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Octupole Correlations in ^{72}Ge

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Abstract. Mean-field theories predict the emergence of strong shell gaps for particle numbers 32 and 40 when the nucleus adopts a non-axial octupole (tetrahedral) shape. There is therefore good reason to expect ^{72}Ge, with $Z = 32$ and $N = 40$, to be a strong candidate to exhibit such shapes, and this nucleus was therefore studied via the ^{70}Zn(α,$2n$)^{72}Ge reaction at a beam energy of 30 MeV. Coincident γ-rays were measured with the AFRODITE spectrometer comprising nine Clover detectors. We found no evidence for tetrahedral states in our data. However, our extension of the previously existing level scheme included a new, negative-parity, even-spin band. This band is likely the unfavoured signature partner of the band built on the previously-known $I^{\pi} = 3^{-}$ state at 2515 keV. The two negative-parity bands are interpreted as involving an aligned octupole vibration which evolves to a four-quasiparticle structure at higher spins. This talk presents spectroscopic evidence for the new band, summarizes the spin-parity assignments, and discusses the proposed configuration.

1 Introduction

Mean-field calculations have predicted [1] that nucleon numbers 32 and 40 are tetrahedrally magic, making ^{72}Ge (with $Z = 32$ and $N = 40$) a prime tetrahedral candidate. A new spectroscopic investigation of this nucleus was therefore carried out to search for tetrahedral states. However, none were found [2].

The present conference contribution details the discovery of a new negative parity band in ^{72}Ge, and its interpretation in terms of a $\lambda = 3$ octupole excitation. ^{72}Ge has a moderate ground-state prolate deformation of β_2=0.24 [3]. At this deformation the proton Fermi surface lies close to two orbitals of opposite parity: one of $p_{3/2}$ parentage, and the unique parity $g_{9/2}$ orbital. The scattering of nucleons between such $\Delta j = \Delta \ell = 3$ orbitals is known to give rise to large octupole matrix elements and consequently large octupole correlations, and these are associated with a reflection-asymmetric nuclear shape. The presence of a large number of 3^{-} terms in the wave function lowers the energy of the 3^{-} state. This is indeed true for ^{72}Ge, where the previously known 3^{-}, 2515 keV state is located at the local energy minimum. Octupole excitations have negative parity, and may exist in $K = 0, 1, 2, 3$ forms. They are characterized by strong E1 and /or E3 transitions to the ground state band.

2 Experimental Methods and Analysis

High spin states in ^{72}Ge were populated via the ^{70}Zn(α,2n)^{72}Ge reaction at a beam energy of 30 MeV, using a self-supporting ^{70}Zn target foil of thickness 5 mg/cm^2. The K=200 separated sector cyclotron facility of Ithemba LABS was used to accelerate the pulsed beam with 58 ns between beam bursts. At an incident energy of 30 MeV the dominant residual nuclei were found to be ^{72}Ge (93%) and ^{70}Ge (3%), where the figures in parentheses denote an approximate percentage of the total cross section. The data also included γ-rays emitted following the Coulomb excitation of ^{70}Zn (4%).

Coincident γ-rays were measured with the AFRODITE [4] spectrometer array comprising nine Compton-suppressed Clover detectors and five four-fold segmented Low Energy Photon Spectrometers (LEPS). The Clovers were positioned in two rings, at 90° relative to the beam direction (five Clovers) and at 135° (four Clovers). The LEPS data were not used in the analysis. The master event trigger demanded a two-or-higher-fold coincidence between any of the detectors, in coincidence with the radio frequency signal from the cyclotron. The coincidence time window was set to 150 ns. Under these conditions, and during some 50 hours of beam time, a data set of ~868 million coincident events was acquired.

In the off-line analysis, the raw event data from the Clover detectors were sorted into Radware-compatible [5] matrices. These included the matrices used in the coincidence analysis, and also the Polarization and Directional Correlation from Oriented states (PDCO) analysis.

3 The Level Scheme

The partial level scheme shown in Figure 1 displays only the yrast band and the two negative parity bands discussed in this paper. The yrast band and Band 2 were previously known, although the uppermost transition in each is new. Band 3 is observed for the first time. A detailed discussion of the construction of the level scheme may be found in the full paper [2], and thus only a brief summary is given here of the placement, and of the spin-parity assignments, of Band 3.

The coincidence spectrum displayed in Figure 2 provides experimental evidence for the placement of Band 3. It shows the γ-rays in coincidence with one of the band members, the 760 keV γ-ray, which feeds the 3829 keV level. In the spectrum one can see not only all the remaining observed band members (580, 997, 1120 keV), but also the links (1056 and 1520 keV) to the yrast band, the decay out (699 keV) of the 3829 keV level to Band 2, the decay out (747 keV) of the same level to one of the positive parity bands (omitted from the level scheme) and the lowest three yrast transitions (834, 894, 1044 keV) below 6_1^+.

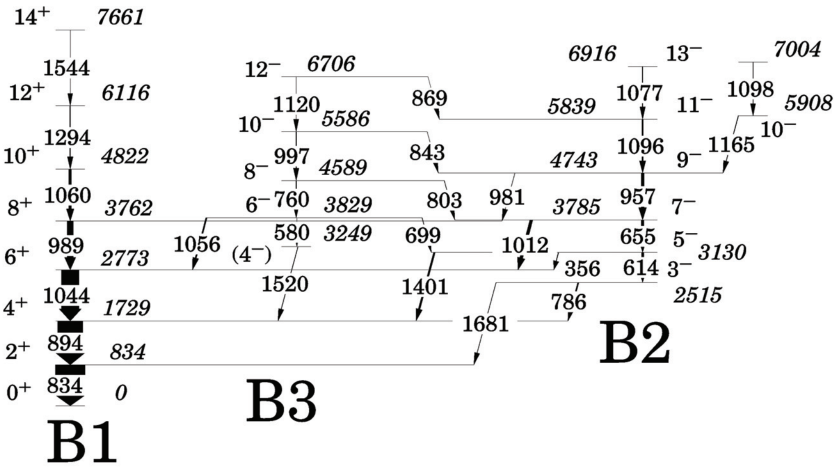

Figure 1. Partial decay scheme for ^{72}Ge, showing only the yrast band (Band 1) and the two negative parity bands. Arrow widths indicate transition intensities; uncertain I^π values appear in parentheses; the energies are in keV.

No transitions *above* 6_1^+ in the yrast band are present in the spectrum. This is proof that the 1056 keV transition which links Band 3 and the yrast band must feed the 6_1^+ yrast level.

The spins and parity of Band 3 were assigned following a thorough PDCO analysis of the linking transitions to Bands 1 and 2, and also of transitions within the band. First of all, the character of the decay-out transitions to levels in

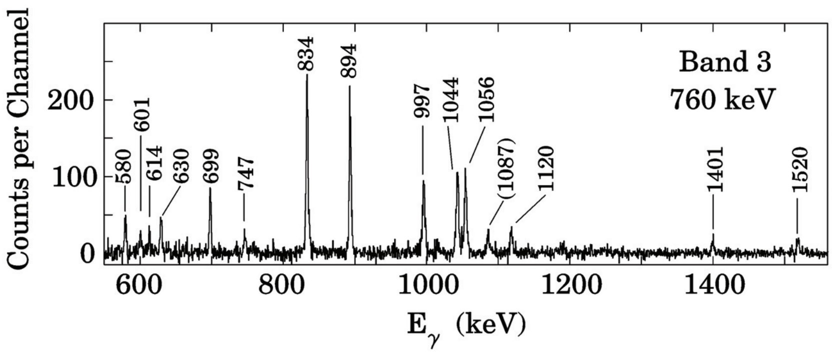

Figure 2. A coincidence spectrum obtained by setting an energy gate on the Clover-Clover matrix at 760 keV. All of the labelled γ-ray peaks could be included in the level scheme, except the one in parentheses. The spectrum clearly shows the transitions linking Bands 2 and 3, below the gating transition. The 630 and 747 keV transitions are not included in Figure 1.

Band 2, for which I^π are already known [6], was established. For example, the R_{DCO} values for two of the linking transitions, 699 and 803 keV, are respectively $0.37(5)$ and $0.46(9)$. When these were compared with theoretical predictions, they were found to be consistent *only* with mixed M1/E2 character. The respective polarization anisotropies $P = +9(13)\%, \; -28(22)\%$ are also consistent with this interpretation, in which $P < 0$ is expected. This established the parity of Band 2 as negative, and the respective spin-parity of the 3829 and 4589 keV states as 6^- and 8^-. In fact the spin-parity of all levels in Band 3, except for the 3249 keV level, could be established by PDCO analysis. Although it was not possible to firmly establish whether the 3249 keV level is 4^- or 5^+, we tentatively assigned it 4^- after considering the alignments shown in Figure 3C, which suggest that it may indeed be a band member.

4 Interpretation of the Negative Parity Bands

In order to understand the physics of Band 2, we compare it with an analogous structure in the $N = 40$ isotone ^{74}Se, which also displays an odd-spin, negative parity band (Band 5 in reference [7]). Band 2 and its isotonic analogue display similarities but also important differences, and both may hold clues to its structure. Among the similarities are the respective band-head excitation energies $E(3^-)$, 2515 and 2349 keV, and initial alignments of $\sim 2.5\hbar$, as shown in Figure 3A. Further, the decay out of the respective 3^- states have considerable $B(E3)$ strength: 9.2 W.u. for ^{74}Se [7] and 23.7 (51) W.u. for ^{72}Ge [8]. This is a fingerprint of high octupole collectivity. It is therefore likely that Band 2 is an octupole rotational band, like its partner in ^{74}Se. Indeed, the doubly-even Ge isotopes are systematically observed to exhibit octupole vibrational 3_1^- states, for example ^{70,74,76}Ge [9, 10].

The ^{74}Se analogue was interpreted by Döring *et al.* [7] in terms of octupole and 2-qp excitations. It is natural to ask, in view of these strong similarities, whether Band 2 can also be given this interpretation. However several differences between the bands suggest non-identical structures. For example, the significantly larger $B(E3)$ strength for Band 2 suggests greater octupole collectivity than ^{74}Se. The alignments and also the kinematic moments of inertia of these two octupole bands were plotted in Figure 3 to highlight some of the differences between the isotones. Differences are evident between both the alignments (Figure 3A), and the kinematic moments of inertia (Figure 3B). For example, below the AB crossing, the ^{74}Se octupole band maintains an alignment of $\sim 3\hbar$ greater than that of the ^{74}Se yrast band. In ^{72}Ge, however, the alignment of Band 2 displays an upbend at ~ 0.25 MeV, where it changes from $\sim 2.5\hbar$ to $\sim 5\hbar$ greater than the yrast alignment. The kinematic moment of inertia of Band 2 shows an upbend at the same frequency, whereas that of the ^{74}Se analogue is flat. This indicates a structural change in Band 2 at ~ 0.25 MeV which is not exhibited by the ^{74}Se octupole band. This change is also reflected in the plot of the static moment of inertia of Band 2, at $(\hbar\omega)^2 \simeq 0.1$ MeV^2, as shown in reference [2].

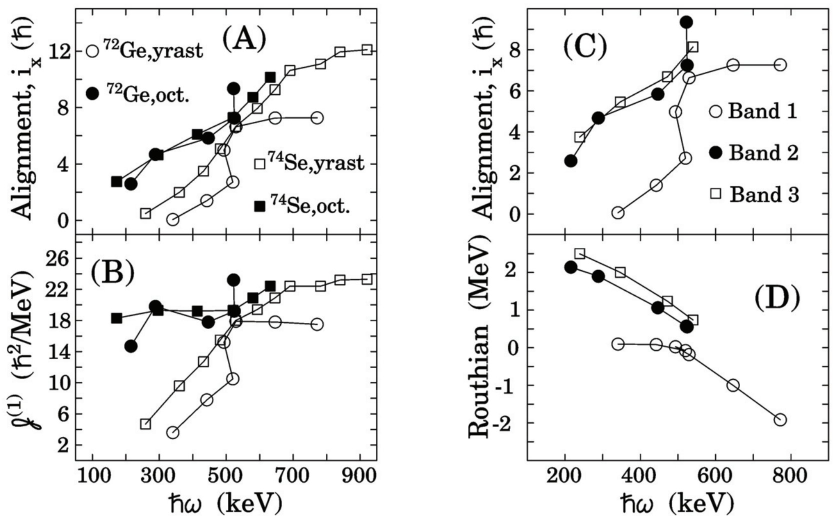

Figure 3. On the left are the alignments (panel A) and kinematic moments of inertia (panel B) of the yrast and octupole bands of the isotones ^{72}Ge and ^{74}Se. These are, respectively, Bands 1 and 2 of ^{72}Ge, and Bands 2 and 5 of ^{74}Se, in reference [7]. On the right are the alignments (panel C) and routhians (panel D) of the yrast band (Band 1) and negative parity Bands 2 and 3 of ^{72}Ge. The chosen Harris parameters, $J_0 = 3.0$ MeV^{-1} and $J_1 = 8.5\ \hbar^4$ MeV^{-3}, imposed zero alignment on the first data point of Band 1. Therefore the ordinate denotes relative alignment.

We therefore propose that the bottom of Band 2 is an aligned octupole vibration. At higher rotational frequencies, between ~ 0.25 and ~ 0.5 MeV, the wavefunction changes to involve 2 quasiparticles. This accounts for the large $\sim 5\hbar$ difference in alignment between the yrast band and Band 2. The quasiparticles cannot be the A or B neutrons, because at ~ 0.5 MeV the band undergoes the AB crossing, and presumably evolves to a 4-qp structure. The ^{74}Se analogue of this band was also given the 2qp→4qp interpretation [7]. It is not clear to what extent the octupole vibrational character persists to high spins.

We now consider how to interpret the new band, Band 3. At low spins, Figure 3C shows that the alignment patterns of Band 3 and Band 2 are nearly parallel, suggesting a common underlying intrinsic structure. Further, the moments of inertia of these two bands are almost identical below the upbend (in Band 2), as may be seen in the full paper [2]. This may also be expected for bands with similar configurations. In both cases the moments of inertia are significantly larger than that of the yrast band. This may be due to a larger deformation or reduced pairing associated with the proposed 2-qp configuration. The two bands are connected by several $\Delta I = 1$, $M1/E2$ transitions, commonly observed in signature-partner bands. Figure 3D shows that the experimental routhians of the band lie above those of Band 2, with an energy splitting of ~0.42 MeV at frequency 250 keV, and they lie about 2.4 MeV above those of the yrast band. We therefore interpret this even-spin band as the hitherto unobserved $\alpha = 0$, unfavoured signature partner of Band 2.

Finally, we consider the question of why no tetrahedral states were observed in the data. Even though the mean field calculations predicted tetrahedral shell gaps at nucleon numbers 32 and 40, the potential energy surface plot for ^{72}Ge showed no tetrahedral minimum, as discussed in reference [2]. A possible explanation for this may be that there exists a delicate balance between shell effects and pairing. Zberecki *et al.* [11] performed Hartree-Fock calculations with Skyrme interactions to predict the energy as a function of the tetrahedral deformation parameter β_{32}, for the nuclei $^{80,98}_{40}$Zr. Without pairing, an energy minimum is predicted at $\beta_{32} \sim 0.24$. However, the minimum disappears upon the inclusion of pairing. This indicates that there may be competition between the stabilizing effects of pairing on the one hand and tetrahedral correlations on the other. Whereas the tetrahedral shell gap favours the formation of a tetrahedral minimum, pairing correlations are strongest for a spherical shape, and are smaller in the tetrahedral minimum. In this scenario, therefore, a tetrahedral shape is not favoured.

5 Summary

The present conference contribution has focused on octupole and tetrahedral correlations in the nucleus ^{72}Ge, as studied in the ^{70}Zn(α,2n)^{72}Ge reaction at a beam energy of 30 MeV. There was no firm evidence for the existence of tetrahedral structures in our data. There is however evidence for strong octupole correlations in ^{72}Ge. A new negative-parity $\alpha = 0$ band is likely the signature partner of the previously known $\alpha = 1$ negative-parity band, the new band being the unfavoured partner. We have interpreted these structures as a rotation-aligned octupole vibration coupled at intermediate spins to 2-qp, and probably evolving to a 4-qp excitation above a rotational frequency of 0.5 MeV. The further evolution of this band with increasing spin awaits investigation.

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