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Abstract: The γ-spectrum of the ^{70}Zn(p,nγ)^{70}Ga reaction was measured with Ge(Li) spectrometers at 3, 3.5 and 4 MeV bombarding proton energies. 47 γ-rays were assigned to ^{70}Ga and the energies (E_γ) and relative intensities (I_γ) of γ-rays were determined. The electron spectrum of the reaction was measured with high transmission superconducting magnet transporter Si(Li) and mini-orange Si(Li) spectrometers. Internal conversion coefficients were determined for eight ^{70}Ga transitions. The level scheme of ^{70}Ga, γ-branching ratios, multipolarity of transitions, level spins and parities were deduced. The energies of low-lying ^{70}Ga levels were calculated on the basis of the parabolic rule derived from the cluster-vibration model. This calculation provided a simple classification of several multiplet states in ^{70}Ga for the first time.

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NUCLEAR REACTIONS $^{70}Zn(p,n\gamma)^{70}Ga$, E = 3, 3.5 and 4 MeV; measured E_γ, I_γ, E_{ce}, I_{ce}. Deduced multipolarity of transitions, ^{70}Ga levels, γ-branching ratios,**J**,π. Ge(Li) γ, superconducting magnet transporter Si(Li) and mini--orange Si(Li) electron spectrometers. Enriched target.

1. Introduction

The energy levels of the ^{70}Ga nucleus were studied so far from the following reactions: (p,n) [1-3], (p,pnγ) [4,5], (p,nγ) [6,7,9-16], (n,pγ) [3], (n,γ) [12, 17-19], (d,p) [9,12,20-22], (d,pγ) [12], (d,t) [12,20,21], (α,pγ) [12], (α,pnγ) [23], (α,d) [24].

As a result of the investigations detailed information is available on the energies of reaction γ-rays, ^{70}Ga level energies, angular distributions and threshold energies of γ-rays, on γ-branching ratios and γγ-coincidence relations, transferred angular momentum values (in nucleon transfer reactions), etc.

Nevertheless the determination of the internal conversion coefficients (ICC) of the ^{70}Ga transitions is totally missing. Rester et al. [7] have observed only the K conversion electron line of the 188 keV transition in the ^{70}Zn(p,nγ)^{70}Ga reaction, but they did not give multipolarity even for this transition. Our knowledge on spins and parities of the excited levels is incomplete. Kearns and Mo give account of the existence of 75 ^{70}Ga excited levels in their compilation [25], but definite spin and parity values can be found only at 10 levels. Finally theoretical level-scheme calculation was not performed till now on the ^{70}Ga nucleus.

In the present work we have measured the γ and internal conversion electron spectra of the ^{70}Zn(p,nγ)^{70}Ga reaction. The high transmission, superconducting magnet transporter and mini-orange Si(Li) electron spectrometers enabled the observation of very weak lines too, which were not seen as yet. As a result of investigations multipolarities were determined for eight ^{70}Ga transitions, as well as new data were obtained for the level scheme, spin-parity values, and γ-branching ratios. The parabolic rule derived from the cluster-vibration model enabled the description of level energies of several low-lying multiplets in ^{70}Ga for the first time.

2. Experimental apparatus and methods

The isotopic composition of the enriched zinc metal used for target preparation and the Q energy values of the $^{A}Zn(p,n)^{A}Ga$ reactions are shown in table 1. Zinc target layers of 0.2-1.0 mg/cm^2 thickness were evaporated in vacuum on $<$0.37 mg/cm^2 carbon or aluminium supports.

Table 1.

The irradiation of targets was performed with the proton beam of the 5 MV Van de Graaff accelerator of the Institute of Nuclear Research (Debrecen).

For the γ-spectrum measurements Ge(Li) detectors of 25 and 70 cm^3 effective volumes and $\approx$3 keV resolution (at 1333 keV) were used. The energy and efficiency calibration of the spectrometers was carried out with ^{133}Ba and ^{152}Eu sources. For the accurate energy determination some "internal" calibration lines were also used, such as the strongest lines of ^{181}Ta and $^{64,66,68,70}Zn$, as well as the 508.2±0.2, 651.1±0.2, and 690.9±0.2 keV lines of ^{70}Ga [13]).

The internal conversion electron spectrum was measured with a superconducting solenoid magnet transporter spectrometer [27]). Two Si(Li) detectors were mounted 9 cm under and 9 cm above the thin target. The effective surface and thickness of the detectors were 110 mm^2 and 3 mm, respectively. Under the influence of the strong (1.9 in other case 2.75 T) magnetic field of the superconducting solenoids, the majority of emitted electrons has reached the Si(Li) detectors, while the detection efficiency of the background radiations (scattered protons, neutrons, X- and γ-rays etc.) remained low. The transmission of the spectrometer in the investigated electron energy interval was ≈76 % from 4π and the resolution (FWHM) ≈3.5 keV at $E_e \approx 300$ keV. In the interest of δ-electron background reduction +18 kV potential was switched to the target and ≈0.2 mg cm^{-2} thick aluminium foils were placed before the detectors.

The electron spectrum measurements were repeated also with a mini-orange Si(Li) spectrometer [28]. The maximum transmission of this spectrometer was ≈3 % from 4π and its resolution was ≈2 keV at E_e=177 keV. The magnetic configuration of the mini-orange spectrometer was chosen so that electrons of $170 \lesssim E_e \lesssim 520$ keV energy were transmissed to the detector.

For energy and efficiency calibration of the electron spectrometers we have used ^{133}Ba, ^{152}Eu, and ^{207}Bi sources.

The measurements were performed with the aid of a 4096 channel analyser. For the processing of spectra we have used a PDP 11/40 computer and the FORGAMMA program [29].

3. Experimental results

The γ-spectra were measured at 3, 3.5 and 4 MeV bombarding proton energies (at θ=55° and 90° to the beam direction). The internal conversion electron spectrum measurements were performed at 3.5 and 4 MeV proton energies. The intensity of the bombarding beam was between ≈ 10 and ≈ 100 nA.

Typical γ and internal conversion electron spectra of the ^{70}Zn(p,nγ)^{70}Ga reaction are shown in fig.1.

Fig. 1.

The electron spectrum of fig. 1. was measured with the mini-orange Si(Li) spectrometer. In order to decrease the disturbing effect of the 21.1 min β^{-}-activity of ^{70}Ga the bombarding proton beam was pulsed (one ≈0.4 μs wide pulse in every 4 μs) and the electron spectrum was measured only during the beam pulses [30].

The energies and relative intensities of γ-rays assigned to ^{70}Ga are given in table 2.

Table 2.

The multipolarity of the 187.6 keV ^{70}Ga γ-transition was accepted as pure E2 by Morand et al.[23] on the basis of angular distribution and lifetime data. The intensities of the internal conversion electron lines were normalized so that the α_K ICC for this transition should correspond to the theoretical E2 value taken from the tables of Hager and Seltzer [31]. The ICC-s of the ^{70}Ga transitions and the derived multipolarities are given in table 3.

Table 3.

It is known that the angular distribution of the γ-rays and internal conversion electrons may be anisotropic related to the bombarding beam direction. Nevertheless we think that the experimental conversion coefficients, given in table 3, are correct within the ±(10÷36)% error limit for the following reasons.

a) The γ-spectrum measurements were performed at $\theta=55^{o}$ related to the proton beam direction. At this angle the $P_2(\cos\theta)$ Legendre-polynomial has zero value in the expression $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$, describing the angular distribution. In our measuring geometry the $A_4P_4(\cos\theta)$ members give only small (less than ±4%) corections for the 187.6, 318.5, 344.5, 363.8, 374.5, 393.9, 508.1, and 690.8 keV γ-rays, according to the γ angular distribution measurements of Najam et al. [13]).

Our measurements also confirmed that - in the average - there is no strong anisotropy in the γ-radiations. In some experiments we have measured the γ-spectra at two angles. The spectra obtained at $\theta=55^{o}$ and 90^{o} were normalized to identical reaction events by using a fixed position (monitor) Ge(Li) detector. It was found that the $I_{90^{o}}/I_{55^{o}}$ intensity ratios were equal to one within the ±10 % experimental error for the 154.9, 187.6, 318.5, 363.8, 374.5, 508.1 and 690.8 keV γ-rays.

b) The conversion electron spectrum measurements with the mini-orange spectrometer were performed at $\theta \approx 125^{\circ}$, where $P_2(\cos\theta) \approx 0$. In the case of the superconducting magnet transporter spectrometer the electrons were integrated in a very wide range of angle, approximately from $\theta = 90-76^{\circ}$ to $90+76^{\circ}$. Thus these electron spectrum measurements were also insensitive to angular distribution.

4. The level scheme of ^{70}Ga

The level scheme construction was based on the energy and intensity balance of transitions, but the former level energy [Finckh et al. [2]), Tanaka et al. [3])], γγ-coincidence and γ-threshold [Arnell et al. [12])], and other results, as well as the compilation of Kearns and Mo [25]) were also taken into account. The obtained level scheme below 1300 keV excitation energy is shown in fig. 2.

Fig. 2.

The γ-branching ratios have been determined for several levels. These are given in the level scheme behind the transition energies. As a general rule our γ-branching ratios agree well with the results of Najam et al. [13]).

In the forthcoming part we shall discuss mainly the spin and parity values of the ^{70}Ga levels.

The spin of the ground state was found to be 1 from atomic beam experiments [Ehlers et al. [32])]. As the ^{70}Ga decays with allowed β^--decay to the 0^+ ground state of ^{70}Ge (log ft = 5.1 [Bunker et al. [33])]), the parity of the ^{70}Ga ground state is positive.

The spin and parity of the 508.2±0.1 keV level is 2^+ on the basis of (d,p) and (d,t) studies [20,21]) as well as γ angular distribution measurements [13]). We have found the multipolarity of the 508.1 keV γ-radiation to be M1. This confirms the positive parity and is in accordance with the 2 spin value.

The parity of the 650.9±0.2 keV level is positive according to the neutron transfer experiments [20,21]. On the basis of the angular distribution of the 651.2 keV γ-radiation the spin of the state may be 1 or 2 [13].

As the multipolarity of the 690.8 keV radiation was found by us to be E1, the parity of the 690.8±0.1 keV level is negative and the spin may be limited to 2, 1 or 0. From these I = 2 spin value was accepted on the basis of the angular distribution measurements of Najam et al. [13].

To the 878.3±0.3 keV level 4^- spin-parity value was assigned, as the multipolarity of the 187.6 keV transition is pure E2 [23] and there is no transition to ground state. Similarly to the 901.3±0.2 keV level may be assigned $I^\pi = 4^+$ value, as the 393.1 keV transition has E2 multipolarity and no transition to the ground state was observed [23]. The 4^+ spin-parity value is in accordance with earlier data obtained by other methods.

The (d,t) measurements [21] indicate positive parity for the 995.5±0.1 keV level. The positive parity was confirmed by our measurements too, because the multipolarity of the 344.5 keV transition feeding the 650.9 keV $1^+,2^+$ level was found to be M1. From the measurement of the angular distribution of the 996 keV γ-ray Najam et al. [13] came to the conclusion that the spin of the level is 2. The level decays to $I^\pi=1^+$, 2^+; 2^+ and 1^+ states, which does not contradict the 2^+ spin--parity value.

We have found that the 318.5 keV transition has M1 or E1 + M2 multipolarity, which determines 1-3 spin for the 1009.4±0.3 keV level.

From these spin values the first two are preferred, as the level decays to 2^- and 1^+ states.

To the 1014.7±0.2 keV level Najam et al. [13]) assigned 1-3 spin value from γ angular distribution measurement. As the level decays with M1 transition to the 650.9 keV $1^+,2^+$ state, the parity of the level must be positive.

The transferred neutron angular momentum values in (d,t) reaction [21]) indicate positive parity for the 1023.9±0.2 keV level. Based on γ angular distribution measurements the spin of the level may be 2 or 3 [Najam et al. [13])].

Morand et al. [23]) have assigned $I^\pi = 5^-$ value to the 1033.2±0.3 keV level. We have found that the the 154.9 keV transition is of dipole character, which is in accordance with the spin-parity value.

The (d,p) reaction studies [20,21]) indicate negative parity for the 1101.4±0.3 keV level. From the γ angular distribution measurement of Najam et al. [13]) follows that the spin of the level may be 4-1. The higher spins are preferred as there is no transition to the ground state.

Based on γ angular distribution measurements Najam et al. [13]) assigned I = 1,2 spin values both to the 1135.4±0.1 and 1140.4±0.1 keV levels.

The parity of the 1203.8±0.2 keV level is positive, as for this state $\Delta\ell_n = 1$ neutron angular momentum transfer was determined by Dohan and Summers-Gill [21]). The γ angular distribution measurements indicate I = 2 spin value [13]).

Based on the neutron transfer measurements [20,21] the parity of the 1236.4±0.4 keV level is negative. According to Dohan and Summers-Gill [21] the expected spin value is I = 5. Morand et al. [23] give I = 6.

The γ angular distribution measurements of Najam et al. [13] indicate a spin of 2 for the 1244.6±0.1 keV level.

On the basis of neutron transfer experiments [21] negative parity may be assigned to the 1252.8±0.3 keV level. As the level decays with M1 transition to the 4^- state, the spin (and parity) of the level may be $3^-,4^-,5^-$. From these values the first two are preferred, because the level decays also the 690.8 keV 2^- state.

The 1258.7±0.2 keV level has positive parity, as it decays through M1 transition to the 1023.9 keV 2^+, 3^+ state. This statement is in accordance with the results of the neutron transfer measurements [20,21]. The spin of the level may be 1-4.

5. Proton-neutron multiplet states in ^{70}Ga

The interpretation of the ^{70}Ga level scheme is difficult because of the absence of any detailed theoretical calculation.

In the $^{70}_{31}Ga_{39}$ nucleus we may expect shell-model type excitations of the odd proton and neutron quasi-particles and the coupling of different single quasi-particle states.

The energies of proton states may be taken from the neighbouring $^{69,71}_{31}Ga$ nuclei. According to the proton transfer experiments [34-37] and cluster-vibrational model calculations [Paar [38]] the ground, the first and second excited states of ^{69}Ga have as dominant components single quasi-particle proton configuration: 0 keV $\pi\tilde{p}_{3/2}$, 318 keV $\pi\tilde{p}_{1/2}$, 574 keV $\pi\tilde{f}_{5/2}$, respectively. Similar configurations may be expected also in $^{71}_{31}Ga_{40}$ [Riccato and David [35]] for the ground, the 390 and 487 keV excited states.

The cluster-vibrational calculations show that the strongest component of the ^{69}Ga ground state has $\pi(p_{3/2})^3_{3/2}$ configuration (67 %), but it has also a $\pi(f_{5/2})^2_0 p_{3/2}$ component (10 %) [38]. On the basis of $^{71}Ga(^3He,d)^{72}Ge$ studies Ardouin et al. [39] came to the conclusion that, beside the main $\pi(p_{3/2})^3_{3/2}$ component, the ground state of ^{71}Ga may contain also an admixture of $\pi(f_{5/2})^2_0 p_{3/2}$ configuration up to 20 %.

The energies of neutron states were taken from the neighbouring $^{69}_{30}Zn_{39}$ nucleus. According to the neutron transfer experiments [40-42] $\nu\tilde{p}_{1/2}$, $\nu\tilde{g}_{9/2}$ and $\nu\tilde{f}_{5/2}$ configurations may be assigned to the ground, 438 keV and 531 keV states, respectively.

The configurations of the low-lying ^{71}Ga and ^{69}Zn states are shown in fig. 3a. In zeroth-order approximation the energies of the ^{70}Ga multiplets can be obtained by addition of the energies of the quasi-proton and quasi-neutron states (see fig. 3b).

Fig. 3.

The neutron transfer experiments (Yntema [20], Dohan and Summers-Gill [21])) provided valuable data on the configuration of ^{70}Ga states (see fig. 3d).

In the 1^+ ground and 2^+ 508 keV states the last neutron is mainly in $\nu p_{1/2}$ state [20,21]; it is, the dominant configuration of these states is $\pi p_{3/2} \nu p_{1/2}$.

The 1^+, 2^+ 651 keV level was excited both in (d,p) and (d,t) reactions with $\Delta\ell_n$=1 and 3 angular momentum transfer [21] so it has mainly $\pi p_{3/2}\nu(f_{5/2}+p)$ configuration.

The 2^- 691 keV level apparently was not populated in a one-step direct process in (d,p) and (d,t) reactions. One possible explanation of this fact is that the proton is here in $f_{5/2}$ excited state [21,23]. According to fig. 3b the lowest 2^- state has probable $\pi f_{5/2} \nu g_{9/2}$ configuration.

The 4^- 878 keV, 5^- 1033 keV and 6^- 1236 keV levels were strongly excited in (d,p) reaction with $\Delta\ell_n$=4 neutron angular momentum transfer [20,21]. The excitation of levels may be observed also in (d,t) reaction, but weakly [21]. All these indicate that the dominant components of these levels have $\pi p_{3/2} \nu g_{9/2}$ configuration [21,23]. According to the g-factor measurement and calculations of Taylor and Hutcheon [22] the 879 keV state contains also roughly 35 % admixture of some undetermined configurations.

The 902 keV 4^+ level was strongly excited in (d,t) and more weakly in (d,p) reactions with pure $\Delta\ell_n=3$ [20,21]. Similarly the 1023 keV 2^+, 3^+ level was also strongly excited in (d,t) reaction with $\Delta\ell=3$ (although here is a weak $\Delta\ell_n=1$ component too) and weakly in (d,p) [21]. All these facts indicate that the main components of the levels have $\pi p_{3/2}\nu f_{5/2}$ configuration.

The configuration of the 1372.5 keV 7^- state is likely $\pi f_{5/2}\nu g_{9/2}$ according to Morand et al. [23].

We describe here the low-lying levels of ^{70}Ga by using the parabolic rule derived from the cluster-vibrational model. In this approximation the proton-neutron residual interaction is a consequence of the quadrupole and spin vibration phonon exchange between the proton (quasi-proton) and the neutron (quasi-neutron) through the nuclear core. As a result of this interaction the $E[(j_p j_n)I]$ energies of the multiplets split as a function of the nuclear spin (I) [V. Paar [43]]:

$$E[(j_p j_n)I] = E_{j_p} + E_{j_n} + \delta E_2[(j_p j_n)I] + \delta E_1[(j_p j_n)I],$$

$$\delta E_2[(j_p j_n)I] = -\alpha_2 \left\{ \frac{[I(I+1) - j_p(j_p+1) - j_n(j_n+1)]^2 + I(I+1) - j_p(j_p+1) - j_n(j_n+1)}{2 j_p (2 j_p+2)\, 2 j_n (2 j_n+2)} + V \right\}.$$

$$\delta E_1[(j_p j_n)I] = -\alpha_1 \left\{ \frac{I(I+1) - j_p(j_p+1) - j_n(j_n+1)}{(2 j_p+2)(2 j_n+2)} \right. .$$

Here E_{j_p} and E_{j_n} denote the (quasi-)proton and (quasi-)neutron energies, respectively, which were taken from the experimental data of the neighbouring nuclei (see fig. 3a).

$(j_p j_n)I = |j_p - j_n|, \ldots j_p + j_n$, where j is the total angular mementum quantum number of the nucleon. α_2 and α_1 are the quadrupole-vibrational and the spin-vibrational coupling strengths, respectively. The definition of ϑ and coefficients are given in ref. [43]).

The dependence of the coupling strength on the occupation probability of levels may be described by the following approximative formulae

$$\alpha_2(j_p j_n) = \alpha_2^{(0)} |(U_{j_p}^2 - V_{j_p}^2)(U_{j_n}^2 - V_{j_n}^2)|,$$
$$\alpha_1(j_p j_n) = \alpha_1^{(0)},$$

where V_j^2 is the probability of occupation of the j level, $U^2 = 1 - V^2$. The knowledge of occupation probability is important also for the determination of the ϑ parameter. The occupation probabilities of the quasi-particle states may be calculated from the pairing force of superconducting type, from the single particle energies, chemical potential (λ) and the pairing gap parameter (Δ) which characterizes the diffuseness of the Fermi surface. We are using the following BCS occupation probabilities:

$$V^2(\pi\tilde{p}_{3/2}) = 0.54 \qquad V^2(\nu\tilde{p}_{1/2}) = 0.29$$
$$V^2(\pi\tilde{p}_{1/2}) = 0.09 \qquad V^2(\nu\tilde{g}_{9/2}) = 0.10$$
$$V^2(\pi\tilde{f}_{5/2}) = 0.34 \qquad V^2(\nu\tilde{f}_{5/2}) = 0.93,$$

obtained from $\lambda_p = 0.06$ MeV and the other parameters from ref. [44]). The λ_p value was taken in accordance with the hole-like character of the $3/2_1^-$ state in ^{71}Ga, as seen from the CVM calculation [38]): this value is half-way between $\lambda_p(^{65}_{29}Cu_{36}) = -0.08$ and $\lambda_p(^{73}_{33}As_{40}) = 0.2$ MeV.

The $\alpha_2^{(0)}$ was calculated from the experimental data of the neighbouring $^{68,70}_{30}$Zn and $^{70,72}_{32}$Ge nuclei on the basis of the formula $a_2^{(o)}=382\ \beta_2^2(\hbar\omega_2)^{-1}$, where $\hbar\omega_2$ is the energy of the first 2^+ state in MeV and β_2 is the deformation parameter [45]. The mean of the obtained values is $a_2^{(o)}=21$ MeV.

The $a_1^{(o)}$ value was calculated from the expression $a_1^{(o)}\approx 20/A$ MeV (A is the mass number).

The results of the calculations are shown in fig. 3c. The lowest-lying multiplet is the $\pi\tilde{p}_{3/2}\nu\tilde{p}_{1/2}$. The ground and the first 2^+ excited states of ^{70}Ga correspond obviously to the 1^+ and 2^+ members of the doublet. The $E(1^+)<E(2^+)$ prediction of the parabolic rule is in agreement with the experimental data.

It is very probable that the lowest lying 4^+ level (at 901.3 keV) is a member of the $\pi\tilde{p}_{3/2}\nu\tilde{f}_{5/2}$ multiplet (see fig. 3b), therefore the energies of the multiplet were normalized to this state. The experimental 1023.9 keV, $I^\pi=2^+$, 3^+ state may correspond to the 3^+ member of this multiplet, and similarly the 995.5 keV 2^+ and 650.9 keV 1^+, 2^+ states to the 2^+ and 1^+ members, respectively.

The $\pi\tilde{p}_{3/2}\nu\tilde{g}_{9/2}$ multiplet was normalized approximately to the 1033.2 keV 5^- and 878.3 keV 4^- experimental levels. The experimental equivalents of the 6^- and 3^- levels may be the 1236.4 keV 6^- and 1252.8 keV $(3\text{-}4)^-$ levels, respectively.

According to the experiments the 690.8 keV, 2^- state (with a $\pi f_{5/2}\nu g_{9/2}$ component) is the lowest one from the negative parity states. Normalizing the members of the $\pi\tilde{f}_{5/2}\nu\tilde{g}_{9/2}$ multiplet to this state, really one can find in the vicinity of the theoretical 3^- and 7^- levels experimental ones with $I^\pi=(3,4)^-$ at 1101.4 keV and 7^- at 1372.5 keV.

The low spin, positive parity members of the $\pi\tilde{p}_{1/2}\nu\tilde{p}_{1/2}$ and $\pi\tilde{f}_{5/2}\nu\tilde{p}_{1/2}$ multiplets appear obviously at higher energies than it was predicted by the zeroth-order approximation of fig. 3b.

Finally we remark that these simple calculations do not lay claim to the complete description of the low-lying levels of ^{70}Ga. The calculations served only as a guide for the identification of several proton-neutron multiplet states.

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Figure captions

Fig. 1 Tipical parts of the γ and internal conversion electron spectra of the $^{70}Zn(p,n\gamma)$ ^{70}Ga reaction. N_γ and N_{e^-} are counts in channels. The energies are shown only at ^{70}Ga lines.

Fig. 2 The proposed level scheme of ^{70}Ga. (Circles at the end of arrows show γγ-coincidence relations on the basis of the work of Arnell et al. [12])).

Fig. 3 Proton-neutron quasi-particle multiplet states in ^{70}Ga.

a) Experimental level energies and configurations of the lowest three states of the ^{71}Ga and ^{69}Zn nuclei.

b) The zeroth-order classification of the low-lying ^{70}Ga states.

I is the spin of the nuclear state.

c) The splitting of some states of fig. 3b due to quadrupole and spin vibrational one-phonon exchange. N means normalization point.

d) Experimental levels of ^{70}Ga below ≈1300 keV.

Table 1

Isotopic composition of the Zn target (enriched in ^{70}Zn)*
and the Q energy values of the $^{A}Zn(p,n)^{A}Ge$ reaction [26]

	^{70}Zn	^{68}Zn	^{67}Zn	^{66}Zn	^{64}Zn
Isotopic composition, %	70.2	12.4	1.7	7.3	8.4
Q(p,n), MeV	-1.4	-3.7	-1.8	-6.0	-7.9

*according to the measurement certificate of Techsnabexport (Moscow)

Table

The energy (E_γ at $\theta=90^{\circ}$) and relative intensity (I_γ at $\theta=55^{\circ}$) *of* γ-rays observed in the $^{70}Zn(p,n\gamma)^{70}Ga$ reaction at E_p=4 MeV

$E_\gamma \pm \Delta E_\gamma$ (keV)	$I_\gamma \pm \Delta I_\gamma$	$E_\gamma \pm \Delta E_\gamma$ (keV)	$I_\gamma \pm \Delta I_\gamma$
154.9±0.1	77 ± 4	794.6±1.0	10 ± 3
187.6±0.3	302 ± 48	798.6±0.3	51 ± 6
203.2±0.2	11 ± 1	851.1±0.2	45 ± 6
234.8±0.1	22 ± 3	867.0±0.3	11 ± 4
318.5±0.2	≤198	872.3±0.4	≤13
344.5±0.2	11 ± 1	D 904.9±0.3	15 ± 3
363.8±0.1	40 ± 2	930.4±0.6	6 ± 2
374.5±0.1	93 ± 6	948.5±0.3	14 ± 3
D 393.1±0.1	141 ± 13	983.0±1.0	27 ± 5
410.6±0.2	35 ± 2	995.9±0.3	44 ± 7
426.8±0.2	34 ± 3	1002.8±1.0	≤10
431.8±1.0	≤10	D 1010.5±1.0	48 ± 13
444.3±0.4	26 ± 2	* 1014.4±0.6	≤88
487.2±0.1	≤76	1023.3±0.5	6 ± 2
508.1±0.1	1092 ± 73	1044.3±1.0	68 ± 10
515.7±0.1	62 ± 13	1125.4±0.2	50 ± 8
554.3±0.5	≤93	1135.4±0.1	173 ± 28
561.7±0.4	31 ± 3	1140.4±0.1	118 ± 20
608.5±0.5	≤16	1203.8±0.2	≤82
632.3±0.2	45 ± 4	1244.6±0.1	107 ± 20
645.7±0.2	110 ± 10	1307.0±0.4	34 ± 4
651.2±0.1	372 ± 34	1312.1±0.3	117 ± 13
690.8±0.1	≥1000 ± 98	1337.0±1.0	≤8
755.0±0.2	45 ± 5	1359.8±0.4	40 ± 5

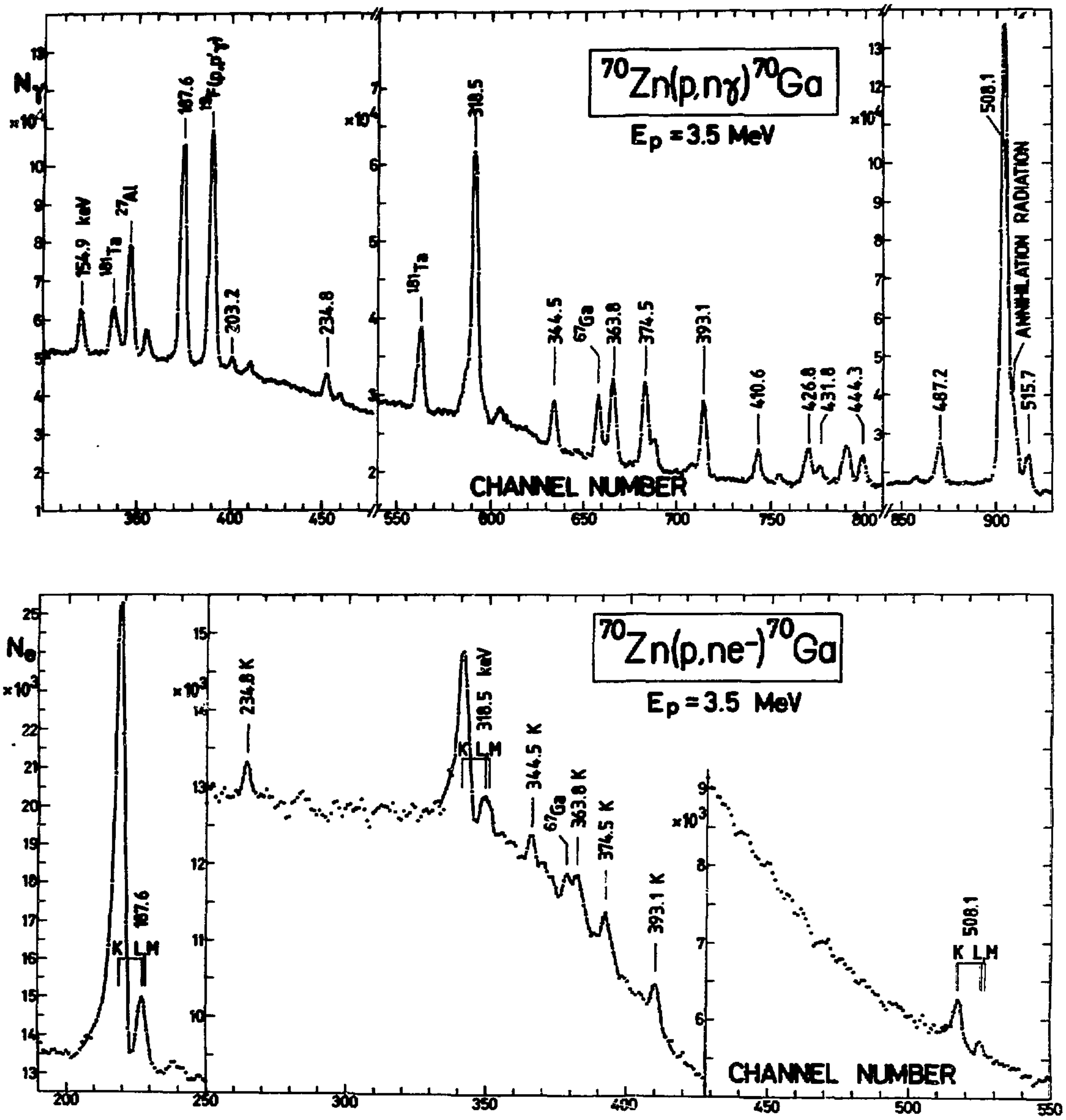
D According to Najam et al. [13]) the γ-line is doublet

* This energy was taken over from the work of Najam et al. [13])

Table 3
Multipolarity of ^{70}Ga transitions

E_γ, keV	Experimental ICC $\alpha_K x10^3$	Theoretical ICC, $\alpha_K x10^3$ [29]				Multipolarity	
		E1	M1	E2	M2	Present work	Former results [23]
154.9	14.0 ± 5	15.4	19.5	120	141	Dipole	M1
187.6	≡ 58.6	8.72	11.9	58.6	73.8	≡ E2	E2
234.8	7.3 ± 1.7	4.50	6.75	25.6	35.4	M1	
318.5	3.8 ± 1.0	1.89	3.19	8.61	13.5	M1 or E1+M2	
344.5	2.6 ± 0.8	1.52	2.65	6.56	10.7	M1	
363.8	2.2 ± 0.5	1.31	2.33	5.44	9.05	M1	
374.5	2.1 ± 0.5	1.22	2.17	4.94	8.30	M1	
393.9 *	2.2 ± 0.4	1.07	1.94	4.21	7.21		
508.1	0.97± 0.12	0.553	1.07	1.84	3.42	M1	
690.8	0.28± 0.10	0.269	0.543	0.746	1.47	E1	

* According to Najam et al. [13] the line is doublet. Morand et al. [23] give E2 multipolarity for the 393.3 keV transition (from the 901.8 keV level).



^{70}Zn(p,nγ)^{70}Ga
E$_p$ = 3.5 MeV
N$_γ$
CHANNEL NUMBER
154.9 keV
^{181}Ta
^{27}Al
187.6
^{19}F(p,p'γ)
203.2
234.8
318.5
344.5
^{67}Ga
363.8
374.5
393.1
410.6
426.8
431.8
444.3
487.2
508.1
ANNIHILATION RADIATION
515.7
^{70}Zn(p,ne$^-$)^{70}Ga
E$_p$ = 3.5 MeV
N$_e$
CHANNEL NUMBER
187.6
K L M
234.8 K
318.5 keV
344.5 K
363.8 K
374.5 K
393.1 K
508.1

Fig. 1

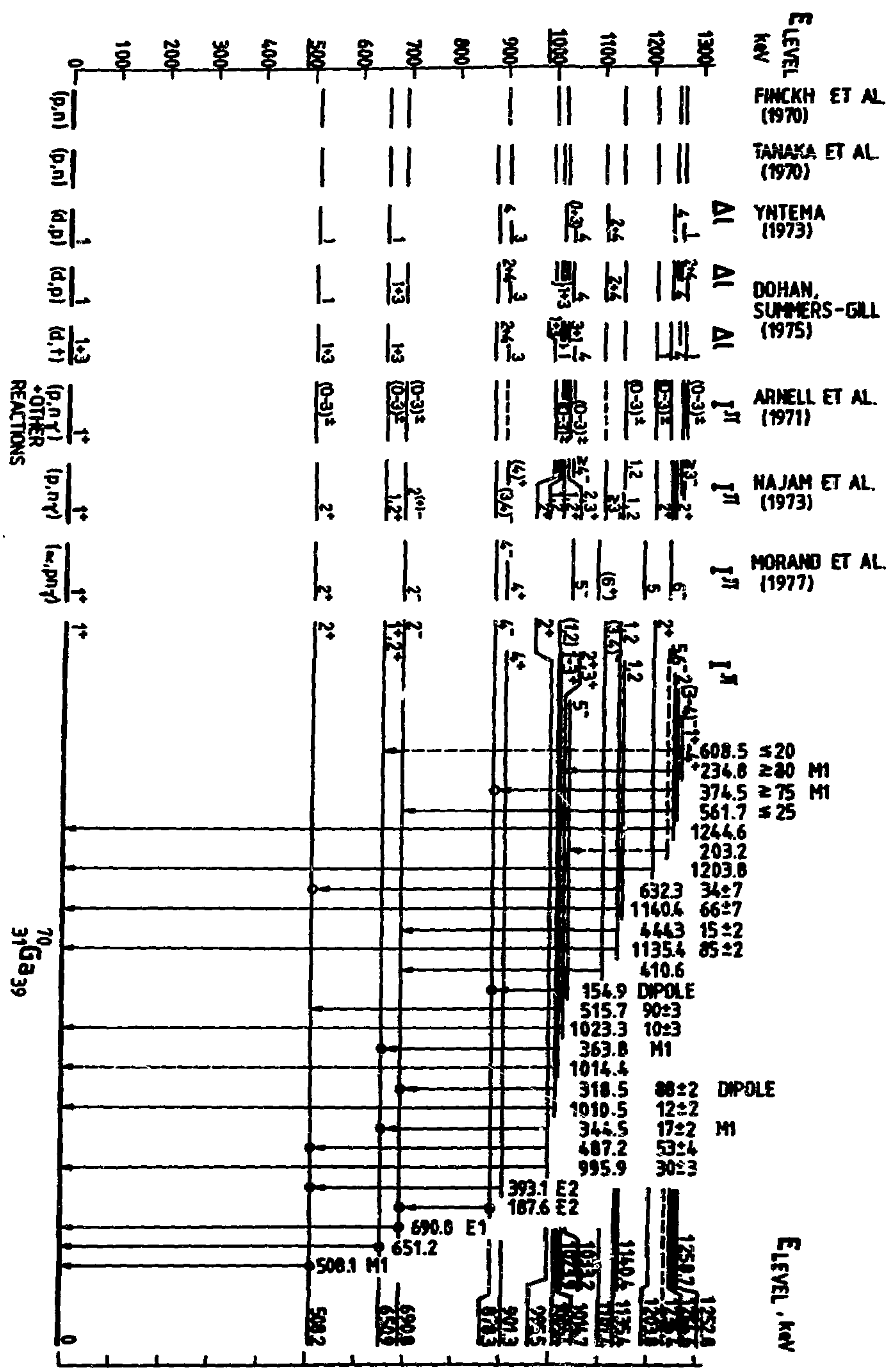
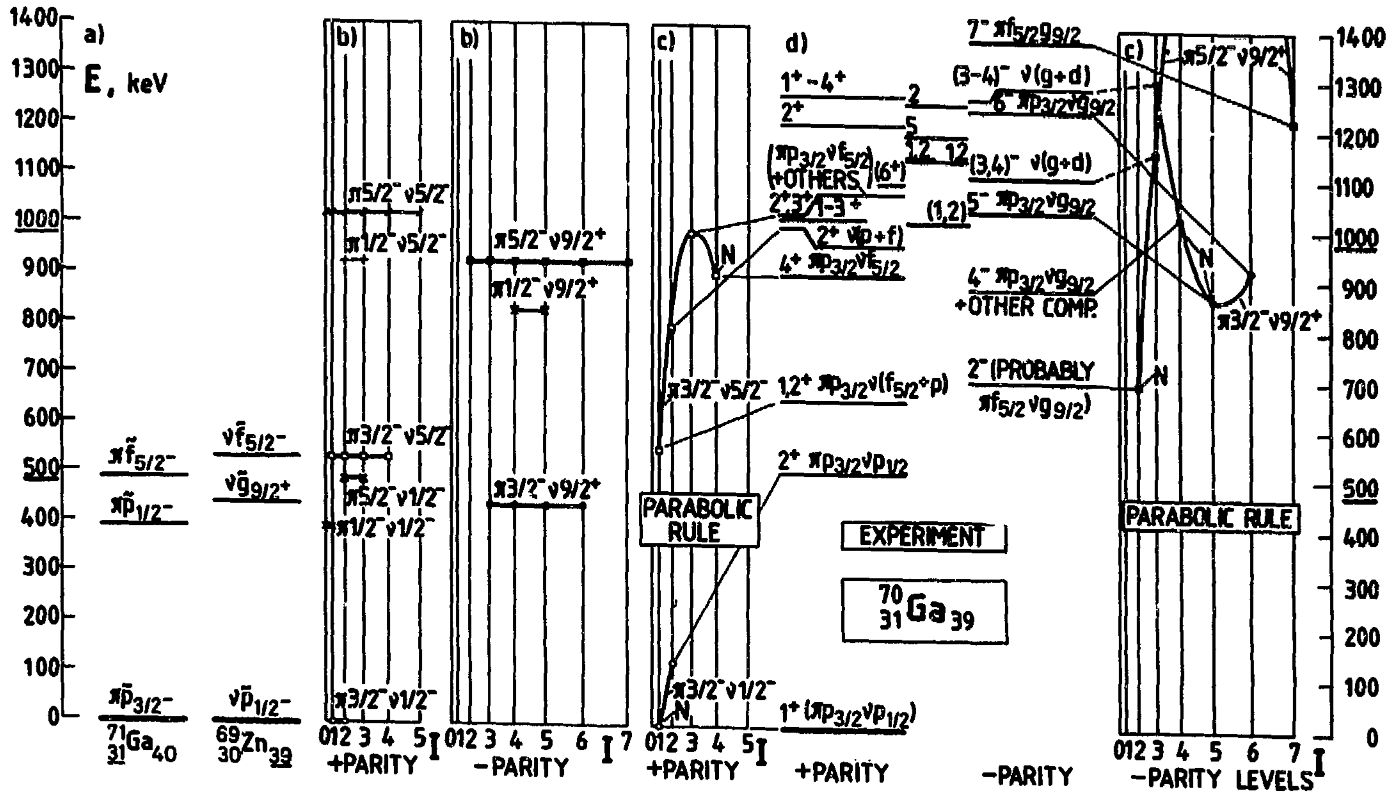

E LEVEL keV
FINCKH ET AL. (1970)
TANAKA ET AL. (1970)
YNTEMA (1973)
DOHAN, SUMMERS-GILL (1975)
ARNELL ET AL. (1971)
NAJAM ET AL. (1973)
MORAND ET AL. (1977)
(p,n)
(d,p)
(d,t)
(p,n γ) +OTHER REACTIONS
(p,n γ)
(α,pn γ)
E LEVEL, keV

Fig. 2



a)
E, keV
b)
+PARITY
b)
-PARITY
c)
+PARITY
PARABOLIC RULE
d)
+PARITY
-PARITY
EXPERIMENT
c)
-PARITY LEVELS
PARABOLIC RULE

Fig. 3