Excitation of low-lying state by E3 transition in reaction with real photons

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Abstract

The yield of the isomeric state $^{117m}\text{Sn}$ ($E_{iso} = 314.58$ keV) has been measured in $(\gamma, \gamma')$ reaction by activation method with the bremsstrahlung end-point energy from 2.1 to 3.0 MeV. Only one intermediate state (IS) responsible for the isomer feeding has been found. The excitation energy of the IS ($2.25 \pm 0.05$ MeV) and photoproduction integral cross section ($0.022 \pm 0.002$ eV b) have been deduced. Microscopic calculations within the Quasiparticle-phonon model have been performed to learn on the IS structure. We conclude that the IS is excited in the present experiment by the $E3-$transition.

Key words: $^{117}\text{Sn}(\gamma, \gamma')^{117m}\text{Sn}$, $E_0 = 2.1 - 3.0$ MeV, deduced isomer integrated cross section, Quasiparticle-phonon model calculations.

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Isomers in atomic nuclei are the levels with the total angular momentum $J_{iso}$ significantly different from the one of the ground state $J_{g.s.}$. They appear in the spectra due to the shell structure of a mean field and their excitation energy in odd-mass nuclei does not exceed a few hundred keV. For these reasons, decay
of isomers into the ground state is strongly hindered and their lifetime vary for milliseconds to days depending on the spin difference $\Delta J_{iso} = |J_{g.s.} - J_{iso}|$.

Isomers are populated after decay of intermediate state(s) (IS) with the energy of 2-4 MeV and finite branching to the isomeric level. These IS are excited, e.g., by bremsstrahlung radiation with the end-point energy of 2-5 MeV. The previous experiments [1,2,3,4] have already shown that the number of such IS which are linked to both the ground and isomeric states, is very small, i.e. one-two states per MeV in spherical nuclei. There was also a set of experiments in which the isomeric states were populated in the ($\gamma$,n) reaction via excitation and cascade decay of the giant dipole resonance [5,6].

Up to now, analysis of the IS excited in the bremsstrahlung technique has been performed only for nuclei with $\Delta J_{iso} = 3, 4$ involving $E1 - E2$ (or $E2 - E1$) and $E2 - E2$ sequences for the isomer population [1,4,7]. The best studied example is $^{115}$In [2,3,7,8,9] for which this type of experiments have been supplemented by nuclear resonance fluorescence (NRF) $^{115}$In($\gamma, \gamma'$)$^{115m}$In studies [7].

In this letter we report our results on the isomer photoproduction in $^{117}$Sn (the isotopic abundance is 7.68 %). It has the stable ground state with the spin and parity $J^{\pi}_{g.s.} = 1/2^+$. The isomeric state in this nucleus has the excitation energy $E_{iso} = 314.58$ keV and $J^{\pi}_{iso} = 11/2^-$. Thus, the spin difference $\Delta J_{iso} = 5$ and at least the $E2 - E3$ sequences is need to populate the isomer from the ground state. The $T_{1/2}$ value is very large for the isomeric state and equals to 13.60 days.

The decay scheme of the isomer in $^{117}$Sn is presented in Fig. 1. Due to the presence of the $J^{\pi} = 3/2^+$ level at $E_x = 158.56$ keV, the isomer decays predominantly to this level by the $M4$ internal conversion process with the relative probability ($\gamma$-line intensity) of $I_\gamma = 2.113$. For the direct decay to the ground state, $I_\gamma = 0.000423$. The 158.56 keV level decays into the ground state with $I_\gamma = 86$ by $M1 + E2$ $\gamma$-transition.

The only work in which the $^{117m}$Sn IS integrated cross sections have been determined is Ref. [3]. The experiments have been performed for the bremsstrahlung end-point energies 4 and 6 MeV. The obtained integrated cross sections ($\sigma\Gamma$) are $(3.20 \pm 0.47)$ eV b and $(8.80 \pm 0.26)$ eV b, respectively. Unfortunately, low experimental resolution did not allow the IS determination.

Our experiment have been carried out in the National Science Center “Kharkiv Institute of Physics and Technology” at the 3 MV electrostatic electron accelerator ELIAS having an energy resolution 50 kV and a beam intensity up to 500 $\mu$A. The investigation of the isomeric states population have been performed using activation technique.

Bremsstrahlung spectra have been generated by electrons irradiating of 0.5 mm
Fig. 1. Decay scheme of the isomeric $J_{\text{iso}}^\pi = 11/2^-$ state in $^{117m}\text{Sn}$ [10]. See text for details.

Fig. 2. $\gamma$-ray spectrum measured after bremsstrahlung irradiation of Sn target with the end-point energy of 2.1 (top) and 2.7 MeV (bottom).

thickness Ta converter. Samples of natural Sn (0.2 mm thick and 15 mm in diameter) have been placed in the photon beam behind the converter. The photoactivities have been measured with Ge(Li) detector by observing the 158.56 keV $\gamma$-rays emitted in the cascade of the isomeric level decay. The detector sensitive volume is 50 cm$^3$ and the energy resolution is 2.5 keV for 1332 keV of $^{60}$Co source. The schematic layout of photoactivation experiment and standard procedure for activation data development is described elsewhere [9].
The obtained spectra for two different values of the end-point energy $E_{\gamma\text{max}}$ are shown in Fig. 2. The measurements have performed with the electron beam current $I = 170 \mu A$, irradiation time $t_{\text{irr}} = 240$ and 120 min, cooling time $t_c = 28$ and 31 min and spectra measurement time $t_m = 60$ min for $E_{\gamma\text{max}} = 2.1$ and 2.7 MeV, respectively.

The spectrum in the bottom part of Fig. 2 is typical for the end-point energy $E_{\gamma\text{max}} > 2.25$ MeV. The strong sharp line at 158.56 keV indicates that the $J^{\pi} = 3/2^+$ level at this energy is fed after cooling by decay of the isomeric state. The absence of such a line in the top part of Fig. 2 means that the isomer is not populated for $E_{\gamma\text{max}} < 2.25$ MeV.

The measured isomer yield $Y(E_{\gamma\text{max}})$ is presented in Fig. 3 as a function of the bremsstrahlung end-point energy. This quantity is defined as the number of activated nuclei $N_{\text{iso}}$ normalized to the number of target nuclei $N_T$ per cm$^2$ and the number of incident electrons $N_e$:

$$Y(E_{\gamma\text{max}}) = \frac{N_{\text{iso}}(E_{\gamma\text{max}})}{N_T N_e}.$$  

(1)

The error bars include systematic and statistical errors. Their average value is 10-15%. The solid line in Fig. 3 represents the $\chi^2$ fit of the data points assuming the linear dependence of the isomer yield as a function of the end-point energy.

The linear dependence of the isomer yield breaks each time when the end-point energy of the bremsstrahlung radiation reaches the energy of an IS state feeding the isomer. We conclude from the data in Fig. 3 that there is only
one IS of this type in $^{117}$Sn in the energy interval between 2 and 3 MeV. The excitation energy of this state is $2.25 \pm 0.05$ MeV.

The energy of the IS in $^{117}$Sn obtained in the present experiment, is very close to the energy of the first $3^-$ state in the core $^{116}$Sn nucleus which is $2.266$ MeV. This allows us to suppose that the IS is excited from the ground state by the $E3$-transition.

The isomer yield can be also calculated as

$$Y(E_{\gamma \text{max}}) = \int_{E_c}^{E_{\gamma \text{max}}} \sigma_\gamma(E_\gamma) N(E_\gamma, E_{\gamma \text{max}}) dE_\gamma$$

(2)

where $E_c$ is a cutoff energy, $\sigma_\gamma(E_\gamma)$ is the reaction cross section as a function of the photon energy $E_\gamma$ and $N(E_\gamma, E_{\gamma \text{max}})$ represents the continuous bremsstrahlung spectral density with the end-point energy $E_{\gamma \text{max}}$.

Accounting for the fact that only one IS has been found in the present experiment and assuming a small width of this level, reduces Eq. (2) to:

$$Y(E_{\gamma \text{max}}) = (\sigma_\gamma)_{\text{is}} N(E_{IS}, E_{\gamma \text{max}}).$$

(3)

The number of photons $N(E_{IS}, E_{\gamma \text{max}})$ with the IS energy $E_{IS}$ for each bremsstrahlung end-point energy in Fig. 3 has been calculated by mathematical modeling of the bremsstrahlung spectra with GEANT 3.21 program [11]. The number of launches was $10^7$ and we used $E_c = 0.5$ MeV and the interval of grouping of 0.01 MeV.

The integrated cross section for the isomer population in $^{117}$Sn has been determined as $(0.022 \pm 0.002) \text{ eV b}$. This value is about two orders of magnitude lower than $(\sigma_\gamma)_{\text{is}}$ for isomer population in nuclei with $\Delta J_{\text{is}} = 3$ and 4 reported in Ref. [1] for $^{81}$Br, Ref. [4] for $^{89}$Y and Ref. [2] for $^{115}$In. It has been concluded from theoretical analysis that the IS in these nuclei are excited from the ground state either by non-collective $E1-$ transition in $^{81}$Br [1] or by collective $E2-$ transition in $^{89}$Y [4] and $^{115}$In [7]. Very small value of $(\sigma_\gamma)_{\text{is}}$ in $^{117}$Sn supports our guess that the IS is excited in this nucleus by the $E3$-transition and calls for theoretical analysis of low-lying states in $^{117}$Sn.

Such an analysis has been performed within the Quasiparticle-phonon model (see for details Refs.[12,13,14]) which has been very successful in application to studies of the isomeric state population in nuclei with $\Delta J_{\text{is}} = 3$ and 4 [1,4,7]. The ground and excited states of $^{117}$Sn have been described by the wave function which includes quasiparticle–, [quasiparticle $\otimes$ 1 phonon]– and [quasiparticle $\otimes$ 2 phonons]– configurations. The model parameters have been adjusted to reproduce the experimental $B(E2)$ and $B(E3)$ values of the $2^+_1$ and $3^-_1$ states, respectively, in the neighboring even-even $^{116}$Sn core nucleus.
Table 1
Properties of the IS in $^{117}$Sn responsible for the isomer feeding.

| Energy (MeV) | $(\sigma\Gamma)_{iso}$ (eV b) |
|--------------|-------------------------------|
| Experiment   | $2.25 \pm 0.05$ 0.022 $\pm$ 0.002 |
| Theory       | 2.44 0.026 |

The calculation reproduce very well the excitation energy of the $3/2^+$ state in $^{117}$Sn (0.15 MeV) and slightly underestimate the energy of the isomeric $11/2^-$ state (0.17 MeV). Among many excited state in the energy interval between 1.5 and 3.5 MeV, we have found only one state which is linked to both, the ground and isomeric states. It is $7/2^-$ state at the excitation energy of 2.44 MeV with the wave function:

$$|7/2^- > = 0.19 \cdot 2f_{7/2} + 0.90 \cdot [3s_{1/2} \otimes 3_{1^-}]_{7/2^-} - 0.14 \cdot [1h_{11/2} \otimes 2_{1^-}]_{7/2^-} + \ldots$$ \(4)$$

where $2_{1^+}$ and $3_{1^-}$ mean the lowest $2^+$ and $3^-$ phonons of the core nucleus excitation.

This state is indeed excited from the ground state by the $E3$-transition to the second component of its wave function (4). Although this is the main component of the wave function, the state decays predominantly to the isomeric state from its third component by the $E2$-transition with the branching ratio $\Gamma_{iso}/\Gamma_{tot} = 0.97$. The calculated value of the cross section for the isomer population in $^{117}$Sn($\gamma, \gamma'$) reaction via this state is 0.026 eV b and agrees very well with the experimental findings.

One finds in literature [10] two levels in $^{117}$Sn at 2160 and 2280 keV, both of them have been assigned as $5/2^-$, $7/2^-$ from the $L = 3$ transfer in $^{117}$Sn(p,p'). Apparently, the above discussed $7/2^-$ state in calculation corresponds to one of them. The calculation also yields $5/2^-$ state at 2.50 MeV with the $[3s_{1/2} \otimes 3_{1^-}]_{5/2^-}$ configuration as the main component in its wave function. But this state has no branching to the isomeric state. Which of the levels at 2160 and 2280 keV is our IS can be distinguished in the NRF experiment from the energy of the line at $E_{IS} - E_{iso}$.

To conclude, the population of the isomer in $^{117}$Sn has been studied in reaction with the bremsstrahlung radiation with the end-point energy from 2.1 to 3.0 MeV. Only one intermediate state responsible for the isomer feeding has been found in this energy interval. The properties of this state from the present experiment and theoretical analysis are summarized in Table 1. In our opinion, we have convincing evidence that this IS is excited in this extremely selective reaction by the $E3$—transition from the ground state.
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