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A novel $\Delta J = 1$ sequence in ^{78}Ge: possible evidence for triaxiality

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A sequence of low-energy levels in $^{78}_{32}$Ge$_{46}$ has been identified with spins and parity of 2^+, 3^+, 4^+, 5^+, and 6^+. Decays within this band proceed strictly through $\Delta J = 1$ transitions, unlike similar sequences in neighboring Ge and Se nuclei. Above the 2^+ level, members of this sequence do not decay into the ground-state band. Moreover, the energy staggering of this sequence has the phase that would be expected for a γ-rigid structure. The energies and branching ratios of many of the levels are described well by shell-model calculations. However, the calculated reduced transition probabilities for the $\Delta J = 2$ in-band transitions imply that they should have been observed, in contradiction with the experiment. Within the calculations of Davydov, Filippov, and Rostovsky for rigid-triaxial rotors with $\gamma = 30^\circ$, there are sequences of higher-spin levels connected by strong $\Delta J = 1$ transitions which decay in the same manner as those observed experimentally, yet calculated at too high an excitation energy.

Atomic nuclei exist in a variety of shapes, with closed-shell ones adopting spherical symmetry, and those between closed shells possessing varying degrees of spheroidal deformation. For most deformed nuclei, the ground states are characterized by axially-symmetric configurations with equilibrium shapes corresponding to either prolate or oblate ellipsoids. However, in many cases, strong deviations from axial symmetry in the nuclear mean field have been observed. Evidence suggests that some nuclei, especially those in the so-called transitional regions between closed shells, exhibit structural features suggestive of shapes with broken axial symmetry. The parameter β is often used to describe an ellipsoid that deviates from spherical symmetry, yet retains axial symmetry. A deviation from axial symmetry is denoted by the γ parameter [1]. These axially-asymmetric nuclei are often described phenomenologically using two major models. The rigid-triaxial rotor model of Davydov and Filippov (DF) [2] assumes a collective potential with a stable minimum at a fixed value of γ, and, hence, a rigid triaxial shape. Subsequently, Davydov and Rostovsky [3] published expressions for the description of higher-spin states. In contrast, the γ-unstable model of Wilets and Jean (WJ) [4] incorporates a γ-independent collective potential, with wave functions spread out in the γ direction resulting in a so-called γ-soft structure.

The description of axially-asymmetric nuclei and the corresponding behavior of triaxial rotors has been a subject of much interest in nuclear-structure research [5–8]. While significant progress has been made in recent years towards understanding static and dynamic effects due to triaxiality at high angular momenta [9–14], open questions remain. One issue that has attracted much attention is whether axially-asymmetric nuclei are characterized by γ-rigid or γ-soft triaxiality in their ground-state configuration. Finding experimental evidence for low-energy static triaxiality has remained a challenge since, as summarized in Ref. [15], the underlying signatures have not been fully realized. Several studies [16, 17] have now established that the low-energy spectra of most asymmetric nuclei have structures that are generally more complex and often lie between the geometrical predictions of the DF rigid-triaxial rotor model and the WJ γ-soft prescription.

The presence of a sequence of excited states built upon the second 2^+ level at low excitation energy in deformed nuclei is generally regarded as a prerequisite for triaxiality [1–4]. However, such γ bands are most often associated with a vibration rather than a rigid triaxial shape. The staggering pattern, defined by

$$S(J) = \frac{[E(J) - E(J-1)] - [E(J-1) - E(J-2)]}{E(2^+_1)},$$

was proposed as a means of distinguishing a rigid structure from a γ-soft sequence [15]. For level energies with a dominant $J(J+1)$ spin dependence, such as found in axial rotors, all S values will be positive. For sequences in nuclei where the axial symmetry is broken, however, this function alternates between high and low values, as each odd-spin state is pushed closer to the even-spin state either above it (γ soft) or below it (γ rigid) in the band [15]. As a result, the soft and rigid cases can be distinguished by whether the even-J values for S are negative or positive, respectively. Based on this approach, the energy pattern of the γ band in ^{76}Ge, shown in Table I, suggests rigid triaxial deformation [18]. Specifically, the phase of the odd-even staggering S was shown to be consistent with the DF-model prediction.

The identification of ^{76}Ge as a possible rigid triaxial nucleus was foreshadowed theoretically by Larsson *et al.* [19], and then by Ragnarsson, Nilsson, and Sheline [20]. In the latter work, a potential-energy surface with a deep triaxially-deformed ground-state minimum centered at $\beta = 0.27$ and $\gamma = 35°$ was reported for ^{76}Ge. Furthermore, Larsson *et al.* [19] predicted non-axial shapes due to gaps in the single-particle spectrum for nuclei with neutron and/or proton numbers of 26, 32, 44, and 46 when $\beta \sim 0.3$ and $\gamma \sim 30°$. Other, more recent calculations [21] support the view of triaxiality in ^{76}Ge. Decades after the Larsson work, experimental confirmation of predictions by their approach were reported in the numerous examples of triaxiality near the ground states of the even-even $^{108-114}_{44}$Ru nuclei [22, 23] as well as in the presence of two coexisting triaxially deformed shapes in $^{72}_{32}$Ge [24].

In this Letter, a markedly different sequence of levels with spins 2^+ - 6^+ built upon the 2^+_2 state is reported in ^{78}Ge. As discussed below, although qualitatively similar to sequences in adjacent ^{72,74,76}Ge nuclei, this "band" is quantitatively different to the extent that it might possibly be viewed as a candidate for the long-sought DF rigid-triaxial rotor with $\gamma \sim 30°$. Hence, this sequence is designated by a new label, "κ band", as opposed to the traditional "γ band" applied to the even Ge neighbors. This κ band differs from the γ ones by the absence of $\Delta J = 2$ crossover transitions into lower members of the sequence, as well as by the absence of transitions into *any* of the lower-energy yrast and near-yrast states, other than the ground state, that could be populated by $\Delta J = 2$ transitions. Another puzzling property of the κ band is the presence of strong $E1$ transitions that both populate and depopulate various levels of the sequence.

The data on ^{78}Ge presented here were obtained with the Gammasphere array [25] at the ATLAS facility at Argonne National Laboratory following multi-nucleon transfer reactions of a 530-MeV ^{76}Ge beam with a thick $\sim 50\,\mathrm{mg/cm^2}$ ^{238}U target, and 450-MeV ^{76}Ge beams with $\sim$ 50mg/cm^2 ^{208}Pb and $\sim$ 31mg/cm^2 ^{198}Pt targets. Details about the experimental conditions and analysis procedures can be found in Refs. [26, 27]. In addition, data measured under similar experimental conditions with ^{64}Ni, ^{70}Zn, and ^{82}Se beams at energies ∼20% above the Coulomb barrier on thick ^{197}Au, ^{208}Pb, and ^{238}U targets were also examined for confirmation of the results presented below. Earlier work on ^{78}Ge has recently been compiled in Refs. [28, 29] and served as a starting point for the study reported here.

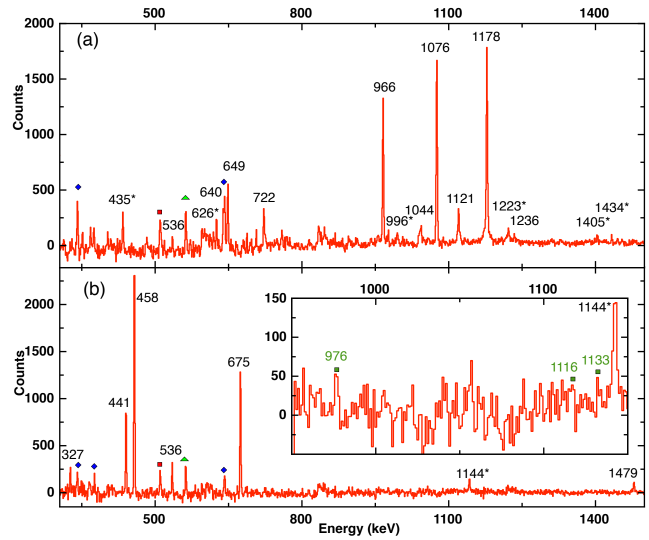

FIG. 1. (Color online). Coincidence spectra from the multi-nucleon transfer reaction of ^{76}Ge + ^{238}U with ^{78}Ge γ peaks labelled by their energies in keV. (a) Spectrum with a double gate placed on the 950.6-keV $4^+_1 \rightarrow 2^+_1$ and the 619.2-keV $2^+_1 \rightarrow 0^+_1$ transitions. (b) Spectrum in coincidence with the 619.2-keV ground-state transition and the 567.1-keV γ ray linking the 2^+_κ and 2^+_1 states. The inset in (b) is an enlargement meant to indicate the absence of the $\Delta J = 2$ crossover transitions discussed in the text. Their locations are indicated by the expected transition energies marked on-line in green. Note that, while very weak, the 976-keV peak is associated with a contaminant transition in another nucleus. The ^{78}Ge peaks identified in these spectra with an * do not appear in the partial level scheme shown in Fig. 2. The green triangles in both spectra mark a transition from the ^{76}Ge beam, while the diamonds correspond to γ rays from the ^{238}U target. A red square marks the positron annihilation peak.

The coincidence spectrum of Fig. 1(a), double-gated on the two lowest ^{78}Ge yrast transitions, depicts a 1076.0-keV γ ray from the previously established 5^-_1 level [30, 31], along with the newly identified $10^+_1 \rightarrow 8^+_1$ transition at 1120.7 keV, as well as other γ rays assigned to ^{78}Ge. The spectrum of Fig. 1(b) illustrates the γ rays feeding into the 2^+_2 (or 2^+_κ) level, and includes the proposed new κ band sequence; i.e., the 535.5-keV $6^+_\kappa \rightarrow 5^+_\kappa$, the 440.8-keV $5^+_\kappa \rightarrow 4^+_\kappa$, the 674.8-keV $4^+_\kappa \rightarrow 3^+_\kappa$, and the 457.8-keV $3^+_\kappa \rightarrow 2^+_\kappa$ transitions. The inset of Fig. 1(b) is a magnification of the region where the crossover $E2$ transitions (i.e., $6^+_\kappa \rightarrow 4^+_\kappa$, $5^+_\kappa \rightarrow 3^+_\kappa$, and $4^+_\kappa \rightarrow 2^+_\kappa$) would be expected. A partial level scheme presenting the sequences of interest here can be found in Fig. 2(a). A more complete scheme will be presented in a forthcoming publication [32].

The spin-parity assignments in Fig. 2 are based on angular-correlation data from the present measurements,

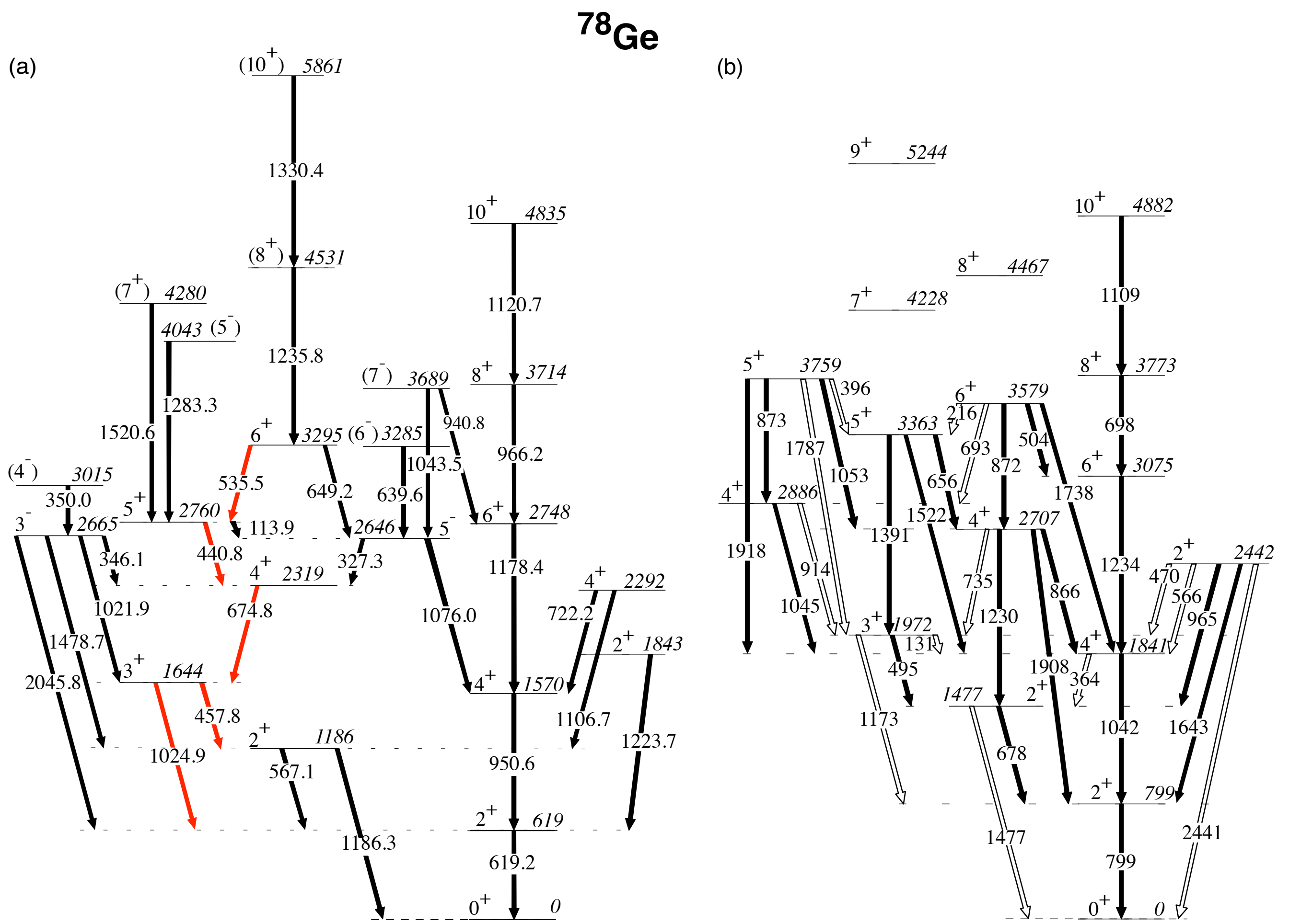

FIG. 2. (Color online). (a) Partial experimental decay scheme for ^{78}Ge. Level and transition energies are in keV. Data for $\Delta J = 1$ transitions in the proposed κ band are given in red. (b) Results from NuShellX calculations in the jj44b model space (see text). Calculated transitions with $< 10\%$ branching ratios are given with open arrows.

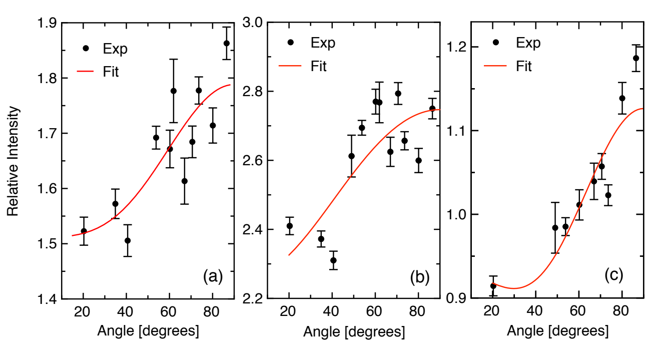

FIG. 3. (Color online). Angular correlations measured in the ^{76}Ge+^{238}U reaction; (a) the 1076.0- keV, $5_1^- \rightarrow 4_1^+$ transition in the 950.6-keV coincidence gate; (b) the 674.8-keV, $4_\kappa^+ \rightarrow 3_\kappa^+$ transition in coincidence with the 1024.9-keV γ ray; and (c) the 457.8-keV, $3_\kappa^+ \rightarrow 2_\kappa^+$ transition in the 619.2-keV gate. The curves are the result of fits to the data with a conventional expansion in terms of Legendre polynomials; i.e., $W(\theta) = A_0[1 + \frac{A_2}{A_0}P_2(\cos\theta) + \frac{A_4}{A_0}P_4(\cos\theta)]$.

complemented by earlier results from (t,p) reaction studies [30, 31] and β decay [33, 34]. Angular correlations [32, 35] for three critical cascades are presented in Fig. 3. In the gate on the 950.6-keV $4_1^+ \rightarrow 2_1^+$ γ ray [Fig. 3(a)], the 1076.0-keV line was identified as a dipole transition. Similarly, in Fig. 3(b) a gate on the 1024.9-keV κ-band transition led to the determination that the 674.8-keV γ ray is also of dipole character. The 2319- and 3295-keV states of the κ band are assigned respective 4^+ and 6^+ quantum numbers based on this work and on the results of the (t,p) reactions [30, 31]. The angular correlations involving the 457.8-keV transition [Fig. 3(c)] support a spin 3 assignment for the 1644-keV level. As a result of this analysis, firm spin and parity assignments are proposed for the levels of the yrast sequence up to the 4835-keV 10^+ state, to the 3^- and 5^- levels at 2665 and 2646 keV, as well as to the $6_\kappa^+ \rightarrow 5_\kappa^+ \rightarrow 4_\kappa^+ \rightarrow 3_\kappa^+ \rightarrow 2_\kappa^+$ cascade. Spin and parity values of 2^+ and 4^+ are firmly established for the levels at 1843 and 2292 keV, respectively, from (t,p) reaction studies.

TABLE I. Staggering values $S(J)$ observed in the even $_{32}$Ge and $_{34}$Se isotopes for $J = 4, 5, 6$.

	^{78}Ge$_{46}$	^{76}Ge$_{44}$	^{74}Ge$_{42}$	^{72}Ge$_{40}$
$S(4)$	0.35	0.09	-0.04	-0.24
$S(5)$	-0.38	-0.03	0.11	0.26
$S(6)$	0.15	0.15	0.14	-0.35
	^{80}Se$_{46}$	^{78}Se$_{44}$	^{76}Se$_{42}$	^{74}Se$_{40}$
$S(4)$	-0.36	-0.25	-0.16	-0.53
$S(5)$		0.25	0.15	0.4
$S(6)$		-0.17	0.03	-0.28

As stated above, the focus of the present discussion is on the κ band; i.e., the sequence of states linked by transitions marked in red in Fig. 2(a). It should be noted that the 5^+ and 6^+ levels of this band are fed from higher-lying states. The latter are likely of a different character in view of the transition energies and the deexcitation pattern involved. Some marked differences can be noted between the properties of the κ band and those observed in the γ bands of the even $^{72-76}$Ge isotopes and of the Se isotones. This is illustrated in Table I where the $S(4)$, $S(5)$, and $S(6)$ values of the staggering parameter are compared. At least three observations can be made. First, the $S(J)$ values in ^{78}Ge are out of phase (as those in Fig. 4 of Ref. [36])with those seen in ^{72,74}Ge and in all the Se isotones. Second, the absolute $S(J)$ values are larger than those in most other Ge and Se even-A nuclei in the immediate vicinity. First, the $S(J)$ values in ^{78}Ge are out of phase with those seen in ^{72,74}Ge and in all the Se isotones. Finally, the oscillations in the $S(J)$ values exhibit the same phase in ^{76}Ge and ^{78}Ge, where the former is the only Ge isotope for which rigid triaxiality has been proposed thus far on the basis of this behavior [18] (see also Fig. 4 of Ref. [36] for a similar behavior in nuclei of other regions suggested to adopt a triaxial shape).

Two approaches have been adopted to describe the observed level structure of ^{78}Ge. Given the success of shell-model calculations performed for ^{76}Ge [37], similar calculations have been carried out [32] for the $^{76-82}$Ge$_{44-50}$ even-A nuclei with the jj44b interaction using NuShellX [38] with a more detailed description of the model space and interaction in the Appendix of Ref. [37]. The calculated results generally agree for both the closed-shell ^{82}Ge$_{50}$ nucleus, where only broken proton pairs are involved, and ^{80}Ge$_{48}$, where one broken $\nu g_{9/2}$ neutron pair is also present. The results for ^{78}Ge are given in Fig. 2(b). Although the positions of many of the levels are reproduced qualitatively, including the $(g_{9/2})^{-2}_{8^+}$ level, no quenching of any of the $\Delta J = 2$ transitions is produced. The level energies of non-yrast states are consistently calculated over 300 keV too high, owing to cross-shell interactions unaccounted for in the jj44 model space. Yet, despite this truncation, the spin assignments

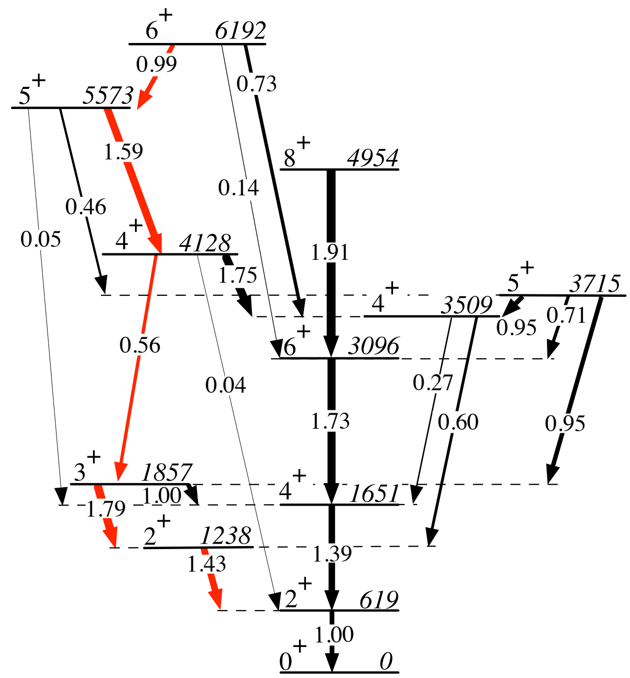

FIG. 4. (Color online). $B(E2)$ and energy-level calculations for ^{78}Ge with $\gamma = 30°$ in the DFR model with energies normalized to the experimental $2^+_1 \to 0^+$ value. The transitions in red depict the equated κ-band transitions. Transitions not shown have a $B(E2)$ value of 0.

of the positive-parity levels are sequentially in agreement. The branching from the 3^+ and 2^+_2 levels are calculated to be less than 2% into the ground-state band, whereas experimentally, the branchings determined in this work are 64% and 52%, respectively. Whether the observed 4^+_κ state should be associated with the 2707- or 2886-keV level is uncertain, but both are calculated to predominantly decay into the ground-state band by 83% (sum of two branches) and 93%, in contrast with the experimental data. The two calculated 5^+ states are different in character with the one at 3363 keV decaying primarily to the 3^+ state, and the 3759-keV one to the yrast 4^+ level. Again, the observed decay patterns do not match the observed branching in the κ band. It is, thus, concluded that the calculated branching ratios from the shell-model calculations do not account for properties observed experimentally.

The second approach adopted here considers calculations within the Davydov-Filippov-Rostovsky (DFR) model at higher excitation energies. The decay pattern for a rigid-triaxial rotor with $\gamma = 30°$ is found in Fig. 4. Several features stand out for these calculations. The 3^+_1 level has the low excitation energy expected of a rigid triaxial nucleus. Three 4^+ levels emerge, located at considerably higher energies than the nearly-degenerate experimental counterparts, with the lowest becoming the second excited state in the ground-state rotational band.

The calculated state at 3509 keV has an inhibited decay to the 3^+ level with branches that appear similar to those for the 4^+ level observed experimentally at 2292 keV, and not for the 4^+_κ state, which has a measured half-life of 43 ps [34]. Experimentally, no transitions were identified feeding into the 2292-keV state, complicating the character of the decay from the predicted 6192-keV 6^+ state. The calculated 4128-keV 4^+ state, on the other hand, has a strong branch to the 3^+_1 level with inhibited transition strength to the other lower-energy $2^+_{1,2}$ and 4^+_1 levels. The decay of this level indicates a large $B(E2)$ value to the 3509-keV 4^+ state. Experimentally, these states are 17 keV apart, with a transition that cannot be observed with Gammasphere. Two 5^+ levels also come forth, the upper of which exhibits a strong branch to the calculated 4^+_3 level with an inhibited transition strength to other, lower-energy 4^+ levels. The experimental equivalent of the 5^+ state at 3715 keV could not be identified. A second 6^+ state emerges as well with a strong branch to the second 5^+ level similar to the observations for the 3295-keV level.

Hence, a pattern is found in which pairs of states with the same spin and parity are present with the upper member decaying largely by a $\Delta J = 1$ transition as observed in the κ band. However, the DFR model predicts the states above 3^+ at much higher energies than found experimentally, states that have not yet been observed, and a $B(E2) \approx 0$ value for the $2^+_2 \to 0^+$ transition. This nonzero $B(E2)$ value in ^{78}Ge is contrary to that predicted by the DFR and that experimentally found in neighboring triaxial ^{76}Ge [18].

To summarize, the level structure of ^{78}Ge has been considerably expanded in the present work. A structure, the κ band, reminiscent of the γ bands observed in the lighter, stable, even Ge isotopes, has been delineated over the 2^+ to 6^+ range with, however, marked differences in the feeding into and the decay out of the sequence. It appears that with only four neutron holes and four proton particles with respect to the doubly-magic ^{78}Ni, this nucleus displays a rather complex interplay between single-particle and collective degrees of freedom. A number of the observed features can be accounted for in shell-model calculations using one of the most recent effective interactions. On the other hand, aspects of the decay pattern with enhanced $\Delta J = 1$ transitions and quenched $\Delta J = 2$ transitions within the band are in line with expectations of the DFR model assuming a rigid triaxial shape with $\gamma = 30°$. These observations remain challenging to describe and further experimental and theoretical work is required to elucidate the properties of ^{78}Ge further.

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