EXCITATION OF ISOMERIC ACTIVITIES IN ^{71}Ge, ^{78}Br AND ^{79}Br USING 14.8 MeV NEUTRONS

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The cross-section for the production of the isomeric states in ^{71}Ge, ^{78}Br and ^{79}Br were measured using 14.8 MeV neutrons. The half-lives and energies of these isomeric activities weie remeasured for checking the assignments. As a result of the experiment the following values were obtained for the measured activities:

Target, reaction and isomeric nucleus	E [keV]	Half-life [sec]	Cross-sections [mb]
^{73}Ge$(n, 2n)^{71m}$Ge	175	$(20.4\pm1)10^{-3}$	487 ± 50
^{79}Br$(n, 2n)^{78m}$Br	150	$(111\pm10)10^{-6}$	(220 ± 40) $(1+\alpha_{tot})$
^{79}Br$(n, n')^{79m}$Br	208	5	230 ± 30

Experimental results for isomeric ratios in $(n, 2n)$ reaction are compared with the statistical theory predictions.

Introduction

This paper reports continued investigations of isomeric activities with half-lives in the 10^{-5} — 10 sec range produced by fast neutrons from $T(dn)$ reaction.

Ge and Br were chosen as targets because earlier studies had indicated the existence of short-lived isomers excited in other types of reactions.

In view of the increasing use of Ge(Li) detectors for promt- and delayed-gamma studies in fast-neutron reactions a knowledge of the cross-sections for neutron reactions in germanium is also of interest.

In the following estimation of the spins for isomeric state of the ^{71m}Ge and ^{78m}Br will be presented based on the statistical model predictions. This estimation is useful in checking the spin assignments made by methods of nuclear spectroscopy.

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Experimental procedure

The experimental arrangement used was a modified and improved version of that discussed in [1].

The isomeric states were produced by irradiations of target materials in the neutron flux from the pulsed neutron generator of our Institute. The 14.8 MeV neutrons were produced by bombarding a thick tritium target with a 175 keV deuteron beam. The beam spot on the tritium target was defined to be 4 mm in diam. Neutron intensities were monitored by counting the alpha particles from $T(d, n)^4He$ reaction. A solid-state detector was used. The detector was placed at 170° with respect to the direction of the deuteron beam leaving the space arround the tritium target free for performing the experiments.

Discs of natural germanium specpure samples of different sizes were used with their weight varying from 2 to 12 g. Natural bromine was used in the form of tribromoaniline ($Br_3C_6H_4N$) powder pressed into flat tables of known weight and area.

The gamma-ray activity was counted while the deuteron beam was deflected off the tritium target by the beam pulsing system [2]. Isomeric activity was detected by gamma-ray measurements using $1\frac{1}{2}'' \times 1''$ NaI(Tl) crystal and the 400 channel Victoreen analyser. The same geometry was used throughout the investigation. The samples were placed in a special plastic sample holder.

Results and discussion

$^{71}_{32}Ge_{39}$

The level scheme of ^{71}Ge was studied by many authors [3, 4]. The only well known levels of ^{71}Ge are: the ground state with a $\frac{1}{2}$ — assignment, a level at 175 keV with a $\frac{5}{2}$ — assignments and a 198 keV level with a $\frac{7}{2}+$ or $\frac{9}{2}+$assignments (Fig. 1). For. the 175 keV transition ($\frac{5}{2} - \rightarrow \frac{1}{2} -$) the $E2$ multipolarity has been established from the internal conversion coefficient measurements [5–7, 12, 13]. The 7×10^{-8} sec half-live of the 175 keV transition was measured with the delayed coincidence technique [5].

The 23.3 keV transition has not been observed but its conversion electrons have been reported [5, 6]. By proton and deuteron irradiation of separated isotopes Schardt and Goodman [8] and independently Morosov [9] have identified ^{71}Ge as the isomeric nucleus in the $^{71}Ga(pn)^{71m}Ge$ [8, 9] and $^{70}Ge(dp)^{71m}Ge$ [8] reactions. Also Alexander and Brinckmann [10] have reported 175 keV gamma-ray with half-life 20 ms which they attribute to the isomeric level in ^{71}Ge produced in the $^{70}Ge(n, \gamma)^{71m}Ge$ reaction.

Consideration of the known levels in ^{71}Ge at 198 and 175 keV suggest that the 23 keV transition between these levels is responsible for the observed half-life of the 175 keV gamma ray.

The isomeric level in ^{71}Ge is excited in our work in the reaction $^{72}Ge(n, 2n)^{71m}Ge$. No attempt was made here to irradiate separated isotopes of Ge since the assignments of the isomer by [8–9, 10] to ^{71}Ge seems to be quite unambiguous.

The energy of the gamma-ray measured here is 175 ± 1 keV (Fig. 2). The decay curves were taken with the multichannel analyser working in the multiscaler mode. The value for

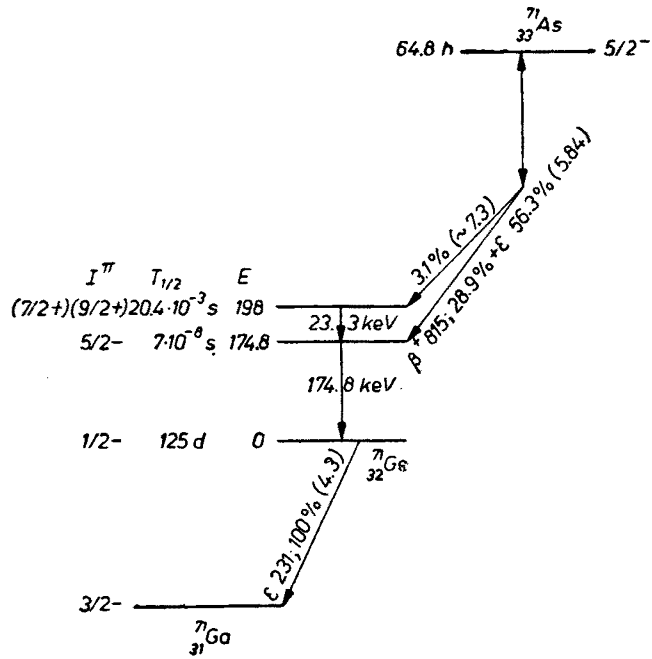

Fig. 1. Decay scheme of ^{71m}Ge

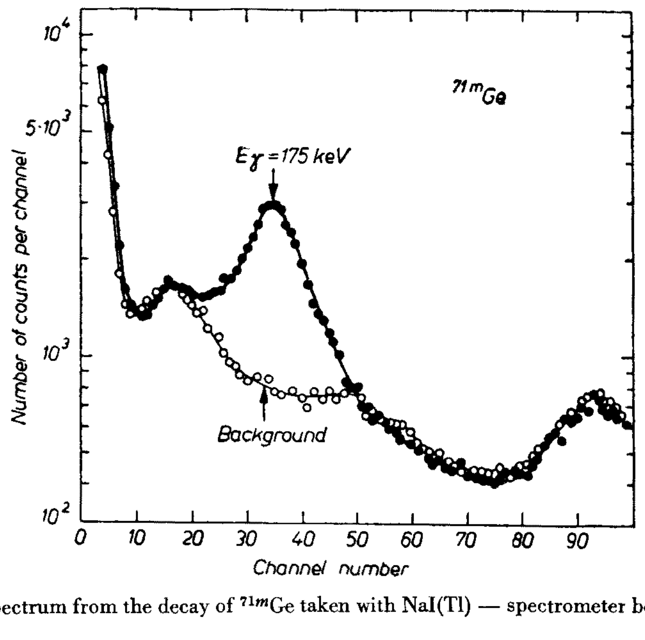

Fig. 2. Gamma ray spectrum from the decay of ^{71m}Ge taken with NaI(Tl) — spectrometer between neutron pulses

half-life of 175 keV gamma ray activity (see Fig. 3) obtained by least-square fit is (20.4 ± 1) msec.

The previous estimation of the cross-section for excitation of the isomeric activity in ^{71}Ge by 14 MeV neutrons as reported by Glagolev *et al.*, [11] is 300 ± 150 mb. In our

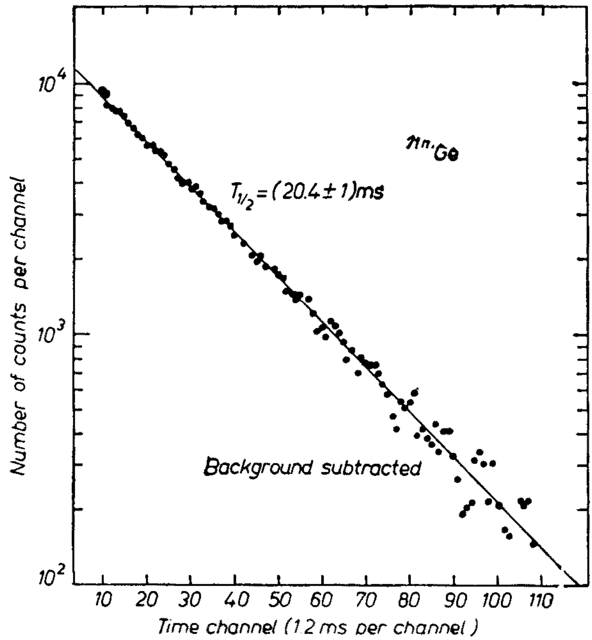

Fig. 3. Decay curve for isomeric gamma-ray from ^{71m}Ge. Correction have been made for background

experiment the value (487 ± 50) mb was obtained. The cross section formula which is useful in this case was given in our earlier work [1].

As long as the spin value of the 198 keV level was not established by a spectroscopic method, we can apply the statistical model of $(n, 2n)$ reaction to estimate this value. Therefore, the isomeric cross-section ratio for ^{71}Ge was analyzed versus spin value of the ^{71m}Ge level. The method of Huizenga and Vandenbosch [14] was applied in computations. To estimate the spin value we must also know the total $(n, 2n)$ cross-section for ^{72}Ge$(n, 2n)^{71}$Ge. Recently Pearlstein [15] has computed cross-sections at neutron energies 13.1, 14.1 and 15.1 MeV for a large number of isotopes, which agree excellently with the available experimental data. More recently, Gardner [16] has attempted to estimate $(n, 2n)$ cross-sections by relating them to charge-particle reaction cross-sections, such as $(p, 2n)$ and $(\alpha, 2n)$. Gardner's predicted absolute $(n, 2n)$ cross-section for 14–15 MeV neutrons on germanium isotopes agree with Pearlstein predictions. Following the computational procedure outlined by Pearlstein [15] the predicted $(n, 2n)$ cross-section at 14.8 MeV calculated for ^{72}Ge$(n, 2n)^{71}$Ge is estimated as equal to 800 mb. In Fig. 4 the value of the isomeric cross-section ratio for ^{71}Ge is plotted versus the spin value of the isomeric level in ^{71}Ge. As can be seen from Fig. 4 the value of $\frac{7}{2}$ is prefferred for the spin of isomeric level in ^{71}Ge. In order to check our procedure

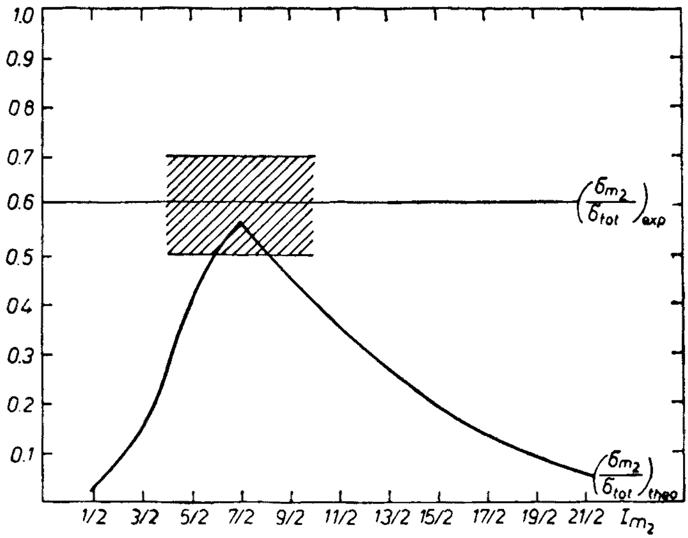

Fig. 4. The isomeric cross-section ratios for ^{71}Ge *versus* spin value of ^{71m}Ge. The solid lines are the results of calculations using Gilbert and Cameron level density formulas (*Can. J. Phys.*, **43**, 1446 (1965))

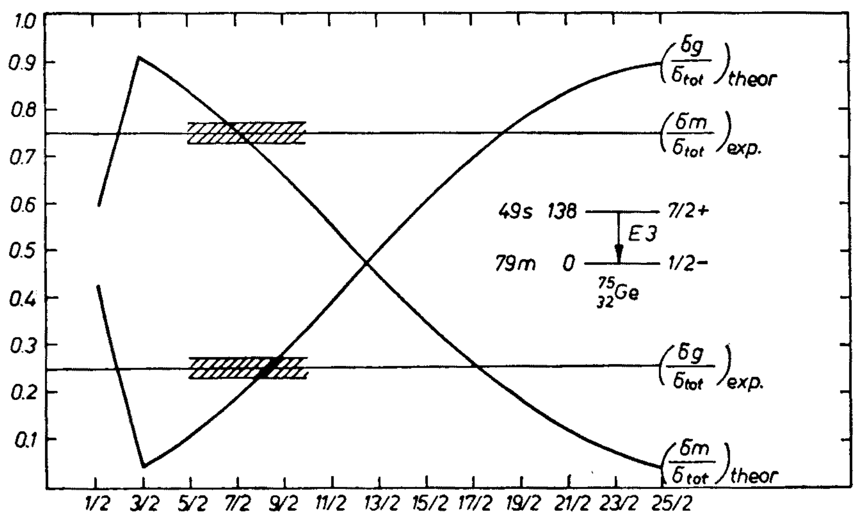

Fig. 5. The isomeric cross-section ratios for ^{75}Ge *versus* spin value of ^{75m}Ge. The solid lines, are the results of calculations using Gilbert and Cameron level density formulas (*Can. J. Phys.* **43**, 1446 (1965))

the well known spin value in ^{75m}Ge was estimated using experimental values of cross-sections for ^{76}Ge$(n, 2n)^{75m}$Ge for which all values were known from Refs [17, 18]. As can be seen from Fig. 5 the agreement with spectroscopic data is good.

$^{78m}_{35}Br_{43}$

The level structure of odd-odd nuclei is less well known than those of odd-*A* and even-even nuclei because of their greater complexity. The ^{78}Br is one of them.

The decay of the 6.4 min ground state of ^{78}Br were investigated by very many authors [19]. Log ft values and branching to the ground state and the first 2+ excited state of ^{78}Se suggest a spin and parity assignment 1+ for the ground state of ^{78}Br. The 127 ± 5 μs isomeric transition in ^{78}Br was first observed by Duffield and Vegors [20] in (γ, n) reactions on natural Br, but they made no assignment. Mc Carthy *et al.*, (21) have observed the same isomeric transition formed in the reaction ^{77}Se(d, n)^{78}Br. Schardt and Goodman [22] have studied the transition in detail. They produced ^{78}Br in the metastable state by the (p, γ) and (p, n) reactions on separated ^{77}Se and ^{78}Se respectively and observed two gamma rays in cascade: 149 keV and 32 keV. The isomeric level is at 181 keV, has a half-life of 118 ± 1.5 μs. The half-life and energy indicate that the transition with energy 149 keV is $M2$ but a slow $E2$ is also not excluded.

The 125 μs activity from ^{78m}Br was produced in our work using 14.8 MeV neutrons in the ^{79}Br(n, 2n)^{78m}Br reaction. Alongside the main activity of ^{78m}Br, ^{79m}Br with 4.8 sec half-life, ^{78g}Br with 6.4 min half-life and ^{80g}Br with half-life 17.6 min were also observed. Fig. 6

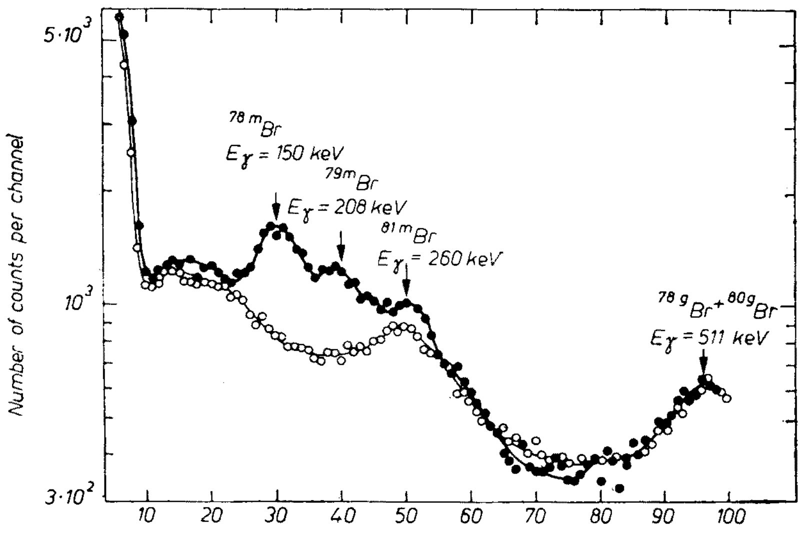

Fig. 6. Gamma-ray spectrum from the decay of ^{78m}Br, ^{79m}Br, ^{81m}Br and ^{78g}+^{80g}Br taken with NaI(Tl)—spectrometer between neutron pulses

shows typical example of an observed gamma-ray spectrum between neutron bursts. Analysis of the decay curve of 149 keV gamma-line of ^{78}Br yielded a half-life of 111 ± 10 μs as shown in Fig. 7. The high value of the error is caused by the sweep velocity and the sweep linearity of our oscilloscope which was used in TAC. Therefore special care was taken in the present experiment to eliminate the 208 keV line from ^{79m}Br and separate only the 149 keV line from ^{78m}Br for correct measurement of gamma-ray spectrum of ^{78m}Br. The detector pulses were displayed in two 100-channel pulse height analysers, each gated by variable gate-variable delay circuits. If the delays in the two gate circuits were chosen different from each other, the two analysers would display the gamma-ray spectrum of the irradiated

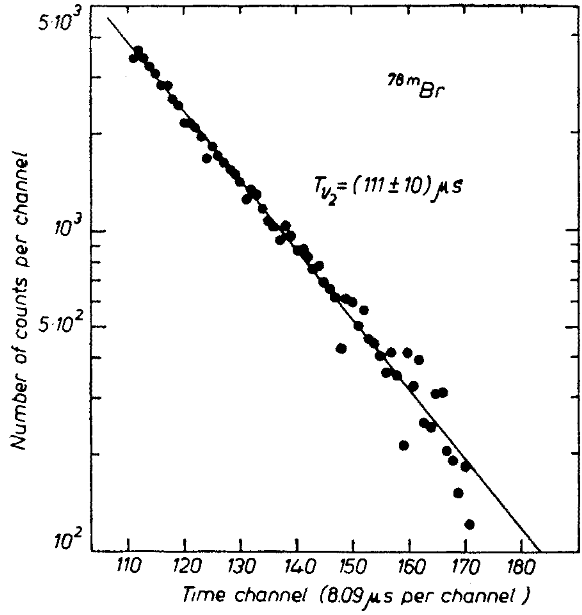

Fig. 7. Decay curve for isomeric gamma-ray from ^{78m}Br. Correction have been made for background

target at two different time intervals after irradiation; *i.e.* the spectrum of isomeric level in ^{78}Br was measured during one half-life (100 μs) and was delayed 25 μs, the lenght of the second gate was also one half-life and was delayed by 6–7 half-lives of isomeric transition.

To calculate the cross-section for excitation of isomeric activity in ^{79}Br(n, 2*n*)^{78m}Br reaction both kinds of spectra were taken into account and the following formula was used:

$$\sigma = \frac{N_\gamma \lambda \beta}{T_{tot} \varepsilon f n_0 N_n S \eta} \tau(1+\alpha_{tot})$$

where: N_γ — the number of counts under the photopeak, λ — the decay constant, ε — the peak to total ratio for the NaI(Tl) crystal, T_{tot} — the total efficiency of the gamma-counter, f — the correction factor for the absorption of gamma-rays in the sample, η — the abundance of the isotope in the sample, n_0 — the number of nuclei per cm^2, N_n — the total neutron flux, S — the solid angle of the sample with respect to the neutron source, τ — the dead time correction, α_{tot} — the total conversion coefficient, β — the time correction factor:

$$\beta = \frac{T_b(1-e^{-\lambda T})}{(1-e^{-\lambda T_b})(1-e^{-\lambda T_c})e^{-\lambda T_d}}$$

where: T_b — the neutron burst width (sec), T_c — the counting interval (sec), T_d — the time delay between the end of burst and beginning of counting, T — the lenght of one cycle(sec).

The cross-section formula contains the total conversion coefficient α_{tot} which is up to now undetermined. The value obtained by us for the cross-section for excitation of ^{78m}Br activity in (*n*, 2*n*) reaction is (220±40) mb without the factor $(1+\alpha_{tot})$.

No spins of ^{78}Br have been measured directly: the spins and parities assigned in ^{78}Br by Schardt and Goodman [22] were based mainly on the energy and half-life. Hence spin parity assignment $2\pm$ and $4\pm$ were made for 32 and 149 keV levels respectively. On the basis of analogy with other odd-odd nuclei in this region, one might expect two low-lying levels with spins $2-$ and $5-$. As the α_K of the 149 keV isomeric transition is not known it is impossible to decide between the various possibilities. It is thus natural to assume the possible $E2$, $M2$, $E3$ and $M3$ multipolarities. The values of conversion coefficients for these multipolarities were taken from the tables of Sliv and Band [7]. The spins, parities and modes of decay together (see Fig. 8) suggest a close analogy between low energy levels of ^{78}Br and ^{80}Br. In ^{80}Br, two isomeric states are known $2-$ at 37 keV and $5-$ at 85 keV.

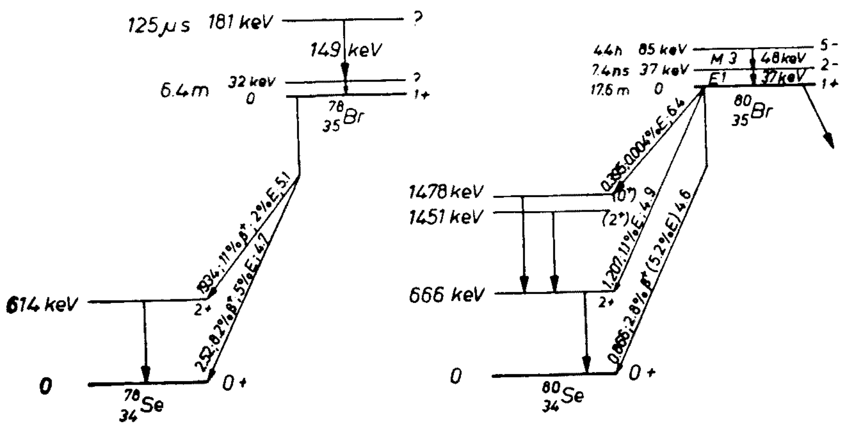

Fig. 8. Decay schemes of ^{78m}Br and ^{80m}Br

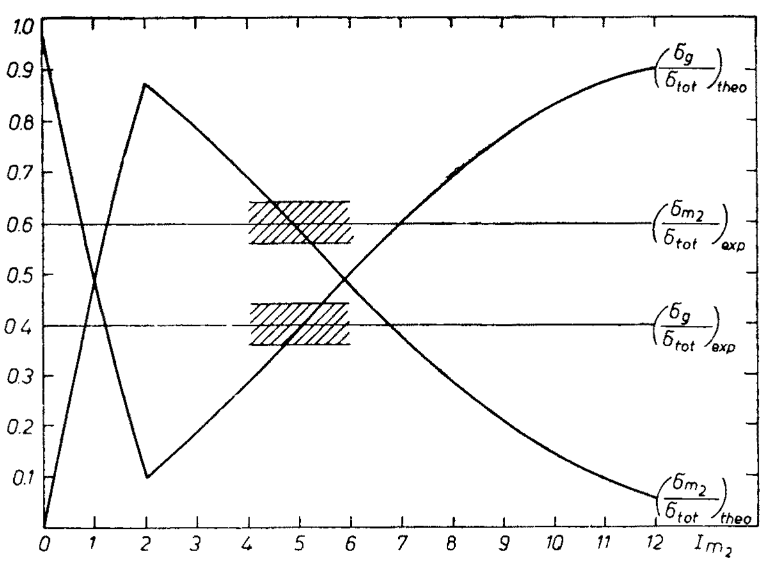

Fig. 9. The isomeric cross-section ratios for ^{80}Br *versus* spin value of ^{80m}Br. The solid lines are the results of calculations using Gilbert and Cameron level density formulas (*Can. J. Phys.* **43**, 1446 (1965))

The $M3$ character of the isomeric transition in ^{80}Br has been established by internal conversion measurements [19] and by the atomic beam method [23], [24].

As it has been shown for $^{114m2}In$, [1] ^{71m}Ge and ^{75m}Ge it is possible to apply the statistical model in order to estimate the spin value in ^{80}Br. In Fig. 9 the isomeric cross-section ratio for ^{80}Br is analysed *versus* the spin value of the ^{80m2}Br using the data of Ref. [25]. As it is seen from Fig. 9 the spectroscopic data and statistical model estimation give exactly the same value. This same procedure was applied to ^{78}Br. For calculation of the isomeric cross-section ratio the data of the present paper and the data from Ref. [25] were used. Unfortunately the results obtained (Fig. 10) in this way are not in agreement with predictions

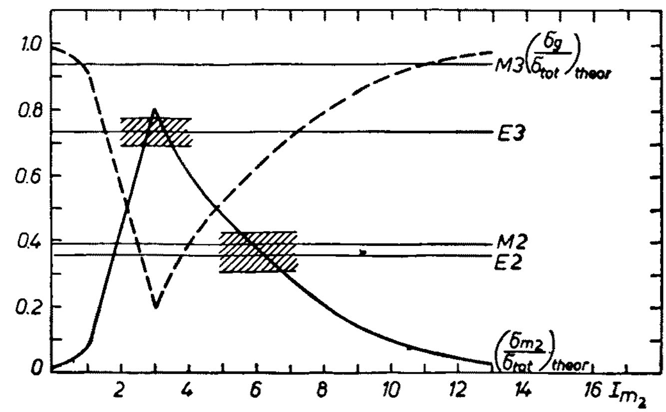

Fig. 10. The isomeric cross-section ratios for ^{78}Br *versus* spin value of ^{78m}Br. The solid lines are the results of calculations using Gilbert and Cameron level density formulas (*Can. J. Phys.* **43**, 1446 (1965))

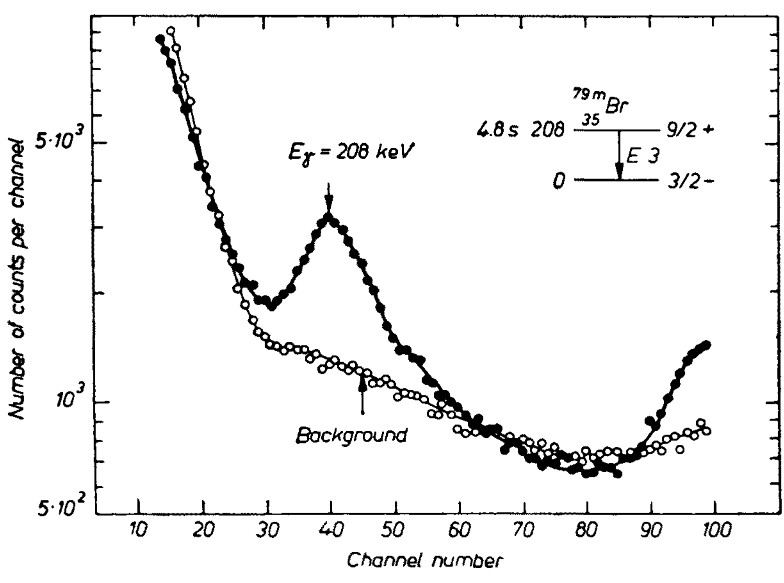

Fig. 11. Gama ray spectrum from the decay of ^{79m}Br taken with NaI(Tl)-spectrometer between neutron pulses

of Schardt and Goodman [22] that the most plausible multipolarity of 149 keV transition is $M2$. From Fig. 10 it is seen that:

1. $M3$ multipolarity is excluded,
2. the low spin value of the 181 keV level is possible only for $E3$. This result is very difficult to explain.

^{79m}Br

The decay of ^{79m}Br ($T_{1/2} = 4.8$ sec, $E_\gamma = 208$ keV) was investigated by several authors [26–31]. The conversion electron spectrum has been investigated by Schmidt-Ott and Flammersfeld [30] and conversion coefficient were determined to be $\alpha_K = 0.25 \pm 0.02$ and $\alpha_{tot} = 0.28 \pm 0.05$, yielding the multipolarity $E3$ for the isomeric transition. While in previous investigations the isomer was produced either by fast neutron irradiations [27, 30, 31], by proton bombardment *via* (p, γ) reaction [28] or with a linear electron bremsstrahlung [29], in our work the (n, n') reaction at 14.8 MeV neutron energy was used. In Fig. 11 the gamma-ray spectrum of ^{79m}Br taken with NaI(Tl)-spectrometer between neutron pulses is shown. The half-life of ^{79m}Br isomer was estimated as equal to about 5 sec. The measurements of the half-life of ^{79m}Br were performed with the pulsed neutron source. Existing components from activities induced by fast neutrons in NaI(Tl) crystal (11 sec and 38 sec) renders the measurement of this value.

The obtained cross-section for excitation of isomeric activity in ^{78}Br for 14.8 MeV (calculated from the formula reported in [1]) is equal to 230±30) mb.

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