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# Possible excited deformed rotational bands in $^{82}$Ge

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Excited states of neutron-rich nucleus $^{82}$Ge were studied from the spontaneous fission of $^{252}$Cf. Eleven new transitions and seven new levels in $^{82}$Ge were identified by using X(Dy)-$\gamma-\gamma$ and $\gamma-\gamma-\gamma$ triple coincidences. Possible excited deformed rotational bands are observed, for the first time, in this nuclear region. Coexistence of the spherical ground and deformed excited shapes is proposed in $^{82}$Ge. These deformed rotational bands can be formed by 2-particle, 2-hole excitations with the $0^+$ pairing energy states of the $\nu 9/2[404]^{-2}\otimes 1/2[431]^2$ configuration across the N=50 closed shell.

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Recently, neutron-rich nuclei around the doubly magic nucleus, $^{78}$Ni, have attracted much attention as to whether or not spherical shell gaps at Z=28 and N=50 are quenched. The interest in these nuclei is because they are closely related to the r-process nucleosynthesis responsible for the formation of the heavy elements above the iron isotopes, as well as the expected exotic nuclear structure for these nuclei. Recently, several experiments have been carried out identifying excited states in nuclei in the N=50 region. Winger et al. [1] by studying the levels in $^{84}$Ge, suggested a possible reduction of the Z=28 shell gap for the double magic $^{78}$Ni core by studying nuclei beyond N=50. Padgett et al. [2], essentially the same group as in Ref. [1], by studying the $\beta$ decay of $^{81}$Zn to the levels in $^{81}$Ga provided evidence for a strong neutron shell gap at N=50. Van de Walle, et al. [3], in a Coulomb excitation experiment, by comparing their extracted B(E2;$0^+\rightarrow 2^+$) values for Zn isotopes with large-scale shell-model calculations, came to the conclusion that these nuclei have a strong N=50 shell gap and a strong core polarization at Z=28.

It has been known since the year 2007 that another r-process waiting-point nucleus, $^{130}$Cd, responsible for the solar r-process abundance peak around A=130 does not have a N=82 shell quenching effect [4,5]. In the case of $^{130}$Cd, shape coexistence has been invoked without shell quenching effects [4]. Therefore, it is interesting to investigate whether the nuclei around N=50 have shell quenching and/or shape coexistence. In terms of exotic nuclear structure, it is challenging to search for other magic numbers in the neutron-rich nuclei.

Since the experimental data for nuclei around $^{78}$Ni are limited, we have made an attempt to identify $^{82}$Ge in our spontaneous fission (SF) data and establish its level scheme. In the present work, the prompt $\gamma$ transitions of $^{82}$Ge(Z=32, N=50) were identified from a $^{252}$Cf SF study. From the analysis of these data, two possible deformed excited rotational bands are proposed, for the first time in the region around $^{78}$Ni. The coexistence of deformed excited rotational and spherical ground bands is reported experimentally in this work. These rotational bands are interpreted in terms of 2-particle, 2-hole excitations with the configuration of $\nu 9/2[404]^{-2}\otimes 1/2[431]^2$ across the N=50 closed shell.

The experimental data were obtained from a $^{252}$Cf spontaneous fission source with 62 $\mu$Ci strength which was sandwiched between two Fe foils of thickness 10 mg/cm$^2$ and mounted in a 7.62 cm diameter plastic (CH) ball to absorb beta rays, conversion electrons and partially neutrons. The prompt $\gamma$ rays were detected by using the 101 Ge detectors of the Gammasphere. A total of 5.7x10$^{11}$ triple- and higher-fold $\gamma$ coincidence events were obtained. The prompt time window is approxiamtely 100ns. The data were analyzed by using the Radware software package [6].

A partial level scheme of $^{82}$Ge was established previously from SF of $^{248}$Cm [7] and beta decay work of $^{82}$Ga [1,8,9]. The previously known $\gamma$ transitions of 646.0, 938.5, 940.5, 984.8, 1176.2, 1348.5 and 1908.9 keV are confirmed in the present work. In the coincidence spectrum (Fig. 1) double-gated on the 1348.5 and 938.5 keV transitions of $^{82}$Ge, the Dy x-ray of 45.6 keV and the 646.0 and 940.5 keV transitions are observed. The Dy x-ray peak at 45.6 keV is the combined peak of Dy $K_{\alpha 1}$ (45.998 keV) and Dy $K_{\alpha 2}$ (45.208 keV) [10] which have the relative intensities of 47.5 and 26.8, respectively. The 176.9 and 273.4 keV transitions of $^{166}$Dy are seen because the 4n partner nucleus of $^{82}$Ge is $^{166}$Dy. In the coincidence spectrum (Fig. 2) double-gated on the 1348.5 keV transition of $^{82}$Ge and the Dy x-ray peaks (see Fig. 2), the 1176.2, 1312.5, 1609.1 and 1707.0 keV transitions are seen. A 2215.3 keV transition from a second $2^+$ state at 2215.3 keV populated strongly in $\beta$ decay is not observed in our work. The 867.2 keV transition depopulating the 2215.3 keV level is also not seen and is at least 10 times weaker than the 938.5 keV transition observed in our data. Nine new $\gamma$ transitions of 191.4, 359.9, 369.6, 512.6, 756.2, 1312.5, 1609.1, 1707.0 and 2524.7 are firmly identified with two more $\gamma$ transitions of 201.9 and 3257.4 keV tentatively assigned from SF of $^{252}$Cf in the present work. A new level scheme of $^{82}$Ge with seven new levels in Fig. 3 is established based on the coincidence relationships and relative intensity comparisons between the $\gamma$ transitions as explained in the following paragraphs.

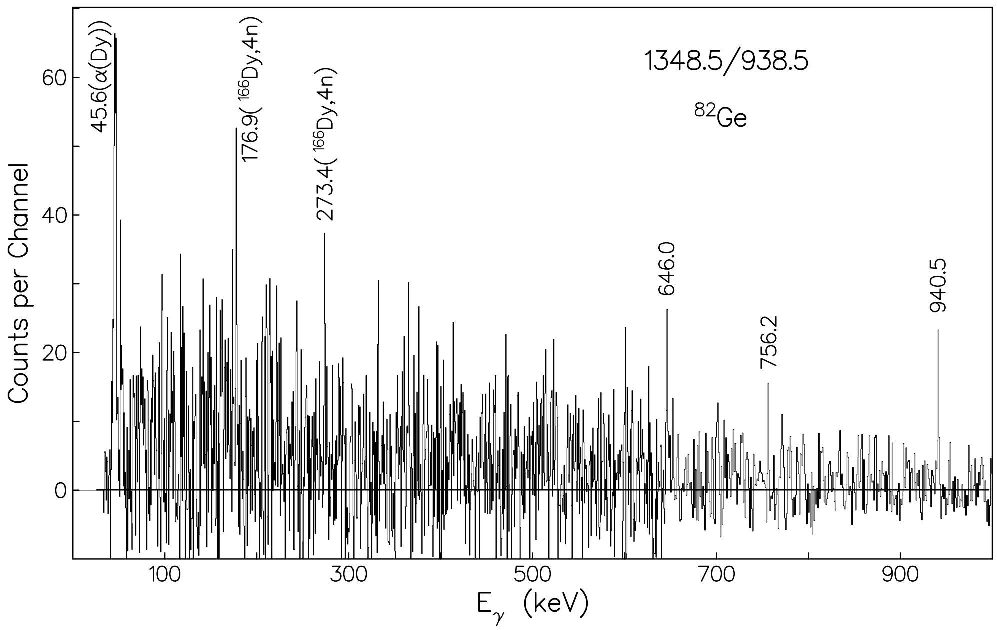


FIG. 1: Coincidence spectrum double-gated on the 1348.5 and 938.5 keV transitions of $^{82}$Ge.

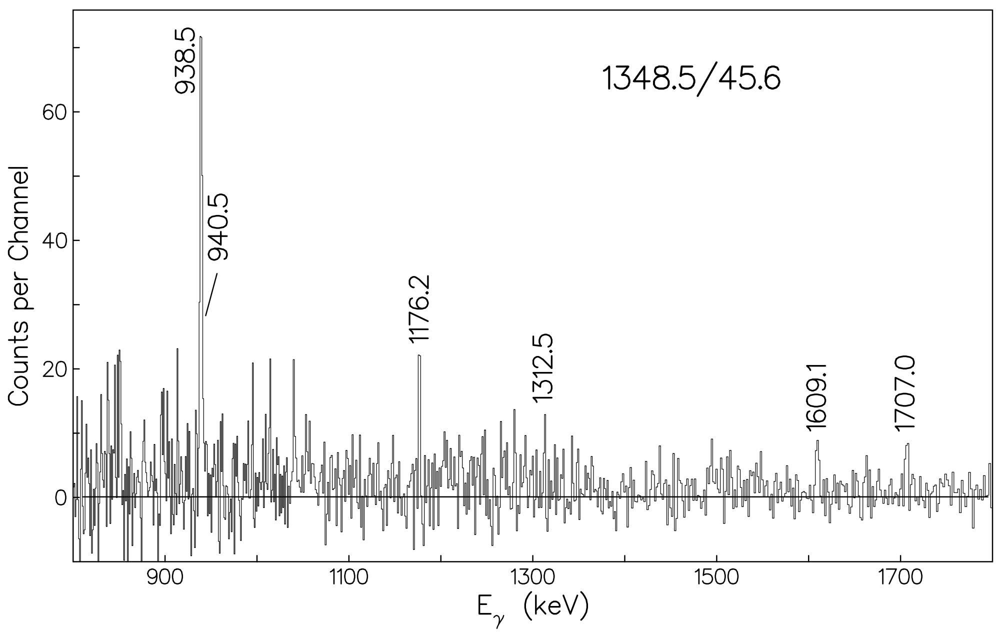


FIG. 2: Coincidence spectrum double-gated on the 1348.5 keV transition of $^{82}$Ge and the Dy x-ray peaks (45.998 and 45.208 keV). Here a little wider gate width (1.5FWHM) at the energy of 45.6 keV was used in order to include two $K_\alpha$ x-ray peaks (45.998 and 45.208 keV). Relative intensities of 45.998 and 45.208 keV x-rays are 47.5 and 26.8, respectively [10].

By comparing Figs. 2 and 4a, one notices that the 1176.2, 1312.5 1609.1 and 1707.0 keV transitions are coincident with the 1348.5 keV transition but not with the 938.5 keV transition. The 1908.9 keV transition (seen in $\beta$ decay) was too weak to be confirmed in Fig. 2. The 369.6 keV transition is seen in the coincidence spectrum (Fig. 4b) double-gated on 1908.9 and 1348.5 keV transitions. Further, the 1908.9 keV transition is observed in the coincidence spectrum double-gated on 369.6 and 1348.5 keV transitions. Also, in the coincidence spectrum(Fig. 5) double-gated on the 1348.5 and 1176.2 keV transitions (seen in $\beta$ decay and confirmed in our work) in $^{82}$Ge, the new 359.9 and 512.6 keV transitions are identified along with the Dy x-ray peak at 45.6 keV. In

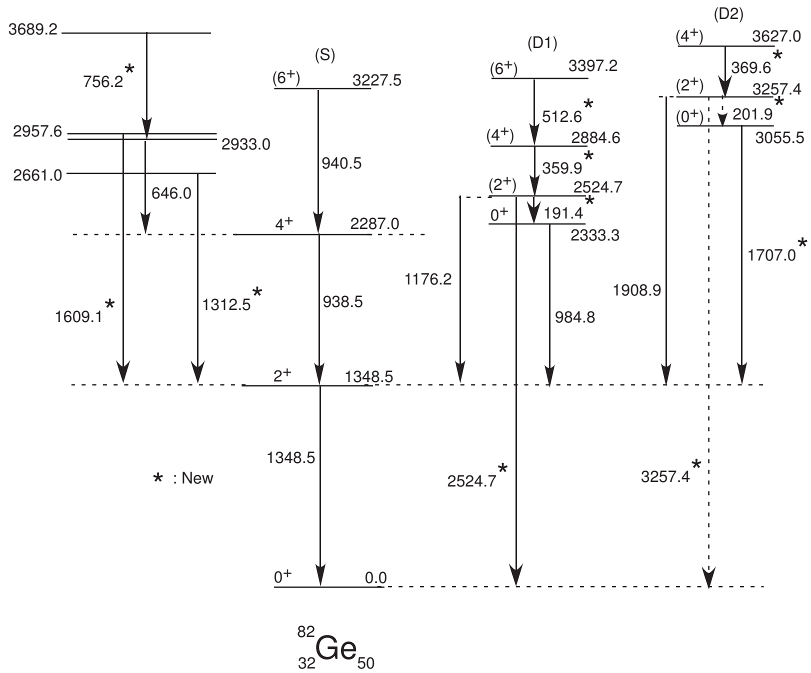


FIG. 3: New level scheme in $^{82}$Ge. New transitions are indicated by ∗. The 646.0, 938.5, 940.5, 984.8, 1176.2, 1348.5 and 1908.9 keV transitions were previously observed [1,7,8,9]. The 2661.0, 2884.6, 2957.6, 3055.5, 3397.2, 3627.0 and 3686.2 keV levels are new.

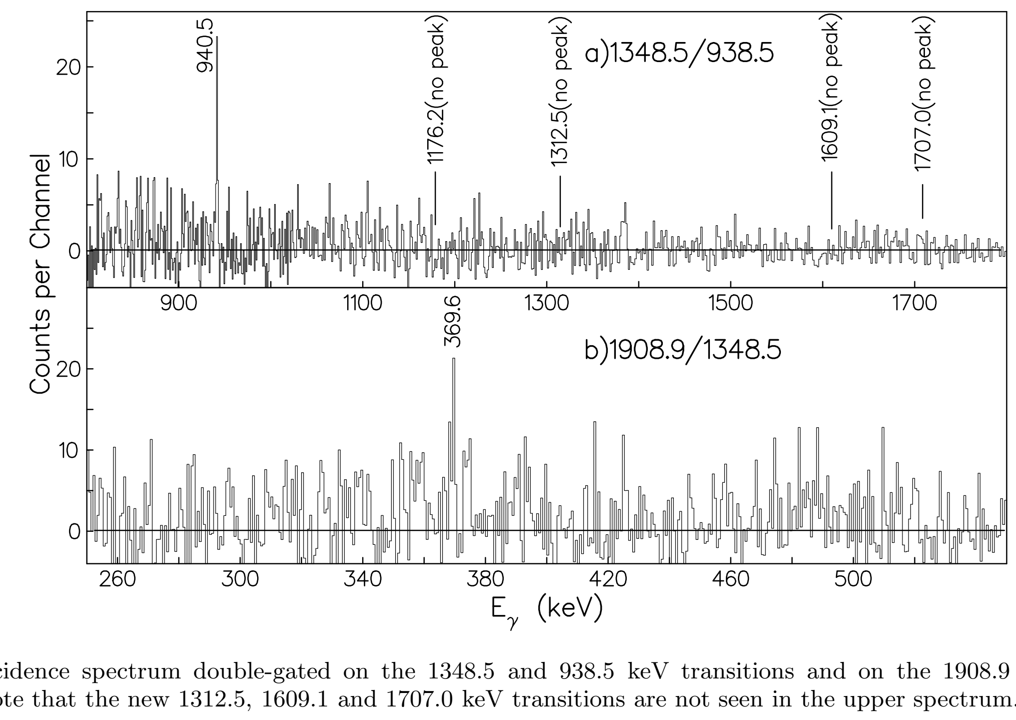


FIG. 4: Coincidence spectrum double-gated on the 1348.5 and 938.5 keV transitions and on the 1908.9 and 1348.5 keV transitions. Note that the new 1312.5, 1609.1 and 1707.0 keV transitions are not seen in the upper spectrum.

the coincidence spectrum (see Fig. 6c) double-gated on the 512.6 and (1176.2 "and gate" 1348.5) keV transitions, the 359.9 keV transition is seen. Therefore, the 512.6 keV transition is placed above the 359.9 keV transition in the $^{82}$Ge level scheme in Fig. 3. The coincidence spectrum double-gated on the 359.9 and 1348.5 keV transitions could not be used to identify the 512.6 keV transition because of the strong interference of the 511.0 keV peak. Note that the intensity of the 512.6 keV transition is about 30% of the 359.9 keV transition intensity in

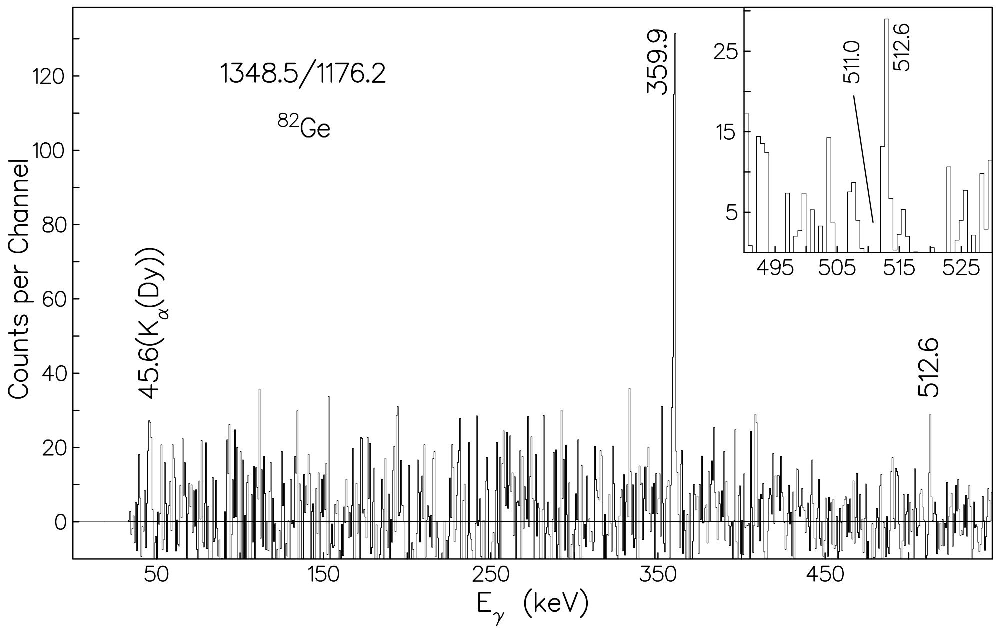


FIG. 5: Coincidence spectrum double-gated on the 1348.5 keV transition and the 1176.2 keV transition in $^{82}$Ge. Note that the 511.0 keV ($e^+e^-$ annihilation peak) peak is not observed.

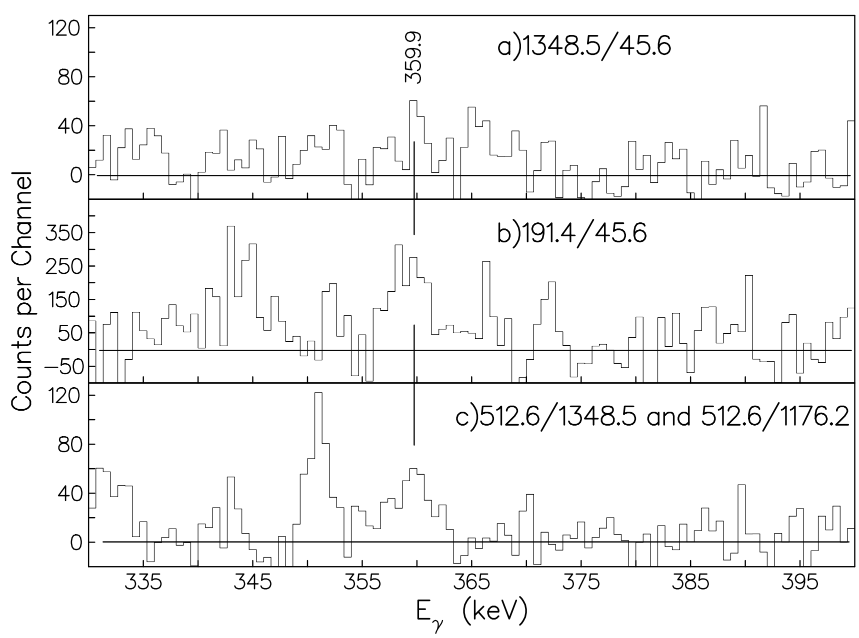


FIG. 6: Coincidence spectrum double-gated on the Dy $K_\alpha$ x-ray peaks (45.998 and 45.208 keV) and the a) 1348.5 and b) 191.4 keV transitions of $^{82}$Ge. The "and"in fig. c means "and gate"adding two spectra. Here a little wider gate width (1.5FWHM) at the energy of 45.6 keV was used in order to include two $K_\alpha$ x-ray peaks (45.998 and 45.208 keV). The 359.9 keV transition is seen in all three spectra.

Fig. 5. The ratio is similar to the intensity ratio of the 940.5 and 938.5 keV transitions. The 191.4 keV transition in band (D1) is placed in the level scheme because the 359.9 keV transition is seen in the coincidence spectrum double-gated on the 191.4 keV transition of $^{82}$Ge and the Dy $K_\alpha$ x-ray peaks (45.998 and 45.208 keV)(see Fig.6b). In the coincidence spectrum double gated on the 1348.5 keV transition of $^{82}$Ge and the Dy $K_\alpha$ x-ray peaks (45.998 and 45.208 keV)(see Fig.6a) the 359.9 keV transition is observed. Similarly, the 201.9 keV transition in band (D2) is tentatively placed because a weak 201.9 keV transition is observed in the coincidence spec-

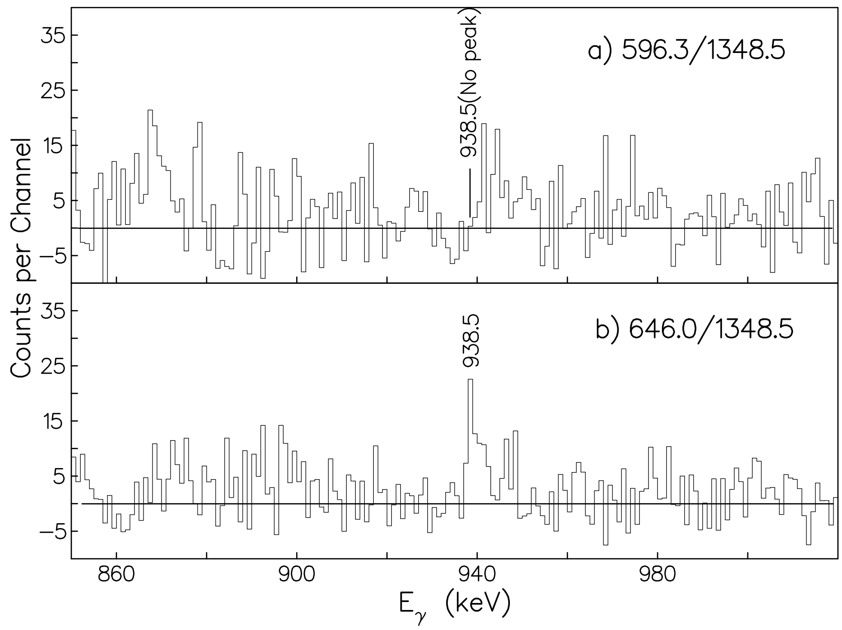


FIG. 7: Coincidence spectrum double-gated on a possible 596.3 and the 1348.5 keV transitions and the 646.0 and 1348.5 keV transitions.

trum double-gated on the 1707.0 and 369.6 keV transitions. The 2524.7 keV transition is identified from the fact that the 359.9 keV transition is seen in the coincidence spectrum double-gated on the 45.6 keV Dy x-ray and 2524.7 keV transition and the presence of a 2524.7 keV transition in the coincidence spectrum double-gated on the 45.6 keV Dy x-ray and 359.9 keV transition. The tentatively assigned 3257.4 keV transition is seen in the coincidence spectrum double-gated on the 45.6 keV Dy x-ray and 176.9 keV transition in $^{166}$Dy. A 596.4 keV transition is reported to depopulate a level at 2883.35 keV in beta decay [1].This might be a transition from our state at 2884.6 keV to the $4^+$ ground band level at 2287.0 keV. However, as seen in Fig. 1 and more clearly in Fig. 7a there is no transition in our coincidence spectra at 596.4 keV. Thus we do not see their 2883.35 keV level nor do we see their levels at 2702.4, 2713.5 and 3014.7 keV. Therefore, our level at 2884.6 keV is a new level. The 938.5 keV transition is seen clearly in the coincidence spectrum double-gated on the 646.0 and 1348.5 keV transitions in Fig. 7b. In the coincidence spectrum double-gated on the 646.0 and 938.5 keV transitions, the 1348.5 and 756.2 keV transitions are seen. Therefore, the 756.2 keV transition is placed above the 646.0 keV transition in the $^{82}$Ge level scheme (Fig. 3).

The $^{82}$Ge nucleus has 32 protons and 50 neutrons. It has four valence protons beyond the Z=28 shell closure and zero valence neutrons beyond the N=50 shell closure. This nucleus has a spherical shape in its ground state band (band (S) in Fig. 3) as easily evidenced from the relatively large $2^+ \rightarrow 0^+$ transition energy. Recently, Gade et al.[11] measured the B(E2) strength for the 1348.5 keV state and deduced a $\beta_2$ value of 0.2. The $0^+$ spin and parity of the 2333.3 keV state were assigned by Hoff et al. [8] and Winger et al. [1]. The 2215.4 (not seen in our work), 2333.3 and 2287.0 keV levels were assigned by Hoff et al. [8] and Rzaca-Urban et al. [7] as the $2^+$, $0^+$ and $4^+$ states, respectively.

The assignment of $2^+$ to the 2524.7 keV level is plausible because it decays to the $0_1^+$, $0_2^+$ and $2_1^+$ states. If we accept $2^+$ to the 2524.7 keV level, then the assignment of $4^+$ and $6^+$ to the 2884.6 and 3397.2 keV levels are reasonable. These states along with the 2333.3 keV $0^+$ level form a band (D1) that has a larger deformation. The energy spacings approximately obey the I(I+1) rule. The 201.9 and 369.6 keV transition energies in band (D2) are similar to the 191.4 and 359.9 keV transition energies, respectively, in band (D1). The 1908.9, 1707.0 and 3257.4 keV transitions between bands (D2) and (S) correspond to the 1176.2, 984.8 abd 2524.7 keV transitions, respectively, between bands (D1) and (S). Because of these similar energy spacings and decay patterns, the spins and parities of the states of the band (D2) are assigned, tentatively, to be the same as band (D1). The 3257.4 keV transition supports the $2^+$ assignment.

The relatively strong 1707.0 and relatively weak 984.8 keV transitions can be explained by the mixing of different deformations as follows. The 191.4 keV transition is weak because most of the transition strength goes out of the 2524.7 keV level by the 1176.2 keV transition. The 191.4 keV transition intensity is distributed to the 2333.3 keV E0 and 984.8 keV E2 transitions. E0 transition strength will be enhanced if two $0^+$ states having different deformations are mixed because the E0 matrix element is sensitive to changes in the mean-square radius [12]. Strong E0 $0_2^+ \rightarrow 0_1^+$ transitions have been observed, for example, in $^{184,186,188,190}$Hg [13,14,15,16] and $^{114,116,118,120,122}$Sn [12] isotopes related to the shape coexistences. The relatively weak 984.8 keV transition in Fig. 2 can be explained by a relatively strong 2333.3 keV E0 transition which would indicate a mixing of the $0_1^+$ and $0_2^+$ states with different deformations. The relatively strong 1707.0 keV transition in Fig. 2 may indicate small or no mixing of the $0_1^+$ and $0_3^+$ states with different deformations.

The $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, $6^+ \rightarrow 4^+$ energies in band (D1) are 191.4, 359.9 and 512.6 keV, respectively, which are very similar to those (192.4, 368.6 and 519.4 keV) of the ground rotational band in strongly deformed $^{104}$Mo. By using the empirical Grodzins formula [17],

$$\beta_2(Ge) = \beta_2(Mo)\sqrt{\frac{A^{7/3}(Mo)E(Mo)}{A^{7/3}(Ge)E(Ge)}}$$

where E is the $2^+ \rightarrow 0^+$ transition energy, we extract a quadrupole deformation of $\beta_2 \approx 0.43(2)$ for bands (D1) and (D2). The quadrupole deformation value of 0.325(12) in $^{104}$Mo extracted from the measured B(E2; $0^+ \rightarrow 2^+$) value [18] was used.

Bands (D1) and (D2) likely have prolate-spheroidal shapes arising from the promotion of a pair of neutrons across the N=50 shell gap. Such pair promotion opens up neutron-pairing energy gain, lowering the gap. Heyde et al. [19] reported that the band head energies around 2 MeV of the excited deformed $K^\pi = 0^+$ rotational bands of the Sn isotopes with the spherical ground deformation can be reproduced by a shell-model calculation including the proton $0^+$ pairing interaction, and the proton-neutron monopole and quadrupole residual interactions caused by proton 2-particle, 2-hole (2p-2h) excitations across the Z=50 magic shell gap. The 2.33 and 3.06 MeV band head energies of the deformed $K^\pi = 0^+$ rotational bands assigned in $^{82}$Ge with the magic number of N=50 may be explained by the promotion of a neutron pair across the N=50 shell gap from $1g_{9/2}9/2[404]$ into $2d_{5/2}1/2[431]$. Then the rotational bands (D1 and D2) can be formed by 2 particle and 2 hole excitations taking into account the $0^+$ pairing energy of the $\nu 9/2[404]^{-2} \otimes 1/2[431]^2$ configuration across the N=50 shell. The neutron $0^+$ pairing interaction, and the proton-neutron monopole and quadrupole residual interactions have to be considered in the shell model calculations. Wood et al. [20] calculated the 2p-2h excitation energies across the N=50 closed shell. In this case, they used, as the core nucleus, $^{78}$Ni with the magic numbers of Z=28 and N=50. Their calculations predict the 2p-2h excited energies around 4 MeV which are higher than our experimental $0^+$ excitation energies. We do not know whether this energy difference is because of the weakening of the N=50 shell gap or the uncertainty in the model. Therefore, a better microscopic approach in theoretical calculations is needed to explain the experimental $0^+$ states.

In conclusion, Eleven new transitions and seven new levels in $^{82}$Ge were identified. Two excited deformed rotational bands are assigned indicating shape coexistence of the spherical ground and deformed excited states in $^{82}$Ge. The quadrupole deformation values of the excited deformed rotational bands are estimated to be around $\beta_2 \approx 0.43(2)$. These deformed rotational bands can be formed by 2-particle 2-hole excitations taking into account the $0^+$ pairing energy of the $\nu 9/2[404]^{-2} \otimes 1/2[431]^2$ configuration across the N=50 shell.

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