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The anomaly in the energy dependence of the yield of the isomer in ^{81}Br by photo-excitation as manifestation of nuclear intermediate structure

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Abstract. The anomaly in the yield of the isomer in ^{81}Br with $J^{\pi} = 9/2^{+}$, $E_{\mathrm{x}} =$ 536 keV and $T_{1/2} = 36$ μs bremsstrahlung produced is observed as a function of the endpoint energy in the energy range 3–4 MeV. This anomaly is interpreted as excitation of the activated state with energy 3.45 ± 0.15 MeV. The excited state with $J^{\pi} = 5/2^{+}$, $E_{\mathrm{x}} = 3.18$ MeV and with a wavefunction with a 13% contribution of the quasiparticle component $2\mathrm{d}_{5/2}$ and a 83% contribution of the 'quasiparticle $\otimes$ phonon' component $[1\mathrm{g}_{9/2}2_1^{+}]$, which provides the resonance in the total scattering cross section and is well linked to the isomeric state, is obtained in the framework of the quasiparticle–phonon model.

1. Introduction

Photo-excitation of the isomers of nuclei is a method which allows one to get information about the interaction of photons with nuclei and the structure of nuclei below the particle threshold. In some nuclei we find 'pygmy' resonances in the total photon scattering cross section at these energies, and these resonances can be considered as possible manifestations of intermediate structure (Laszewski and Axel 1979, Zurmühl *et al* 1982).

Photo-excitation of the isomer levels goes via excitation of the activated states (AS). The total cross section of the photo-excitation of these states must be large (large partial width Γ_0 for the direct transitions to the ground state and predominant contribution of E1–, M1– or E2– components). As a result of direct or cascade γ transitions, part of the energy of these levels is transferred to the isomeric state. Also, the isomer ratio $\Gamma_{\mathrm{iso}}/\Gamma$ must not be small, Γ_{iso} being the sum of partial widths for the direct and cascade photon decay to the isomeric state and Γ being the total AS width.

For the single AS with spin and parity J^{π} the total cross section of the photo-excitation of the isomeric state is

$$\int \sigma_{\mathrm{iso}}\,\mathrm{d}E = \Gamma_{\mathrm{iso}}\Gamma^{-1} \int \sigma_{\mathrm{t}J}\,\mathrm{d}E$$

where $\int \sigma_{\mathrm{t}J}\,\mathrm{d}E$ is the total cross section of the γ scattering on the AS with J^{π}. If we measure energy E in MeV and the partial width of this level Γ_0 in eV we get

$$\int \sigma_{\mathrm{t}J}\,\mathrm{d}E = 3.85\,\frac{2J+1}{2J_0+1}\,E^{-2}\Gamma_0 \tag{1}$$

in units of mb MeV; here J_0 is the spin of the ground state.

Investigating the process of isomer photo-excitation by the bremsstrahlung with various values of the endpoint energy E_e we can obtain the global picture of the AS distribution in the range of E_e variation. We assume that, in the isomer excitation through the isolated AS, out of all photons of the continuum spectrum only the resonance photons with their energy and width defined by the AS properties are involved. The isomer in ^{81}Br was obtained for the first time by photo-excitation by Duffield and Vegors (1958) for $E_e > 5$ MeV.

The thickness of the targets producing the bremsstrahlung is usually comparable with the radiation length. In this case, the isomer yield through the single AS with energy E is proportional to $(E_e - E)$ in the range $E_e - E \leq 1$ MeV, which reproduces the behaviour of the resonance photon flux as a function of E_e normalized by the fixed number of the accelerated electrons stopped in the inner target. That is why the isomer yield as a function of E_e is linear in the interval between the two AS states (Burkhardt *et al* 1955, Booth and Brownson 1967)

The distribution of the AS in nuclei (mainly with the long-lived isomers) with the established location of the AS reveals non-statistical character in the nuclear spectrum at the energies with high level densities (Booth and Brownson 1967, Johnson and Chertok 1970). Development of the photoexcitation technique of the short-lived isomeric states enlarges the number of nuclei available for study. Simple estimations show that in the case of a single AS of energy about 1 MeV, for the typical values $\int \sigma_{\rm iso}\, dE = 10\ \mu$b MeV and $\Gamma_{\rm iso}/\Gamma \sim 0.01$, the value of $\int \sigma_{{\rm t}J}\, dE \sim 1$ mb MeV. The excitation of some AS in stripping reactions indicates that the one-quasiparticle component in the wavefunction of the AS is large. Some levels of ^{167}Er, ^{179}Hf, ^{197}Au, which are known to be the AS for the photo-excitation of the isomeric states in these isotopes (Johnson and Chertok 1970), have also been excited in the stripping reactions: ^{166}Er(d,p) (Harlan and Sheline 1968), ^{178}Hf(d,p) (Vergnes and Sheline 1963) and ^{196}Pt(^{3}He,d) (Munger and Peterson 1978).

2. Measurements of the isomer yield in ^{81}Br

The measurements of the activation curve for the photoproduction of the ^{81}Br isomeric state were performed at the Leningrad State University non-ferromagnetic betatron for the electron energies ranging from 3 to 4 MeV. The electron beam pulse had a duration of 2 μs, the number of electrons being up to 5×10^9 per impulse and the repetition rate being 3–5 cps.

The relative isomeric yield was obtained by measuring the area under the photopeaks of the unresolved doublet of 260 and 276 keV gamma rays from the spectrum of the ^{81}Br isomeric decay.

The sample was 460 g of the bromine chloride powder contained in a $14 \times 135 \times 135$ mm^3 box, placed in the x-ray beam axis at a distance of 35 cm from the betatron target at an angle of 45° with respect to the beam axis.

In view of the low counting rate that was expected it was essential to maximize the efficiency of gamma recording. Obviously a scintillation spectrometer satisfies this demand. The detector was assembled from the three NaI(Tl) 40×40 mm^2 crystals mounted on the photomultipliers. The entire assembly was located in the lead housing perpendicular to the x-ray beam axis. The crystal faces were at a distance of 10 cm from the sample centre.

The decay of the isomeric state was detected in 70 μs periods delayed 25 μs after the x-ray pulses. Figure 1 shows a typical pulse height distribution produced by gamma rays in these conditions. The full curve represents the pulse height distribution of the gamma rays (in the energy scale) for the 4.14 MeV runs, with a total of 10^5 runs. Only pulses with amplitudes exceeding 140 keV were analysed. The broken curve is the background measured with good statistics without bremsstrahlung intensity (no changes in the background with intensity and a dummy target in this energy range).

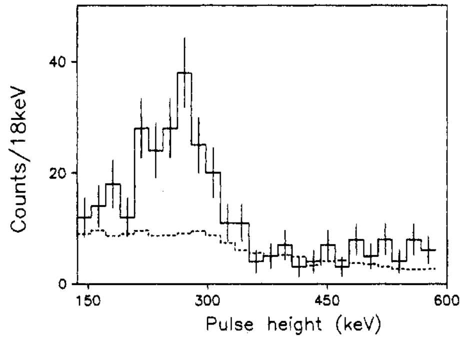

Figure 1. Typical pulse height distribution produced by gamma rays.

The isomeric yield was normalized by the fixed number of the accelerated electrons stopped in the betatron target by a tantalum sheet 1.5 mm thick, i.e. slightly thicker than the range of 4 MeV electron. The electron beam spot had dimensions of 4×2 mm^2 at the target. These factors mainly contributed to make the measurements of electron charge of sufficient efficiency.

The radiation scattered to the detector during the x-ray flash brings about current impulses with slowly reducing components in the photomultipliers. The fluctuations of these current components manifest themselves as a delayed background with a threshold energy depending to a large extent on the energy and the number of the accelerated electrons in the pulses and only slightly on the time delay. In this study the permissible limit of this threshold was 80–100 keV.

By appropriate adjustment of the geometry, using a 1 mm lead screen on the crystal faces, the radiation scattering on to the detector was reduced to a large extent. In order to minimize the gamma spectrum distortions resulting from residual scattered radiation the photomultipliers were gated on only during the registration periods and short recovery electronics was used. To date the need to keep the attenuation of radiation scattered by the sample to the detector to a permissible limit has restricted the possibility of obtaining good statistical data.

Each time, after changing the electron energy, the energy calibration of the scintillation spectrometer was performed with standard gamma sources in runs with a tungsten target of approximately the same thickness and weight as the NaBr sample.

The delayed background resulting from neutrons was negligible.

The data were handled by a computer program specially written for poor statistics by Awaya (1979). The isomer yield normalized as described earlier is presented in figure 2. The error bars here are only the result of the counting statistics.

As the result of the least-squares fit of the isomer yield data to the two straight lines we obtain the energy of the AS, which turns out to be 3.45 ± 0.15 MeV. This

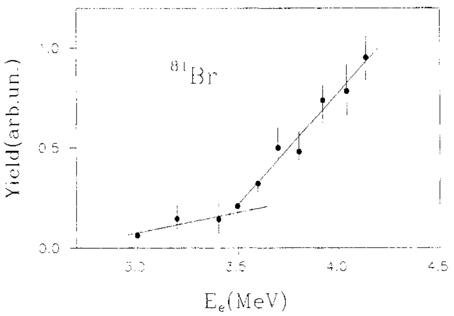

Figure 2. The yield of the isomeric state in ^{81}Br as a function of the endpoint energy E_e in arbitrary units.

level (or may be a group of closely lying levels) is the only strong AS of ^{81}Br in the 3–4 MeV range.

In order to estimate the isomer production cross section we took into account the absorption of the isomer gamma within the NaBr sample, the lead screen transmission and the photopeak efficiency of NaI crystals. The geometry efficiency in close geometry was calculated by the Monte Carlo method. We evaluated the resonant photon flux using the data of the bremsstrahlung spectrum (Sandifer and Taherzadeh 1968). The approximate estimation gives a value of $\int \sigma_{\mathrm{iso}}\, \mathrm{d}E \sim 5\ \mu$b MeV with a large uncertainty of the order of a factor of three, mainly as a result of the large uncertainty in the photon flux.

The Br isotopes are transitional nuclei with a rich variety of properties of their excited states. The information about the intermediate energy levels was obtained mainly from the reactions ^{80}Se(^{3}He, d) (Zumbro *et al* 1983, Evans and Ajzenberg-Selove 1967) and ^{80}Se(α, p2n) (Funke *et al* 1986). The spectroscopic characteristics of most of the discovered levels from 3–4 MeV are unknown, which makes it impossible to compare them with the AS discovered here.

3. The properties of the intermediate states in ^{81}Br

To determine the structure of the AS in ^{81}Br we have calculated the spectrum of the excited states in the energy range 3.0–4.5 MeV in the framework of the quasiparticle–phonon model (QPM) (Vdovin and Soloviev 1983, Voronov and Soloviev 1983, Vdovin *et al* 1985). The wavefunction of the ground and excited states of the odd nucleus has the form

$$\Psi_\nu(JM) = C_J^\nu \left\{ \alpha_{JM}^+ + \sum_{\lambda\mu i} D_j^{\lambda i}(J\nu) \left[\alpha_{jm}^+ Q_{\lambda\mu i}^+\right]_{JM} \right\} \Psi_0 \qquad (2)$$

where α_{jm}^+ is the quasiparticle creation operator with the shell quantum numbers j, m; $Q_{\lambda\mu i}^+$ is the phonon creation operator with the moment λ, projection μ and the RPA root number i; Ψ_0 is the ground state of the neighbouring even–even nucleus. The phonons in the QPM are constructed as a linear combination of two-quasiparticle operators and considered as bosons. To get the spectrum of the states with spin J^π and coefficients C_J^ν and $D_j^{\lambda i}(J\nu)$ for the ν state we solve the secular equation described in detail by Gales *et al* (1988), Vdovin *et al* (1985) and Soloviev *et al* (1980). The numerical calculations have been performed with the code PHOQUS (Stoyanov and Chan Zuj Khuong 1981).

No free parameters are used in the QPM for the description of the odd nuclei except those fitted to obtain the correct reproduction of the neighbouring even–even core properties. The parameters of the effective residual forces which generate the phonon excitations were chosen to reproduce the location and the transition probabilities of the experimentally known low-lying levels (Endt 1979). In this way, we get the isoscalar component of the effective interaction. As for the ratio of the strength of the isoscalar component to the isovector one, it was determined by the location of the giant resonance provided that the spurious state was excluded, and since the radial form factor of the residual forces was used as a derivative of the average field, this ratio was fixed for all the multipolarities. In the numerical calculation we used $1^{\pm}$, $2^{\pm}$, $3^{\pm}$, 4^{+}, 5^{-}, 6^{+} phonons in the wavefunction (2).

The ground state of ^{81}Br is the level $3/2^-$. Since the electromagnetic transitions to the AS go on predominantly due to the E1−, M1− or E2− components, we calculated the spectrum of the states with $J^\pi = 1/2^\pm$, $3/2^\pm$ and $5/2^\pm$. In addition to the excitation energy and structure of these states we also considered the values of the cross section (1) for their photo-excitation from the ground state. The states with the visible values of the photo-excitation $\sigma_{J_i \to J_f}$ are presented in table 1. In this table we also show the contribution of the quasiparticle (α^+) and the main 'quasiparticle $\otimes$ phonon' ($\alpha^+ Q^+$) components to the structure of the states.

As our calculations show, mainly the states with small contribution of the quasiparticle component to the norm of the wavefunction (2) are located in the energy range 3.0–4.5 MeV in ^{81}Br. That is why the valence transitions are strongly suppressed. The components corresponding to the exchange of the collective phonons with large values of $B(\mathrm{E}(M)\lambda)$ are suppressed too. The reason for the suppression is the following. The collective 2_1^+ phonon has too small an energy for the range under consideration whereas the 1^+ phonon forming the M1 resonance lies too high, as do the low-lying, even non-collective, 1^- phonons. The exception is the state with $J^\pi = 5/2^+$ and $E_\mathrm{x} = 3.18$ MeV and to some extent the state with $J^\pi = 1/2^+$ and

Table 1. The excited states in ^{81}Br from the energy range 3.0–4.5 MeV with the largest values of $\sigma_{J_i \to J_f}$ and the contribution of the quasiparticle (α^+) and the main 'quasiparticle $\otimes$ phonon' ($\alpha^+ Q^+$) components to their structure.

Final state	E_x (MeV)	Transition	$\sigma_{J_i \to J_f}$ (mb MeV)	α^+	$\alpha^+ Q^+$
$5/2^+$	3.18	E1	0.375	$2d_{5/2}$(12.9%)	$1g_{9/2}2_1^+$(83.0%)
$1/2^+$	3.65	E1	0.094	$2s_{1/2}$(4.34%)	$1f_{5/2}3_1^-$(94.9%)
$3/2^+$	3.75	E1	0.002	$1d_{3/2}$(2.11%)	$2f_{5/2}3_1^-$(66.6%)
$5/2^+$	3.91	E1	0.007	$1d_{5/2}$(0.49%)	$1f_{5/2}3_1^-$(83.9%)
$1/2^-$	3.97	E2	0.002	$2p_{1/2}$(0.01%)	$2p_{3/2}2_5^+$(99.9%)
$3/2^-$	3.97	E2	0.005	$2p_{3/2}$(0.01%)	$2p_{3/2}2_5^+$(99.9%)
$3/2^-$	4.04	M1	0.043	$2p_{3/2}$(0.38%)	$2p_{3/2}1_1^+$(99.0%)
$1/2^-$	4.18	M1	0.014	$2p_{1/2}$(0.78%)	$2p_{3/2}1_1^+$(99.0%)
$3/2^-$	4.27	M1	0.002	$2p_{3/2}$(0.21%)	$2p_{1/2}1_1^+$(99.3%)
$3/2^+$	4.28	E1	0.003	$2d_{3/2}$(0.97%)	$2p_{3/2}3_1^-$(60.8%)
$5/2^+$	4.29	E1	0.018	$2d_{5/2}$(0.46%)	$1p_{3/2}3_1^-$(51.7%)

$E_x = 3.65$ MeV with a noticeable contribution of the quasiparticle component to the norm of the wavefunction (2).

Now consider in detail the state with $J^\pi = 5/2^+$ and $E_x = 3.18$ MeV. Its reduced transition probability from the ground state is equal to 0.03 e^2 fm^2 and is determined exclusively by the valence E1 transition $3/2^- \to 5/2^+$. The exciting fact here is the value of the one-quasiparticle component in the state. The one-quasiparticle level $\pi(2d_{5/2})$ lies much higher (in our average field it has an energy of 7.1 MeV) but due to the coupling of the quasiparticle and 'quasiparticle $\otimes$ phonon' components in the wavefunction (2), part of its strength, its visible part, is pushed out to lower energies. This effect is vividly demonstrated in figure 3 where the distribution of the $\pi(2d_{5/2})$ component over the excited states with $J^\pi = 5/2^+$ is presented. The low-lying peak in the distribution gives rise to the existence of the AS detected in the experiment. The additional argument (except for the large value of the $\sigma_{J_i \to J_f}$) that the state with $E_x = 3.18$ MeV is the AS we have found, is connected with the main 'quasiparticle $\otimes$ phonon' component, whose contribution to the norm of the wavefunction is larger than 80%. Its quasiparticle part has the quantum numbers $9/2^+$ and thus this component is well linked to the isomeric state $9/2^+$ registered in the experiment.

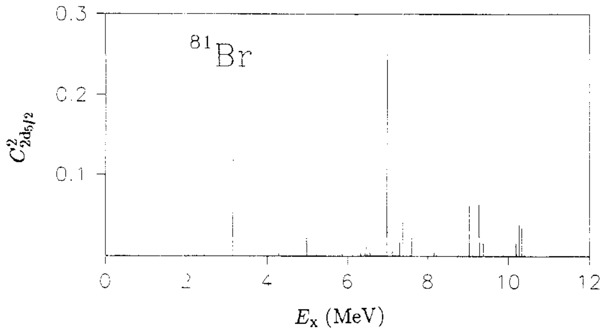

Figure 3. The distribution of the quasiparticle component $\pi(2d_{5/2})$ in ^{81}Br.

What is left is to calculate the decay of the state with $J^\pi = 5/2^+$ and $E_x = 3.18$ MeV to the isomeric state $9/2^+$. In our calculations with the wavefunction (2) the lowest $9/2^+$ has an excitation energy $E_x = 1.63$ MeV; the main contribution to its structure comes from the one-quasiparticle component $1g_{9/2}$, 64%, and from the component $[1g_{9/2}2_1^+]$, 30%. But if we add the next term $\sim \alpha^+ Q^+ Q^+$ to the wavefunction of the ground and excited states, as described in detail by Gales *et al* (1988), Vdovin *et al* (1985) and Soloviev *et al* (1980), the energy of the first $9/2^+$ state is shifted to a value $E_x = 0.87$ MeV, becoming rather close to the experimental one, while the location of the AS $5/2^+$ does not change noticeably. The direct transition between $5/2^+$ and $9/2^+$ states under consideration goes on predominantly ($\sim 90\%$) due to the exchange of the collective 2_1^+ phonon and gives $B(\mathrm{E2}\downarrow) = 386\ e^2\ \mathrm{fm}^4$. Using this value we can make an estimation of the isomer ratio assuming that the direct collective transition provides the main contribution to Γ_{iso} and the main part of Γ comes from the direct transition to the ground state, i.e. $\Gamma = \Gamma_0$. Under these assumptions we get $\Gamma_{\mathrm{iso}}/\Gamma = 6 \times 10^{-2}$. This estimation of the total cross section of the isomer yield through the level with $J^\pi = 5/2^+$ and $E_x = 3.18$ MeV gives the value

$\int \sigma_{\text{iso}}\, dE = 20\ \mu\text{b MeV}$, which is close to the experimental one taking into account the experimental uncertainties.

As for the state with $J^\pi = 1/2^+$ and $E_x = 3.65$ MeV whose excitation cross section is four times lower compared to the state with $E_x = 3.18$ MeV, its contribution to the total cross section of the isomer photo-excitation will be negligibly small since it differs strongly from the isomeric state in spin ($\Delta J = 4$) and in the structure of the wavefunction.

4. Conclusions

The method of photo-excitation of isomeric states by the bremsstrahlung is suitable for the investigation of some intermediate structures below the particle threshold. In photo-excitation of the isomeric state with $J^\pi = 9/2^+$ and $E_x = 536$ keV in ^{81}Br the only strong AS with $E_x = 3.45 \pm 0.15$ MeV in the whole energy range 3–4 MeV has been discovered.

In the framework of the quasiparticle–phonon model this AS is interpreted as intermediate structure—the state with $J^\pi = 5/2^+$, $E_x = 3.18$ MeV and a wavefunction constructed of a quasiparticle component $2d_{5/2}$ with a contribution equal to 13% and a component 'quasiparticle $\otimes$ phonon' $[1g_{9/2}2_1^+]$ with the contribution of 83%. The first component is the low-lying fragment of the quasiparticle state $2d_{5/2}$. The valence transition of the proton from the ground state is the reason for the strong radiative excitation of this level; with a value $B(\text{E1}, \uparrow) = 0.03\ e^2\ \text{fm}^2$. This AS is well related to the isomer level due to the main component of the wavefunction. The theoretical estimate of the total cross section of the isomer yield is in good agreement with the experimental value.

It will be interesting to obtain information from the direct excitation of the level with $J^\pi = 5/2^+$, $E_x = 3.45 \pm 0.15$ MeV and $\Gamma_0 \sim 0.7$ eV in the reactions of inelastic photon scattering or inelastic electron scattering at low momentum transferred.

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