New aspects of chiral symmetry breaking in atomic nucleus

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Abstract. The significant progresses of the chirality in atomic nuclei are briefly reviewed for both experimental and theoretical sides. A particle rotor model is developed which couples several valence protons and neutrons to a rigid triaxial rotor core and applied to investigating the chirality in odd-A nucleus $^{135}$Nd. Static chirality has been shown to be a transient phenomenon surrounding by chiral vibrations. It is found that the $B(M1)$ staggering is associated strongly with the characters of nuclear chirality, i.e., the staggering is weak in chiral vibration region while strong in the static chirality region.

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1. Introduction

Handedness or chirality is a subject of general interest in molecular physics, elementary particles, and optical physics. The occurrence of chirality in nuclear physics was suggested in 1997 by Frauendorf and Meng. This effect is expected to occur in atomic nuclei having triaxial shapes, and in which there are a few high-
\[ j \]
valence particles and a few high-
\[ j \]
valence holes. For a triaxially deformed rotational nucleus, the collective angular momentum favors alignment along the intermediate axis, which in this case has the largest moment of inertia, while the angular momentum vectors of the valence particles (holes) favor alignment along the nuclear short (long) axis. The three mutually perpendicular angular momenta can be arranged to form two systems with opposite chirality, namely left- and right-handedness. These two systems are transformed into each other by the chiral operator which combines time reversal and spatial rotation of 180°, \( \chi = TR(\pi) \). The spontaneous breaking of chiral symmetry thus happens in the body-fixed reference frame. In the laboratory reference frame, with the restoration of chiral symmetry due to quantum tunneling, the so-called chiral doublet bands, a pair of separated \( \Delta I = 1 \) bands (normally regarded as nearly degenerate) with the same parity, are expected to be observed in triaxial nuclei.

2. Fingerprints for chirality in atomic nuclei

After the prediction of the chirality in atomic nuclei, lots of efforts have been made to find out their fingerprints for the experimental observations. Based on one particle and one hole coupled to a triaxial rotor, a set of experimental signatures have been suggested as fingerprints of nuclear chirality, for example, see Refs. [1, 2, 3]. For energy spectra, the chiral bands should contain a pair of nearly degenerate \( \Delta I = 1 \) bands with the same parity. The selection rule for electromagnetic transitions in the chiral geometry has been proposed in Ref. [2]. Further, in ideal chiral pair bands all corresponding physics properties, such as spin alignments, moment of inertia, and electromagnetic transition probabilities, must be identical or, in practice, very similar. [4, 5]

Nevertheless, one should bear in mind that the fingerprints of the chiral doublet bands mentioned above, in particular \( B(M1) \) staggering, are obtained by assuming one proton (neutron) particle and one neutron (proton) hole sitting in a high-
\[ j \]
shell coupled with a triaxial rotor with \( \gamma = 30^\circ \). It is therefore interesting and necessary to investigate the doublet bands with more general cases where \( \gamma \) deviates from 30°.

3. Experimental progress

During the last decade, lots of experimental efforts have been devoted to search for nuclear chirality. In fact, a pair of \( \Delta I = 1 \) bands found in \(^{134}\text{Pr}\) with the \( \pi h_{11/2} \otimes \nu h_{11/2} \) configuration [6] have been reinterpreted in Ref. [1] as a candidate for chiral doubling. Thereafter, in 2001 similar low-lying doublet bands were reported in \(^{55}\text{Cs} \), \(^{57}\text{La} \), and
61Pm \( N = 75 \) isotones of \( ^{134}\text{Pr} \), and an island of chiral rotation was suggested in the \( A \sim 130 \) mass region [7]. Up to now, candidate chiral doublet bands have been proposed in a number of odd-odd nuclei in the \( A \sim 130 \) mass region [7, 8, 9, 10, 11, 12, 13, 14, 15, 16] with the suggested configuration \( \pi h_{11/2} \otimes \nu h_{11/2} \), \( A \sim 100 \) [17, 18, 19] with \( \pi g_{9/2} \otimes \nu h_{11/2} \), and \( A \sim 190 \) [20, 21] with \( \pi h_{9/2} \otimes \nu i_{13/2} \). A few more candidates with more than one valence-particle and hole were also reported in odd-\( A \) [22, 24, 23, 25, 26] and even-even [27] nuclei. Furthermore, the doublet bands in even-even \( ^{106}\text{Mo} \) [28] and \( ^{110,112}\text{Ru} \) [29] are regarded to be soft chiral vibrations, which may exemplify the general chiral geometry, because the non-planar geometry of rotation cannot be directly related to the alignment of high-\( j \) particles and holes with different principal axes [29].

Lifetime measurements are essential to extract the absolute \( B(M1) \) and \( B(E2) \) transition probabilities. Their importance has stimulated experimental programs aimed at identifying chiral doublet bands [30, 31, 32, 33, 34].

4. Theoretical progress

On the theoretical side, chiral bands were first predicted in the particle-rotor model (PRM) and tilted axis cranking (TAC) approach for triaxially deformed nuclei [1].

Chiral rotation has been studied by the Strutinsky shell correction TAC (SCTAC) method with a hybrid potential which combines the spherical Woods-Saxon single-particle energies and the deformed part of the Nilsson potential [35, 36]. Recently, chiral TAC solutions have also been found in \( ^{132}\text{La} \) isotones within the self-consistent Skyrme Hartree-Fock cranking model [37, 38]. The cranked relativistic mean field (RMF) theory has been reported only in the contexts of principle axis rotation [39, 40] and planar rotation [41, 42]. The generalization thereof for searching for chiral solutions, i.e., the aplanar rotation, is still under development. The advantage of the cranked mean field approach and its limitation has been extensively discussed in, e.g., refs. [43, 44].

In contrast, the PRM is a quantum mechanical model and describes the system in the laboratory reference frame and yields directly the energy splitting and tunneling between doublet bands. Chirality for nuclei in \( A \sim 100 \) and \( A \sim 130 \) regions has been studied with the particle-rotor model for certain particle-hole configurations [45, 46], or the core-quasiparticle/core-particle-hole coupling model [13, 47], following the Kerman-Klein-Dönnau-Frauendorf method [48]. With the pairing correlations taken into account to simulate the configurations of multi-particles sitting in a high \( j \)-shell, particle rotor model with a quasi-proton and a quasi-neutron coupled with a triaxial rotor has been applied to study chiral doublet bands [49, 50]. The (quasi-)particle rotor model can well describe the energy spectra and the ratios \( B(M1)/B(E2) \) and \( B(M1)_{\text{in}}/B(M1)_{\text{out}} \) of chiral bands at the whole spin region for many nuclei, for example \( ^{126}\text{Cs} \) in \( A \sim 130 \) mass region [50], \( ^{108}\text{Rh} \) in \( A \sim 130 \) mass region [51], and \( ^{198}\text{Tl} \) in \( A \sim 190 \) mass region [21]. By analyzing the orientation of the angular momentum for the rotor as well as the valence proton and neutron, and the effective angles between these angular momenta, the chiral geometry represented by a remarkable aplanar rotation can be revealed by means of
PRM [49, 51, 21]. It is also noted that the efforts to describe the doublet bands in $^{134}$Pr are not so successful, where other effects may take also important roles [4, 30].

In addition to the PRM and TAC approaches, the so-called doublet bands have been investigated in terms of the interacting boson fermi model [52, 53, 54] and a pair truncated shell model [55], etc.

5. Triaxial $n$-particle-$n$-hole PRM

As mentioned above, apart from odd-odd nuclei, chiral doublet bands have been observed in odd-$A$ nuclei, an exact version of multi-particle and multi-hole coupled with a triaxial rotor model is highly required to describe the doublet bands based on multi-quasiparticle configurations. Recently we have developed a triaxial $n$-particle-$n$-hole PRM to treat more than one valence proton and one valence neutron and applied to the study of nuclear chirality in $^{135}$Nd with the $2p1n$ configuration $\pi h_{11/2}^2 \otimes \nu h_{11/2}^{-1}$ [56].

![Figure 1](image-url)

**Figure 1.** (color online) The excitation energies $E(I)$ for the chiral bands in $^{135}$Nd calculated by the triaxial PRM with configuration $\pi h_{11/2}^2 \otimes \nu h_{11/2}^{-1}$ (open symbols) in comparison with the data (filled symbols) [22, 32] and the corresponding TAC+RPA results (dotted lines) [32]. The energies are relative to the band head $E_0$ of the chiral bands, with a rotor reference subtracted. Take from Ref. [56].

The calculated excitation energy spectra $E(I)$ for the doublet bands A and B in $^{135}$Nd are presented in Fig. 1, together with the corresponding data [22, 32]. For comparison, the results from the random phase approximation (RPA) based on TAC [32] are also included.

The energy splitting between two sister bands is also well described in the TAC+RPA calculations for $I \leq 39/2$, which is the vibrational regime, where the RPA is stable. The energy splitting disappears at $I = 41/2$ in TAC+RPA, where the TAC solution attains static chirality while anharmonic quantal tunneling takes the role of energy splitting. The description of the experiment in the region $I > 39/2$ is beyond
the realm of RPA based on the planar TAC solution. On the other hand, being a quantum theory that is not restricted to small amplitude vibrations, PRM is able to perfectly reproduce the energy splitting for the whole observed spin region, staying within the configuration $\pi h_1^{1/2} \otimes \nu h_{11}^{-1/2}$ and the triaxial rotor.

In addition to energy spectra, the reduced probabilities $B(M1)$ and $B(E2)$ for in-band as well as for the interband transitions are reproduced excellently by the triaxial $n$-particle-$n$-hole PRM. The details can be found in ref. [56].

6. From chiral vibration to static chirality

![Figure 2.](color online) The probability distributions for projection of total angular momentum on the long ($l$-), intermediate ($i$-) and short ($s$-) axis in PRM for the doublet bands in $^{135}$Nd. Take from Ref. [56].

The TAC calculations have suggested that the chiral rotation cannot exist below a certain critical frequency [37]. Before the onset of chirality of the mean field, the precursor of the symmetry breaking occurs as a soft vibration between the right- and left-handed configurations. These chiral vibrations can be studied in the framework of the TAC+RPA and the static chirality is shown to be a transient phenomenon [32, 57].

In Fig. 2, the probability distributions for the projection of the total angular momentum along the $l$-, $i$- and $s$-axes are shown for the doublet bands in $^{135}$Nd. For each PRM state, the probability for the projection $K$ of total angular momentum on quantization axis is given by the square sum of all the expansion coefficients with a certain $K$ quantum number. The probability distributions with respect to the three principle axes are obtained by placing $\gamma$ into different sectors, such that the shape is the same but different principal axis is used for quantization.
For spin $I = 29/2$, near the band head, the probability distribution of two bands differ as expected for a chiral vibration. At spin $I = 39/2$, the probability distributions for band A and B are very similar, which show the characteristics of static chirality. For higher spin, where the energy difference between the chiral partners increases, they attain vibration character again.

7. Reexamination of fingerprints for chirality

Let us come to discuss the fingerprints for chirality, in particular the feature of odd-even staggering of B(M1) values. The electromagnetic transitions of the chiral doublet bands have been discussed for different triaxiality parameter $\gamma$ in PRM with $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration [58]. The $B(M1)$ staggering as well as the resulting $B(M1)/B(E2)$ and $B(M1)_{in}/B(M1)_{out}$ staggering with the triaxiality parameter $\gamma$ were investigated in order to answer whether or not such staggering is a fingerprint to identify the chiral doublet bands.

After careful reexamination of the $B(M1)$ in ref. [58], one finds that the $B(M1)$ staggering is associated strongly with the characters of chirality. The $B(M1)$ staggering is associated strongly with the characters of nuclear chirality, i.e., the staggering is weak in chiral vibration region while strong in the static chirality region.

This result also qualitatively agrees with the recent lifetime measurements for the doublet bands in $^{128}$Cs and $^{135}$Nd. The former case was claimed as a good example revealing chiral symmetry breaking in Ref. [31], where the pronounced $B(M1)$ staggering is exhibited. The latter case was suggested to reveal the chiral vibration motions for $I < 41/2\hbar$ region in Ref. [32], where the weak $B(M1)$ staggering is shown.

8. Multiple chiral doublet bands

Is it possible to exist more than one pair of chiral bands in one single nucleus? Such possibilities of multiple chiral doublet (M\textsubscript{XD}) bands have been demonstrated recently in Ref. [44] with the microscopic triaxial relativistic mean field (RMF) approaches. With the adiabatic and configuration-fixed constrained triaxial RMF theories developed, triaxial shape coexistence, high-$j$ proton hole- and neutron particle-configurations, and possible M\textsubscript{XD} of $^{106}$Rh are suggested.

Ref. [59] has extended the investigation to other rhodium isotopes. The ground states of $^{102,104,106,108,110}$Rh are found to be triaxially deformed. Wave functions from the Cartesian basis are transformed to a spherical basis, and the corresponding configurations of the minima are specified by quantum numbers in spherical basis. Based on the triaxial deformation and the corresponding high-$j$ particle and hole configurations, the existence of M\textsubscript{XD}, are suggested in $^{104,106,108,110}$Rh. The investigation provides not only further support for the prediction of M\textsubscript{XD} in $^{106}$Rh, but also presents new experimental opportunity for the observation of M\textsubscript{XD} in $A \sim 100$ mass region.

In Refs. [44, 59], the time-reversal invariance was assumed from the beginning, i.e.,
the time-odd fields were neglected. In Ref. [60], the configuration-fixed constrained triaxial relativistic mean-field approach has been extended by including time-odd fields and applied to studying the candidate MχD nucleus $^{106}$Rh. It has been found that the calculations including time-odd fields have confirmed the previous prediction of the possible existence of MχD in the configuration-fixed triaxial RMF approach.

9. Summary and perspective

The significant progresses of the chirality in atomic nuclei since 1997 are briefly reviewed. A particle rotor model is developed which couples several valence protons and neutrons to a rigid triaxial rotor core and applied to investigating the chirality in odd-A nucleus $^{135}$Nd. Static chirality has been shown to be a transient phenomenon surrounding by chiral vibrations. It is found that the $B(M1)$ staggering as well as the resulting $B(M1)/B(E2)$ and $B(M1)_\text{in}/B(M1)_\text{out}$ staggering are sensitive to the triaxiality parameter $\gamma$. One cannot exclude the chirality simply by the odd-even staggering of $B(M1)/B(E2)$ values. It is further clarified that for partner bands with near degenerate energy spectra and similar $B(M1)$ and $B(E2)$ transitions, the strong $B(M1)$ staggering can be used as a fingerprint for the static chirality, i.e., the staggering is weak in chiral vibration region while strong in the static chirality region. Nevertheless, the identification of chiral doublet bands is still an open question, which needs more efforts from both experimental and theoretical sides, and continues to be a subject of intense discussions.

Acknowledgments

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