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Level structure of odd-odd ^{68}Ga

A.K. Singh[1], G. Gangopadhyay[1], D. Banerjee[1], R. Bhattacharya[1], R.K. Bhowmik[2], S. Muralithar[2], R.P. Singh[2], A. Goswami[3], S. Bhattacharya[3,a], B. Dasmahapatra[3], and S. Sen[3]

[1] Department of Physics, University College of Science, University of Calcutta, 92, A.P.C. Road, Calcutta-700 009, India
[2] Nuclear Science Centre, New Delhi-110 067, India
[3] Saha Institute of Nuclear Physics, Calcutta-700 064, India

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Abstract. Excited states of ^{68}Ga have been investigated through the ^{55}Mn(^{16}O, 2pn) reaction at projectile energy 55 MeV. The level scheme has been extended up to 7.8 MeV. Altogether six new excited levels could be identified and twelve previously unobserved γ-transitions have been placed in the modified level scheme.

PACS. 27.50.+e 59 $\leq A \leq$ 89 – 23.20.Lv Gamma transitions and level energies – 23.20.En Angular distribution and correlation measurements

In beam γ-ray spectroscopic investigation of nuclei in the mass region $A \simeq$ 60–70 over the past several years has unveiled many interesting aspects of nuclear structure like transition from oblate to prolate shape, octupole collectivity, gamma instability etc. In addition these experiments have also revealed a variety of excitation modes involving different degrees of freedom which are present in both low and high spin regime. For example, the recent studies of the high spin states of Zn [1] and Ge [2,3] nuclei populated through heavy-ion reaction have revealed a large variety of rotational and vibrational degrees of freedom in these nuclei. All these features cannot be explained within a single theoretical model but, in general, these are understood in terms of the gaps in the Nilsson single particle energy at Z, $N = 38$ for prolate and Z, $N = 36$ for oblate deformation. In this mass region the $g_{9/2}$ orbital also plays an important role in producing high spin and one can expect a complex interplay between different types of collective modes as well as collective and single particle excitations. For example, the high spin states above $I = 8\hbar$ in this region are expected to exhibit this complex interplay originating due to alignment of neutrons in $g_{9/2}$ orbital. In fact, this phenomenon was observed in ^{66,68}Ge [2,3] and ^{64}Zn [1]. In the present paper we report the results of our investigation on the high spin states of ^{68}Ga through heavy ion induced reaction. Like other odd-odd nuclei, ^{68}Ga also offers an opportunity to study the residual interaction between a single proton and a single neutron.

The level properties of ^{68}Ga have earlier been studied [5-9] through (p, nγ) and (α, nγ) reactions. Excited levels up to about 4 MeV in energy and spin-parity up to 11^+ were already known from these studies. An isomeric level at 1228 keV (I^π=7^-, $T_{1/2}$= 64 ns.) was identified through the (α, nγ) reaction and has also been studied via the reaction ^{56}Fe(^{15}N, n2p) [9]. No other heavy ion fusion-evaporation reaction has been used to study this nucleus. Information on the levels identified and their properties are available in the compilation by Bhat [10].

In the present experiment, the excited states of ^{68}Ga have been populated through the fusion-evaporation reaction ^{55}Mn(^{16}O, 2pn)^{68}Ga at a projectile energy 55 MeV using the 15UD Pelletron facility at Nuclear Science Centre (NSC), New Delhi. The target ($\sim$ 2 mg/cm^2) of Mn was deposited on a 7 mg/cm^2 gold foil. The Gamma Detector Array (GDA) at the NSC with seven HPGe detectors (25%) along with Anti Compton Shields were utilised for this purpose. The detectors were placed at 45°, 99° and 153° with respect to the beamline. A charged particle detector array (CPDA) consisting of 14 phoswich detectors was used. Each detector of the CPDA is made up of fast-slow Plastic Scintillators, the front one of which is thin (BC400 – 0.1nm), has a fast rise time and used as a ΔE detector and the rear one (BC 444 – 5mm) has a slow rise time and is used as an E detector. This combination was used to identify the channels of interest. Each detector was placed at a distance of 6 cm from the target; four in the forward direction, four in the backward direction and the other six around 90° to the beamline giving a solid angle coverage of $\sim$ 90%. More details of the CPDA may be found in [11]. The other nuclei populated in the experiment were ^{68,69}Ge, ^{65,66}Ga and ^{65,66}Zn. Most of the γ-rays coming from different channels have been found to be non-overlapping. The events were recorded in the list mode with the condition that at least two HPGe detec-

[a] e-mail: sudeb@anp.saha.ernet.in

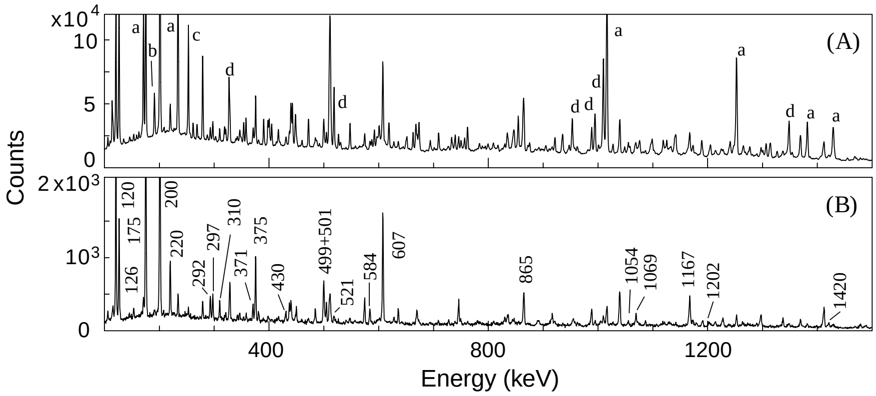

Fig. 1. Total projection spectrum (A) of the γ-γ matrix and projection spectrum (B) of the γ-γ matrix along with an added constraint that two particles hit the CPDA. The letters a,b,c,d refer to the γ-rays from ^{68}Ge, ^{65}Ga, ^{66}Ga and ^{69}Ge, respectively in A. The γ-rays from ^{68}Ga are shown in B.

tors recorded a γ-ray. Imposing an additional constraint, through software gating, that the charged particle array records two particle hits helped us in finding out the γ-rays belonging to ^{68}Ga, as among the residual nuclei produced in the experiment with large cross-section, only ^{68}Ga were produced via two-proton evaporation.

The pulse height of each detector was gain matched to 0.5 keV/channel. The data were sorted in $4K \otimes 4K$ γ-γ matrices. This γ-γ matrix also contained transitions from ^{65}Zn because of the incomplete separation between α and p events in the charged particle array, particularly in the backward direction. Figure 1 shows the total projection spectrum (A) of the γ-γ matrix along with the corresponding spectrum (B) with added constraint, mentioned above, on the charged particle. In spectrum A, major transitions coming from ^{68,69}Ge and ^{65,66}Ga are indicated. The γ-rays coming from ^{68}Ga are shown in the spectrum B. It is easily seen that the γ-rays marked in spectrum A are not present in spectrum B and the channel of interest clearly stands out in it. However, the γ-rays belonging to ^{65,66}Zn are also present in the spectrum, for the reason mentioned above.

It is obvious that due to the presence of an isomeric level of half life 64 ns at 1228 keV (7^-), a very narrow gate on the TAC spectrum would yield little fruitful coincidence information between the transitions de-exciting via cascades to this level and those between the low-lying levels. The data were, therefore, analysed using two TAC gates, one of width 50 ns and another of 125 ns by which we could study cascades above the isomeric level at 1228 keV.

The multipolarities of the observed γ-rays are determined through the directional correlation orientation (DCO) ratio measurements. A separate $4K \otimes 4K$ γ-γ matrix has been generated with the events recorded at 99° along one axis and those recorded at 153° along the other axis. The DCO ratio was then determined as

$$R_{\rm DCO}(\gamma_1) = \frac{\text{I}(\gamma_1 \text{ at } 99^\circ \text{ with } \gamma_2 \text{ at } 153^\circ)}{\text{I}(\gamma_1 \text{ at } 153^\circ \text{ with } \gamma_2 \text{ at } 99^\circ)}.$$

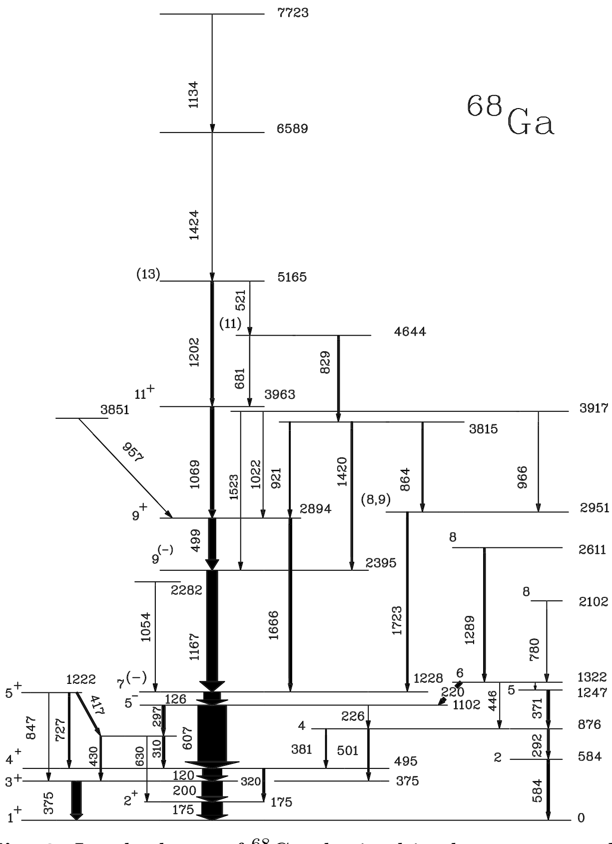

Fig. 2. Level scheme of ^{68}Ga obtained in the present work.

The programme package RADWARE [12] has been used to analyse the data.

The level scheme (fig.2) of ^{68}Ga has been constructed from γ-γ coincidence data, measured γ-ray intensities and the observed multiploarities deduced from the DCO ratio measurements. Altogether six new excited levels could be identified and twelve previously unobserved γ-transitions were placed in the modified level scheme. In fig.2 the thickness of the lines depicting the transitions indicates the relative intensity.

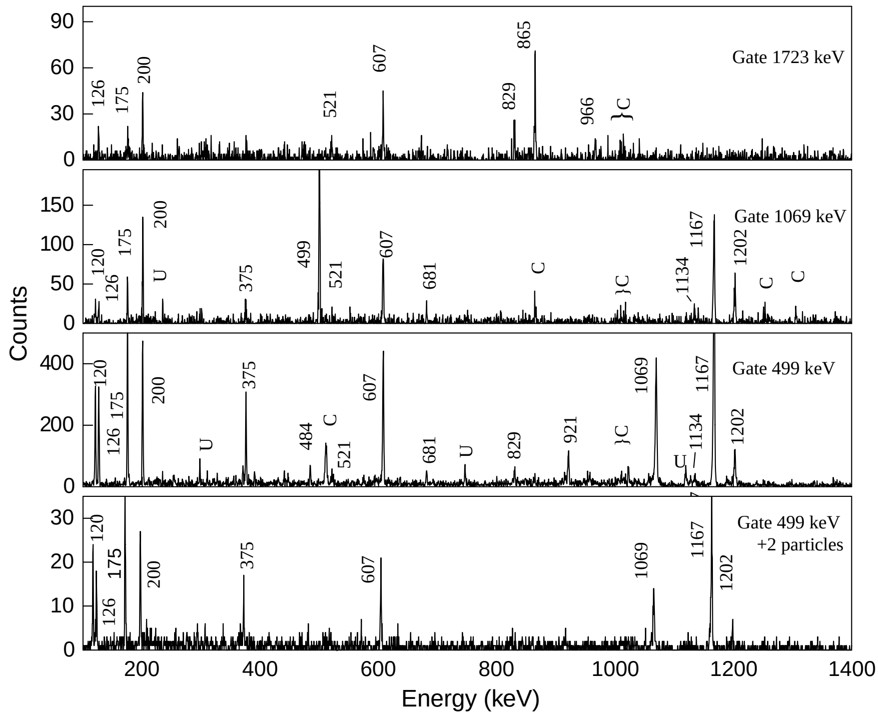

Fig. 3. The partial coincidence spectra obtained with γ-gates at 499 keV, 1069 keV and 1723 keV without any constraint imposed from CPDA. The partial coincidence spectrum for the γ-gate at 499 keV and in coincident with two charged particles is also shown. The unplaced γ-rays are marked U while the contamination lines have been identified by C.

The partial coincidence spectra arising from the gates corresponding to the γ-rays, 499 keV, 1069 keV and 1723 keV are shown in fig.3. The unplaced γ-rays are marked U while the contamination lines have been indicated by C. It may be noted that the ratio of the intensity between the 200 and the 175 keV γ-rays are different for the 499 keV and the 1069 keV gates. This is possibly due to the presence of another 175 keV transition feeding the level at 2894 keV which we have not been able to place in the level scheme. The partial coincidence spectrum for the γ-gate at 499 keV coincident with two charged particles is also shown.

We have confirmed the placement of almost all the γ-rays which have been observed in the α-induced reactions [8] except for the 865 keV transition feeding the level at 1222 keV. We have obtained a γ-transition of equal energy (864 keV) but it has been placed elsewhere in the level scheme. In the low energy region, several γ-rays have been observed which were not observed in the α-induced reaction [8] but known from other studies [6,7]. These include the 630 keV γ-ray (depopulating the 805 keV level), the 446 keV γ-ray (from the 1322 keV level) and the 847 keV γ-ray (from the 1222 keV level).

A number of new connecting transitions between already established levels have also been observed . A γ-ray of energy 1666 keV has been observed which is proposed to decay from the level at 2894 keV ($I^{\pi} = 9^{+}$) to the level at 1228 keV ($I^{\pi} = 7^{-}$). Although the earlier DCO measurement of 499 keV transition depopulating the 2984 keV level [8], did not exclude a spin value 11 for this level, the present observation of this connecting transition rules out this possiblity. It is also proposed on the basis of the present experiment that the level at 3815 keV, besides decaying to the 2395 keV level via a 1420 keV γ-ray, also feeds the 2951 keV and the 2894 keV levels through the γ-rays of energy 864 keV and 921 keV, respectively.

In the present work we are also proposing six new energy levels at 3851, 3917, 4644, 5165, 6589 and 7723 keV. The 3851 keV level decays to the 2894 keV level emitting a γ-ray of energy 957 keV. The level at 3917 keV emits three γ-rays of energy 1523 keV, 1022 keV and 966 keV feeding the levels at 2395 keV, 2894 keV and 2951 keV, respectively. The newly proposed level at 4644 keV is depopulated via two γ-rays of energy 681 keV and 829 keV to the two levels at 3963 keV and 3815 keV, respectively. The level at energy 5165 keV emits a γ-ray of energy 1202 keV to feed the level at 3963 keV. The multipolarity of the 1202 keV γ-ray has been found out to be 2 ($R^{\text{th}}_{\text{DCO}} =$ 1.0 and $R^{\text{exp}}_{\text{DCO}} = 0.8$) and we have tentatively assigned a spin-parity (13^{+}) to the level at 5165 keV. This state also populates the newly proposed level at 4644 keV by emitting a γ-ray of energy 521 keV which has a multipolarity of 2. On the basis of this we have assigned a spin-parity of (11^{+}) to the last mentioned level. Furthermore this 4644 keV state decays via a 829 keV transition whose multipolarity has been found to be 2 ($R^{\text{th}}_{\text{DCO}} = 1.0$ and $R^{\text{exp}}_{\text{DCO}} =$ 1.1) from the DCO ratio measurement, to a state at 3815 keV suggesting a positive parity for this level. The new level at 6589 keV, in turn, decays to the level at 5165 keV by emitting a γ-ray of energy 1424 keV. The level at 7723 keV depopulates to the level at 6589 keV via a γ-ray of energy 1134 keV.

It was shown by earlier workers [8] that the measured spin parities and decay modes of some of the levels in ^{68}Ga are consistent with an interpretation that they arise from coupling a valence nucleon to the neighbouring states of isotopic ^{67}Ga and isotonic ^{67}Zn nuclei.

The high spin levels of ^{67}Ga have recently been studied in detail by Danko *et al.* [13] using heavy ion fusion reaction and the structure of it has been interpreted within the framework of the interacting boson fermion plus broken pair model, including quasi-proton, quasi-proton plus two quasi-neutron, and three quasi-proton fermion configurations in the boson fermion basis states. Most of the states were assigned to quasi-particle plus phonon and three quasi-particle configurations on the basis of their electromagnetic decay properties.

It is interesting to note that almost all the energy levels of ^{68}Ga identified in the present work seem to arise from the coupling of a quasi-neutron to the quasi-proton plus phonon configurations in the neighbouring ^{67}Ga isotope. Only a few levels in ^{68}Ga seem to arise from the coupling to the three quasi-particle configurations in ^{67}Ga.

As regards low energy excitations Morand *et al.* [8] suggested that the 1^+, 2^+, 3^+ and 4^+ states are likely to arise from the coupling of a $f_{5/2}$ neutron (g.s. of ^{67}Zn) with the $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ proton states observed in ^{67}Ga. However, it is interesting to note that a 5^+ state which is likely to arise from the coupling of the $\pi f_{5/2}$ and $\nu f_{5/2}$ configurations at low excitation energy, has not yet been identified.

A few more positive parity levels are also expected to arise from the coupling of $p_{3/2}$ and $p_{1/2}$ neutron with the $f_{5/2}$, $p_{3/2}$ and $p_{1/2}$ proton configurations below 1 MeV. Several levels have indeed been observed in this energy region, but the characterisation of the structure of individual levels is difficult in the absence of sufficient electromagnetic transition data, although excitation energies and decay modes of some of these levels are in reasonable agreement with the results of IBFFM calculations of Timar *et al.* [7]. From the *g*-factor measurement of the 7^- isomeric state at 1228 keV, Filevich *et al.* [9], showed that this state arises predominantly from the $(\pi f_{5/2}, \nu g_{9/2})7^-$ configuration. Several other levels near this excitation energy (1200 ± 200 keV) can also be interpreted [8] in terms of coupling of the $g_{9/2}$ neutron with the $p_{1/2}$, $p_{3/2}$, $f_{5/2}$ and $g_{9/2}$ proton states.

In the present work, several new levels arising from the $(\pi g_{9/2}, \nu g_{9/2})$ configurations have been identified. In ^{67}Ga, a band based on the $\pi g_{9/2}$ state has been identified upto an excitation energy of 8616 keV and spin parity $33/2^+$. According to the theoretical study of this isotope by Danko *et al.* [13], within the framework of interacting boson-fermion plus broken pair model, the $9/2^+$, $13/2^+$, $17/2^+$ and $21/2^+$ members of the band at 2073, 3031, 4198 and 5491 keV, respectively, arise predominantly from the $\pi g_{9/2}$ one quasi-proton plus phonon configuration, whreras the $25/2^+$ state at 6379 keV arise from the $\pi g_{9/2} \otimes (\nu g_{9/2})^2$ configurations. The corresponding intraband transitions 958, 1167, 1293, 888 keV bear a close resemblance to those observed (viz. 1069, 1202, 1424, 1134 keV) in the band identified in ^{68}Ga, based on the 9^+ state at 2894 keV. So it appears that the following members of the band, 2894 keV (9^+), 3963 keV (11^+), 5165 keV (13^+) and 6589 keV states arise from the coupling of a $\nu g_{9/2}$ neutron to the corresponding $g_{9/2}$ proton plus phonon configurations observed in ^{67}Ga. Similarly the 7723 keV state seems to arise from the coupling of the $g_{9/2}$ neutron to the 6379 keV ($25/2^+$) state in ^{67}Ga based on the $\pi g_{9/2} \otimes (\nu g_{9/2})^2$ configurations. Based on these considerations, the spin parity of the 6589 and 7723 keV states appear to be 15^+ and 17^+, respectively.

Two close-lying levels at 3160 ($13/2^-$) keV and 3190 ($11/2^+$) keV have been observed in ^{67}Ga. The state at 3190 keV ($11/2^+$) has been interpreted by Danko *et al.* [13] as arising from the $\pi g_{9/2}$ plus phonon configurations. Considering the similarity of the decay modes, two close-lying levels at 3815 keV and 3851 keV observed in ^{68}Ga may be considered as the counterparts of the above-mentioned levels observed in ^{67}Ga. The level at 3851 keV may arise from the coupling of the $\pi g_{9/2}$ neutron to the $\pi g_{9/2}$ based configuration in ^{67}Ga.

Thus it appears that the energy levels observed in ^{68}Ga can be qualitatively interpreted in terms of a coupling of the motion of a neutron in f, p and g shell to the excitations observed in ^{67}Ga based on the proton motion in the same shells, as well as a few three quasi-particle configurations.

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