], and a pair of negative-parity chiral doublet bands were found in ^{78}Br based on the $\pi(p_{3/2}, f_{5/2}) \otimes \nu g_{9/2}$ configuration [16]. The $E(I) - J^* I(I+1)$, $S(I)$, i_x , MOI and $B(M1)/B(E2)$ ratios for candidate chiral doublet bands of odd-odd nuclei in the $A \approx 80$ mass region are shown in Fig. 8. As shown in Fig. 8, the positive-parity candidate chiral doublet bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configurations in Br isotopes maintain an energy difference ΔE of $\sim 0.4 - 0.6$ MeV and the negative-parity candidate chiral doublet bands with the $\pi(p_{3/2}, f_{5/2}) \otimes \nu g_{9/2}$ configuration in ^{78}Br maintain an energy difference of ~ 0.15 MeV over the observed spin range. In addition, the $S(I)$ show an almost constant value of ~ 25 keV/ \hbar at $8 \leq I \leq 14$ \hbar for these doublet

bands. The MOI, i_x and $B(M1)/B(E2)$ values of these doublet bands are very similar. Meanwhile, the $B(M1)/B(E2)$ values show odd–even staggering as a function of spin. It should be noted that the ΔE for the candidate chiral doublet bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configurations show a decreasing trend as N increases in Fig. 8. The ΔE of candidate chiral doublet bands may reflect the chiral geometry, i.e., more stable chiral geometry corresponds to the smaller energy difference. With an increase of the neutron number N in these odd–odd Br isotopes, the neutron Fermi level approaches the top of the $\nu g_{9/2}$ subshell, and the growing occupancy of neutrons in the $g_{9/2}$ orbital (gradually approaching the ideal hole) will result in more stable chiral geometry. Therefore, the smaller ΔE in odd–odd Br isotopes with larger N can be understood as these Br isotopes with larger N are more suitable for constructing chiral geometry than those with smaller N .

In ^{74}As , the positive-parity doublet bands were identified and assigned the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration [14]. As shown in Fig. 8, the energy difference of the two bands is approximate to 0.4 MeV. The two bands have the similar $S(I)$, MOI and i_x values, and the $S(I)$ exhibits a smooth variation versus spin. The $B(M1)/B(E2)$ values of these two bands are close and show odd–even staggering. Thus, doublet bands in ^{74}As were suggested as chiral doublet bands. This work extended the border of the chiral nuclei in the $A \approx 80$ mass region to $Z = 33$ [14]. In addition, the positive-parity doublet bands were also observed in ^{84}Rb based on the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration [21]. In Fig. 8, the doublet bands of ^{84}Rb have a small energy difference and a relatively smooth variation of $S(I)$ values. The $B(M1)/B(E2)$ ratios for the doublet bands are close to each other and show odd–even staggering with the same phase as a function of spin. These experimental properties are consistent with the fingerprints of chiral doublet bands. However, comparing with the similar MOI and i_x for the doublet bands in ^{74}As and $^{74,76,78,80,82}\text{Br}$, these values in ^{84}Rb show some differences for the doublet bands, which was interpreted as chiral vibrational bands occur because of the γ softness. The observation of chirality in ^{84}Rb extended the border of the chiral island in the $A \approx 80$ mass region to $Z = 37$.

Besides odd–odd nuclei, it is interesting to search for chiral doublet bands (or multiple chiral doublet bands) in odd- A or even–even nuclei in the $A \approx 80$ mass region. In 2022, candidate chiral doublet bands in odd- A nuclei were found by investigating the medium- and high-spin states in ^{81}Kr [20]. The positive-parity doublet bands with the $\pi g_{9/2}^2 \otimes \nu g_{9/2}^{-1}$ configuration and negative-parity doublet bands with the $\pi g_{9/2}(p_{3/2}, f_{5/2}) \otimes \nu g_{9/2}^{-1}$ configuration were identified in odd- A ^{81}Kr [20]. The excitation energies, $S(I)$, MOI, i_x and $B(M1)/B(E2)$ ratios for candidate chiral doublet bands of ^{81}Kr are shown in Fig. 9. As shown in Fig. 9, the $E(I) - J * I(I + 1)$, $S(I)$, MOI and i_x of these two bands are close, and these two bands

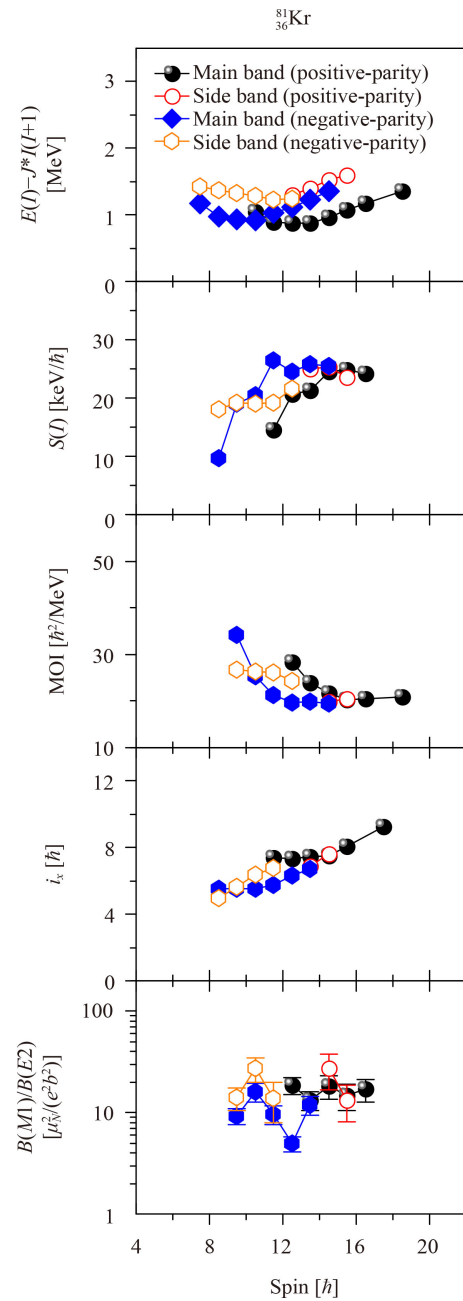


Fig. 9 Same as Fig. 3, but for candidate chiral doublet bands odd- A ^{81}Kr [20].

exhibit smooth variation of $S(I)$ as a function of spin. The $B(M1)/B(E2)$ ratios for each pair of doublet bands are similar and show odd–even staggering with the same phase as a function of spin. These behaviors are consistent with the fingerprints of chiral doublet bands. Thus, these two pairs of bands were suggested as two pairs of chiral doublet bands. This work provided the first example of pseudospin-chiral triplet bands involving the $\pi(p_{3/2}, f_{5/2})$ pseudospin doublet and indicated that chirality can exist not only in odd–odd nuclei but also in odd- A nuclei in the $A \approx 80$ mass region [20].

The $A \approx 80$ mass region is a newly found chiral nuclei region. Compared to the $A \approx 100$ and 130 mass regions, the $A \approx 80$ mass region has a fewer numbers of chiral nuclei. So far, candidate chiral bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration were found in four Br isotopes, enabling systematic study of the evolution of chiral geometry with the neutron number. The conclusion that chiral geometry becomes increasingly stable with an increase in the neutron number was obtained. However, there is still a lack of samples for studying the evolution of chiral geometry with the proton number. Subsequent studies will focus on finding chiral double bands in the isotones and exploring the boundary of chiral island in this mass region.

Up to now, chiral nuclei have been found in the $A \approx 80, 100, 130$ and 190 mass regions, which shows that the chiral symmetry properties are of a general nature and not related only to a specific nuclear mass region. Further experimental efforts on the investigation of chirality in other mass region, even in the neutron-rich and lighter-mass region, are highly expected.

4 Lifetime measurements

It is well known that the transition probabilities carry more stringent information on the chiral geometry than excitation energies. Transition probabilities can usually be deduced from the level lifetimes. Doppler Shift Attenuation Method (DSAM) is a common method to measure the lifetimes of high-spin states in atomic nuclei on subpicosecond range [55]. Nuclei produced in fusion-evaporation reaction recoil into the stopper having large velocities, and the decays occur while the nuclei are still traveling with higher speeds due to the short lifetimes of high-spin states, thus leading the energies of emitted transitions has Doppler-shifted. The relation between the Doppler-shifted $E(\theta, t)$ and unsifted E_0 energy is given by

$$E(\theta, t) = E_0 \left[1 + \frac{v(t)}{c} \cos \theta \right]. \quad (1)$$

The amount of Doppler-shift depends on the velocity $v(t)$ of the recoil and the angle θ of the detector relative to the velocity direction of the recoil, leading to a distribution of energies, also known as “lineshape” of the transition. The lifetime of the nuclear state is then determined from the fitting of the lineshape of the transition. A typical fitting example from ^{76}Br [15] is shown in Fig. 10. In Fig. 10, one can see that, compared to the spectrum detected by the transverse (90°) detectors, the energies of transitions detected by the forward (40°) detectors move towards higher energy and energies of transitions detected by the backward (140°) detectors move towards lower energy.

As an essential probe of nuclear chirality, the

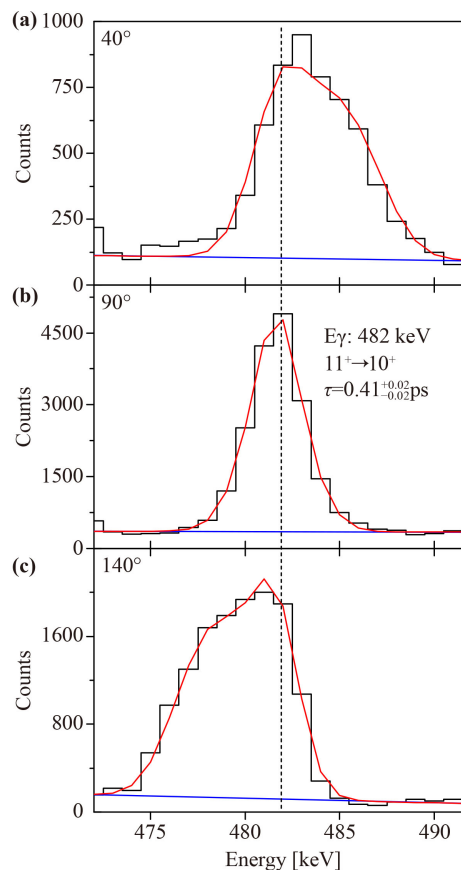


Fig. 10 Doppler broadened lineshape of 482 keV transition in ^{76}Br registered by groups of detectors placed forward (40°), transverse (90°) and backward (140°) with respect to the beam direction. Black line: Experimental data. Red line: Doppler broadened lineshape of the analyzed transition. Blue line: The background.

measurements of transition probabilities have been performed in several nuclei by Chinese researchers.

In the $A \approx 130$ mass region, the electromagnetic transition probabilities in the candidate chiral doublet bands of ^{130}Cs are deduced from the lifetime measurements using DSAM [36]. These results are shown in Fig. 11. One can see that the $B(M1)$ and $B(E2)$ values of the candidate chiral doublet bands of ^{130}Cs are identical within the experimental error limits. The inband $B(M1)$ values show the characteristic staggering, and similar staggering but with opposite phase is observed in the interband $B(M1)$. These experimental results indicate that the reduced transition probabilities for ^{130}Cs are consistent with the characteristic properties of chiral doublet bands.

In Ref. [56], the two strongly coupled negative-parity rotational bands in ^{106}Ag were interpreted as a new type of chiral doublet bands, which have identical single-particle configurations but correspond to different shapes. Later, further lifetime investigations in ^{106}Ag were performed by three research groups. Ref. [57]

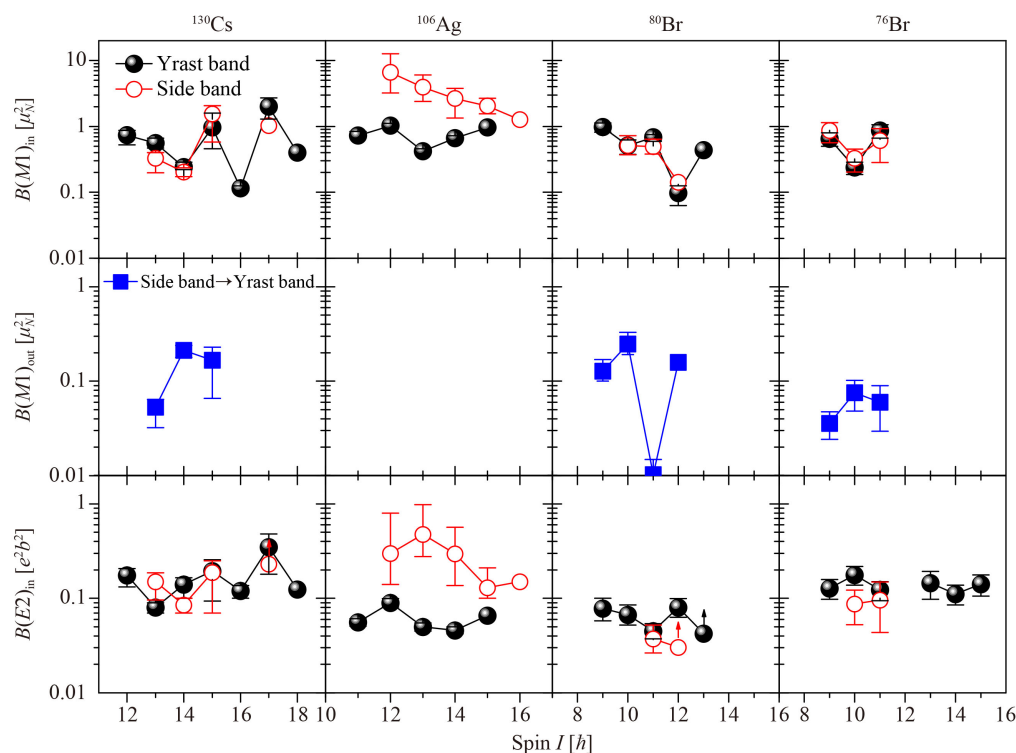


Fig. 11 The reduced transition probabilities $B(M1)$ and $B(E2)$ for candidate chiral doublet bands in ^{130}Cs [36], ^{106}Ag [26] and $^{80,76}\text{Br}$ [15, 18].

reported that the deduced $B(E2)$ and $B(M1)$ rates in the two bands are similar, while Ref. [58] suggested these two lowest-lying bands have different configurations. Zheng *et al.* [26] also performed the lifetime measurements to determine whether or not the candidate chiral doublet bands of ^{106}Ag are in agreement with the chiral fingerprints. Corresponding reduced transition probabilities of ^{106}Ag in Ref. [26] are shown in Fig. 11. The $B(M1)$ and $B(E2)$ values for the doublet bands are not similar, and the staggering of the $B(M1)$ are not observed, as shown in Fig. 11, which indicate that the configurations of the two bands are different, so that the two bands could not be a pair of chiral doublet bands.

In the $A \approx 80$ mass region, the lifetime measurements for the candidate chiral doublet bands were firstly performed in Br isotopes [15, 18]. Corresponding reduced transition probabilities of ^{80}Br and ^{76}Br are shown in Fig. 11. In Fig. 11, one can see that the inband $B(M1)$ and $B(E2)$ values for the doublet bands in $^{76,80}\text{Br}$ are very similar, and $B(M1)$ values exhibit odd–even staggering. In addition, the interband $B(M1)$ values show the staggering having the opposite phase to the inband one. The behaviors of reduced transition probabilities observed in the partner bands of the $^{76,80}\text{Br}$ are consistent with the fingerprints of chiral doublet bands, which indicate that, besides odd–odd Cs isotopes, odd–odd Br isotopes in $A \approx 80$ mass region also represent another territory that exhibits the ideal selection rules expected for chiral

doublet bands.

The lifetime measurements which are essential to extract the absolute electromagnetic transition probabilities are still rare for the chiral nuclei candidates. Lifetime measurements for the more candidate chiral nuclei are highly expected.

It should be pointed out that, despite being a commonly used method for measuring picosecond- or subpicosecond-level lifetimes, a unified treatment of all the uncertainties associated with systematic effects has been a long-standing issue for DSAM. The classical frequentist approach, namely χ^2 minimization, does not inherently provide any uncertainty, but it is a common practice to assume a normal distribution and vary each parameter by one standard deviation while fixing other parameters at plausible values. Uncertainties from different sources are typically evaluated independently and then added quadratically to determine the overall uncertainty. The statistical significance becomes even less rigorous when dealing with upper/lower limits instead of finite values. Multiple parameters often exhibit intricate inter-relationships, and the correlations between them may be either underestimated or overestimated using standard frequentist methodologies. Very recently, to optimize the above problem, Sun *et al.* [59] further applied Markov chain Monte Carlo (MCMC)-based Bayesian parameter estimation methods to DSAM lineshape analyses, providing a reliable uncertainty quantification in a multi-

dimensional parameter space. This work demonstrated the usefulness of Bayesian parameter estimation for DSAM lineshape analyses. Such methods can help to obtain more accurate measured results, leading to more convincing conclusions.

5 Simultaneous breaking of chirality and other symmetries

In addition to chiral symmetry breaking, nuclei can also exhibit other symmetry breakings. Reflection symmetry breaking is observed in nuclei when nucleons near the Fermi surface occupy states of opposite parity with orbital and total angular momentum differing by $3\hbar$, like for example the $\pi g_{9/2}$ and $\pi p_{3/2}$ orbitals in the $A \approx 80$ mass region, or the $\pi h_{11/2}$ and $\pi d_{5/2}$ orbitals in the $A \approx 130$ mass region [60]. Pseudospin symmetry is observed in nuclei when nucleons near the Fermi surface occupy two near degeneracy single-particle states with quantum numbers $(n, l, j = l + 1/2)$ and $(n - 1, l + 2, j = l + 3/2)$ [61], like the $\pi p_{3/2}$ and $\pi f_{5/2}$ orbitals in the $A \approx 80$ mass region, or the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals in the $A \approx 130$ mass region. How these symmetries coexist and affect each other is of great scientific interest.

In 2016, two pairs of positive- and negative-parity doublet bands together with eight strong electric dipole transitions have been identified in ^{78}Br , which were interpreted as multiple chiral doublet bands with octupole correlations [16]. This work reported the first example of simultaneous breaking of chiral and reflection symmetries in nuclei, which indicates that chirality and octupole correlations can coexist in a single nucleus [16]. After that, how do chirality and octupole correlations interact becomes a question of concerned.

Very recently, in order to explore the interplay between chiral and reflection symmetry breakings, the level lifetimes of ^{76}Br and ^{80}Br were studied by the DSAM [15]. The calculated and measured average ΔE in spin range $9^+ - 12^+$ of $^{76-82}\text{Br}$ are shown in Figs. 12(a) and (b), respectively. Thereinto, the calculated ΔE were obtained from the triaxial particle rotor model calculations [62–65] which cannot take into account the effect of reflection-asymmetry. As shown in Fig. 12(a), a lowering of the calculated ΔE as N increases indicates the gradually more stable chiral geometry from ^{76}Br to ^{82}Br . The intrinsic electric dipole moment D_0 is generally considered a good indication of reflection-asymmetry, which can be deduced from lifetimes using following relationships:

$$B(E1) = \frac{0.629 \times 10^{-3} B_\gamma(E1)}{E_\gamma^3(E1)\tau}, \quad (2)$$

$$B(E1; IK \rightarrow I'K) = \frac{3}{4\pi} D_0^2 \langle IK10 | I'K \rangle^2. \quad (3)$$

Figure 12(c) depicts the average D_0 values of ^{73}Br ,

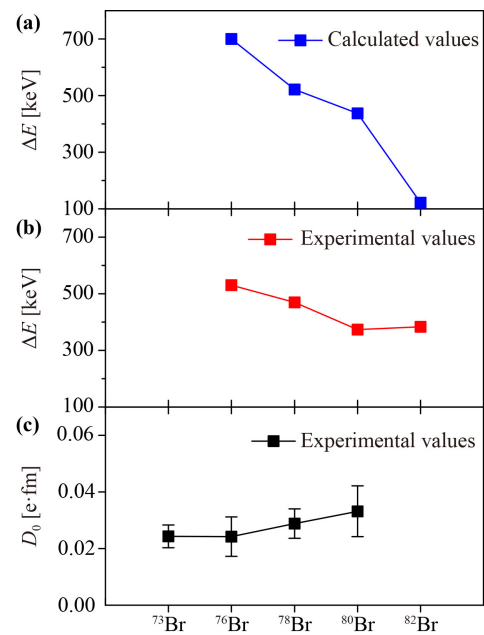


Fig. 12 (a) The calculated and (b) measured energy difference ΔE in ^{76}Br , ^{78}Br , ^{80}Br and ^{82}Br and (c) average D_0 values in ^{73}Br , ^{76}Br , ^{78}Br and ^{80}Br . The data were taken from Refs. [15, 16, 66].

^{76}Br , ^{78}Br and ^{80}Br . In Fig. 12(c), the D_0 values are close to constant within the error, which indicates the nearly identical octupole correlations effect in these Br isotopes as N increases. The measured ΔE shows a distinct decrease until the inversion at ^{80}Br , which is different from the slope of the calculated curve [see Figs. 12(a) and (b)]. The results mean that the most stable chiral geometry present in ^{80}Br instead of ^{82}Br . Thus, the phenomenon of gradually more stable chiral geometry indeed arises even in the presence of octupole correlations. The continuously decreasing ΔE due to the octupole correlations moves the inversion point on the N axis to the left (near the ^{80}Br). It indicates that the octupole correlations may catalyze the formation of chiral geometry instead of destroying it. This work firstly studied the interplay between chiral and reflection symmetry breakings in nuclear system, which provides a meaningful example for investigating the interplay between symmetry breakings. In addition to Br isotopes, coexistence of chirality and octupole correlations has also been observed in ^{74}As [14]. In the $A \approx 80$ mass region, As isotope is expected to exhibit a more stable chiral geometry compared to Br isotope because it has two fewer protons, making it closer to the ideal particle-like configuration. Thus, studying the chirality and octupole correlations in As isotopes may provide a better insights of the evolution of chiral geometry in the presence of octupole correlations in the $A \approx 80$ mass region. Further experimental investigations for searching coexistence of chirality and octupole correlations in As

isotopes are highly expected.

It is worth noting that the configurations of some chiral doublet bands and octupole correlations involve the orbits of pseudospin doublet states. Thus, it is possible to observe the coexistence of chiral symmetry, pseudospin symmetry and reflection asymmetry. In ^{131}Ba , four nearly degenerate positive-parity bands with $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configuration were observed, which were interpreted as pseudospin-chiral quartet bands [37]. In addition, octupole correlations were also observed in ^{131}Ba . This work provided the evidence of the coexistence of chiral symmetry, pseudospin symmetry and enhanced octupole correlations.

Recently, two nearly degenerate positive-parity bands with the $\pi g_{9/2}^2 \otimes \nu g_{9/2}^{-1}$ configuration and three nearly degenerate negative-parity bands with the $\pi g_{9/2}(p_{3/2}, f_{5/2}) \otimes \nu g_{9/2}^{-1}$ configuration have been identified in ^{81}Kr , which were interpreted as chiral doublet bands and pseudospin-chiral triplet bands (pseudospin-chiral triplet bands were firstly introduced in Ref. [67]), respectively [20]. This work provided the first example of coexistence of pseudospin and chiral symmetries in the $A \approx 80$ mass region [20].

It should be noted that the configurations of plenty of nuclei involve the orbits of chiral doublet bands, pseudospin doublet bands and octupole correlations, but the experimental observations of the coexistence of these phenomena are very less. Thus, it is of highly scientific interest to search for the coexistence and interplay of these phenomena.

6 Summary and perspective

Experimental progress regarding nuclear chirality reported by Chinese researchers is reviewed. In particular, the experimental setups, chiral mass regions, lifetime measurements, and simultaneous breaking of chirality and other symmetries are highlighted. According to the present review, it is of highly scientific interest to further explore the boundaries of chiral islands and new chiral mass regions. In addition, it is also important to search for the coexistence and interplay of chirality and other symmetries, like chirality-parity quartet bands in nucleus with both stable triaxial and octupole deformations. Meantime, more lifetime measurements for the candidate chiral nuclei and the measurements of static magnetic dipole and electric quadrupole moments are strongly desirable, which can provide more detailed information about the coupling, configuration and deformation. The further theoretical studies are also needed to fully understand the properties of nuclear chirality. With the recent upgrade of the detector array in CIAE and IMP, more detailed spectroscopic results will become available in China. Therefore, we can expect more exciting results in the field of nuclear chirality in

the future.

Declarations The authors declare that they have no competing interests and there are no conflicts.

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