PHOTOEXCITATION OF ^{87m}Sr BY (γ,γ') REACTION

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The photoexcitation of ^{87m}Sr (energy of isomeric level $E_{iso} = 388.532\,keV$) using the gamma rays produced by electron electrostatic accelerator was examined for the bremsstrahlung end-points energy covered the range from 1.4 to 3.1 MeV. Isomer activation yield was measured and intermediate states (IS) 1228, 1770, 1920 and 2656 keV contribution were observed. Experimental and published nuclear Resonance Fluorescence data were analyzed and photo-activation intermediate state integral cross section determined, which are: 0.090, 0.009, 0.070 and $(1.7 \pm 0.5)\,eV \cdot b$.

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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 the the odd-mass nuclei does not exceed a few hundred keV. For these reason, decay of isomers into the ground state is strongly hindered and their lifetime vary for milliseconds to days depending on the spin difference $\Delta J = |J_{g.s.} - J_{iso}|$ [1]. Isomers are populated after decay of intermediate state(s) with the energy of $(2-4)$ MeV and finite branching to the isomeric level. IS are excited by bremsstrahlung radiation with the end-point energy of $(2-5)$ MeV.

The previous experiments [2 – 5] 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 (γ, n) reaction via excitation and cascade decay of the giant dipole resonance [6]. In this paper we report our results on the isomer photoproduction in ^{87}Sr (the isotopic abundance is 7.00%). It has the stable ground state with the spin and parity $J^{\pi}_{g.s.} = 9/2^{+}$. The isomeric state in this nucleus has the excitation energy $E_{iso} = 388.532\,keV$ and $J^{\pi}_{iso} = 1/2^{-}$. Thus, the spin difference $\Delta J = 4$ and at least the $E2-E3$ sequence is need to populate the isomer from the ground state. The $T_{1/2}$ value is equal 2.81 hours.

The decay scheme of the isomer in ^{87}Sr is presented in Fig.1. The isomer decays to ground states by $M4$ transition with the relative γ - line intensity of $I_{\gamma} = 82.1$. An early work [7] examined the production of ^{87m}Sr by bremsstrahlung with end points which could be varied up to 3 MeV. The tunability of that device allowed three distinct gateways to be identified at 1.22, 1.88 and 2.66 MeV, and their integrated cross sections to be measured.

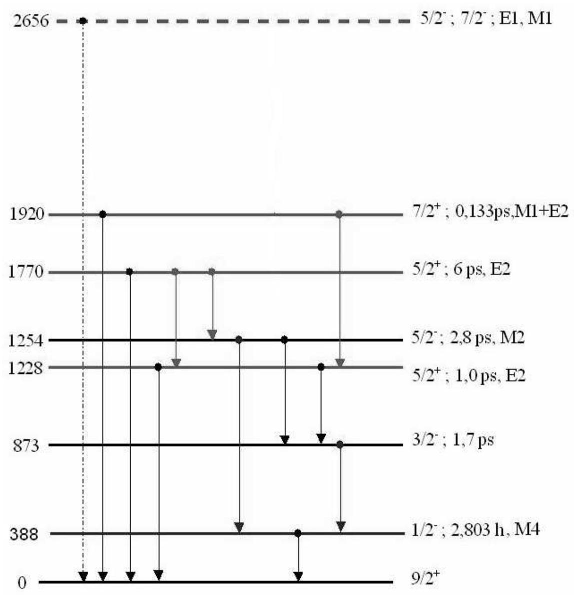

Fig.1. *Decay scheme of the isomeric $J^{\pi}_{iso} = 1/2^{-}$ state in ^{87m}Sr [9]. See text for the details*

They are $0.085^{+0.040}_{-0.030}$, $0.16^{+0.08}_{-0.05}$ and 3.8^{+2}_{-1} $eV \cdot b$ respectively [8]. The next experiment have been performed for the bremsstrahlung end-point energy 4 and 6 MeV [8]. The obtained integrated cross section $(\sigma\Gamma)$ are (3.90 ± 0.13) and (8.70 ± 0.18) $eV \cdot b$, respectively. The low experimental resolution did not allow the IS determination. It is seen that attempts at quantitative IS integrated cross sections still do not converge. Subsequently we reexamined the reaction

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$^{87}Sr(\gamma,\gamma')^{87m}Sr$ used precious electrostatic electron accelerator and spectroscopic nuclear resonance fluorescent data.

The 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 voltage instability $50\,kV$ and a beam intensity up to $500\,\mu A$. The investigation have been performed using activation technique. Bremsstrahlung spectra have been generated by electrons irradiating of $0.5\,mm$ thickness Ta converter. Samples of natural Sr ($0.2\,mm$ thick and $15\,mm$ in diameter) have been placed in the photon beam behind the converter. The photo activities have been measured with Ge(Li) detector by observing the $388.532\,keV$ γ -rays. The detector sensitive volume is $50\,cm^3$ and the energy resolution is about $2.5\,keV$ for $1332\,keV$ of ^{60}Co source. The schematic layout of photo activation experiment and standard procedure for activation data development is described elsewhere [10].

The principal results of the study and details are discussed below. A part of the pulse height γ-spectrum seen in the detector when bremsstrahlung of end-point energy of $2.7\,MeV$ irradiates a strontium scatterer is depicted in Fig.2. It is a typical activated spectrum of our experiment. The $388.532\,keV$ γ-line is seen in all other runs.

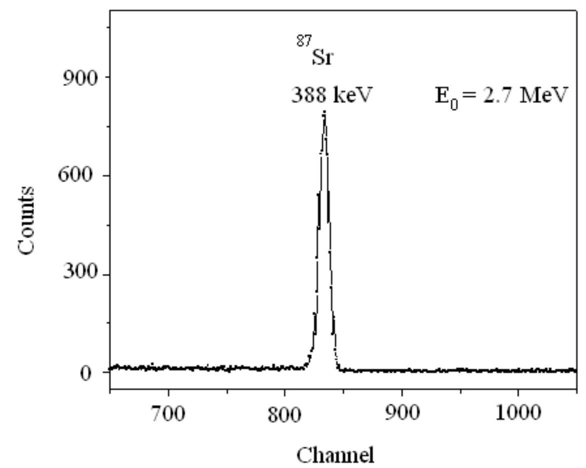

Fig.2. *γ-ray spectrum measured after bremsstrahlung irradiation of Sr target with end -point energy of* $2.7\,MeV$

The reaction yield is defined as the number of activated nuclei N_{iso} normalized to the number of target nuclei N_T per cm^2 and the number of incident electrons N_e:

$$Y(E_{\gamma max}) = N_{iso}/N_e N_T. \tag{1}$$

The experimental $^{87}Sr(\gamma,\gamma')^{87m}Sr$ reaction yield versus end point photon energy is shown in Fig.3 by circles. Full uncertainty values of excitation function were determined as a sum of systematic and statistical errors and on average consists of 10-15%.

The isomer yield can be calculated as:

$$Y(E_{\gamma max}) = \int_{E_c}^{E_{\gamma max}} \sigma(E_\gamma) N_\gamma(E_\gamma, E_{\gamma max}) dE_\gamma, \tag{2}$$

where E_c is cutoff energy, $\sigma(E_\gamma)$ is the total reaction cross-section as a function of the excitation energy E_γ and $N_\gamma(E_\gamma, E_{\gamma max})$ represents the continuous bremsstrahlung spectral density with the end-point energy $E_{\gamma max}$.

The typical widths of resonant intermediate states are small enough to assume that $N_\gamma(E_\gamma, E_{\gamma max})$ is constant over each resonance. Than, equation (2) can be simplified to

$$Y_i = \sum (\sigma\Gamma)^j_{iso} N^j_i (E_{IS}, E_{\gamma max}), \tag{3}$$

where $(\sigma\Gamma)^j_{iso}$ is the isomer excitation integrated cross section through the $j - IS$.

Integrated cross sections of an IS can be determined by solution of equation system (3). From the other side those integrated cross sections is related to its level properties by equation [11]:

$$(\sigma\Gamma)_{iso} = \pi^2 \left(\frac{hc}{E_{IS}}\right)^2 \frac{2J_{IS}+1}{2J_0+1} \alpha_0 \, \alpha_{iso} \, \Gamma. \tag{4}$$

$J_{0,IS}$, are the spins of the g.s. and the intermediate state, Γ describes the total width and α_0, α_{iso} denote the branching ratios for decay into the g.s., isomeric state respectively. If the relevant level properties Γ, α_0, α_{iso}, E_{IS} and J of all intermediate levels are known, and Eq.(2) can be inverted and information on the spectral intensities at the resonance energies can be extracted [11,12]. For ^{87}Sr the available data base [9] provides a complete characterization of all levels contribution to the isomer yield up to bremsstrahlung edge $3.1\,MeV$. The adopted data and derived integrated cross section are summarized in Table.

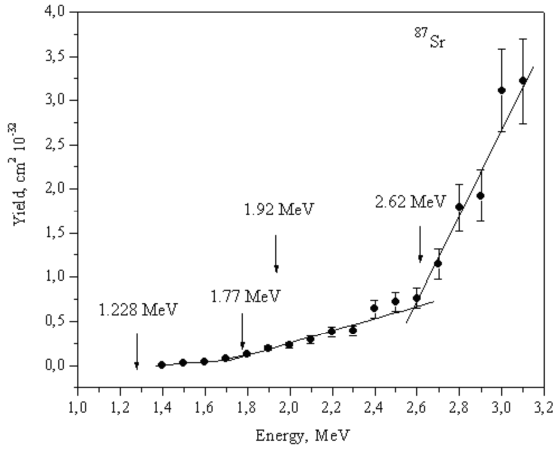

Fig.3. *The ^{87}Sr isomer yield as a function of the bremsstrahlung end-point energy*

The number of photons $N_i^j(E_{IS}, E_{\gamma max})$ in Eq.(3) with the IS energy E_{IS} for each bremsstrahlung endpoint energy in Fig. 3 has been calculated by mathematical modeling of the bremsstrahlung spectra with GEANT 3.21 program. The number of launches was 10^7 and used $E_c = 0.5\,MeV$ and the interval of grouping of $0.01\,MeV$.

A theoretical yield function can be constructed from the Geant photon spectra and tested against the measured result. This method was used in ref. [10] to determine the contribution of low-lying levels and to extract information on previously unknown IS at higher excitation energies. Here, we are concerned with the quality of reproduction of the experimental yield curve for 1228, 1770 and 1920 keV IS using Monte Carlo Geant generated photon spectra. Fig.3 clearly shows that the experimental yield variation for the bremsstrahlung edge less than 2.6 MeV is agree with the calculation including 1228, 1770 and 1920 keV IS. It is seen sharp increasing of experimental yield above 2.6 MeV. Nuclear tables [9] contain no information about IS in ^{87m}Sr for this energy range. More suitable is level 2656 keV IS integrated cross section for $E_{IS} = 2656\,keV$ was calculated from difference between experimental and calculated yield. The result is $(\sigma\Gamma) = (1.7 \pm 0.5)\,eV \cdot b$

Properties of ^{87}Sr levels contribution to the population of the $388.53\,keV$ isomer for $E_{IS} < 3.1\,MeV$ [11]

E_{IS}, keV	J^π	t, ps	L	α_0,%	α_{iso},%	$(\sigma\Gamma)_t$, $eV{\cdot}b$	$(\sigma\Gamma)_e$, $eV{\cdot}b$ [7]	$(\sigma\Gamma)_{iso}$, $eV{\cdot}b$ *this work*
1228	$5/2^+$	1.0	E2	84.82	15.18	0.090	$0.085^{+0.040}_{-0.030}$	-
1770	$5/2^+$	6.0	E2	78.51	21.49	0.0094	-	-
1920	$7/2^+$	0.133	M1+E2	97.5	2.53	0.070	-	-
2656	$5/2^-, 7/2^-$	-	E1, M1	-	-	-	3.8^{+2}_{-1}	1.7 ± 0.5

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ФОТОВОЗБУЖДЕНИЕ ^{87m}Sr В (γ,γ')- РЕАКЦИИ

О.С. Шевченко, Ю.Н. Ранюк, А.Н. Довбня, Э.Л. Купленников, А.А. Немашкало, И.Г. Гончаров, В.Н. Борисенко, В.И. Нога

Исследовано фотовозбуждение ^{87m}Sr в (γ,γ')- реакции с использованием гамма лучей генерируемых электронным пучком, ускоренным электростатическим генератором с граничной энергией тормозного спектра в интервале от 1.4 до 3.1 МэВ. Определен выход изомерной активности и вклад в него промежуточных состояний с энергией 1228, 1770, 1920 и 2656 kэВ. Полученные экспериментальные данные и табличные данные о резонансной флюоресценции были проанализированы и определены интегральные сечения фотоактивационных промежуточных состояний. Они оказались равными 0.090, 0.009, 0.070 и (1.7 ± 0.5) эВ, соответственно.

ФОТОЗБУДЖЕННЯ ^{87m}Sr В (γ,γ')- РЕАКЦІЇ

О.С. Шевченко, Ю.М. Ранюк, А.М. Довбня, Е.Л. Купленніков, А.А. Немашкало, І.Г. Гончаров, В.Н. Борисенко, В.І. Нога

Досліджено фотозбудження ^{87m}Sr в (γ,γ')- реакції з використанням гама-променів, генерованих електронним пучком електростатичного генератора з граничною енергією гальмового спектра в інтервалі 1.4 - 3.1 МеВ. Визначено вихід ізомерної активності і внесок в нього проміжних станів з енергією 1228, 1770, 1920 і 2656 keВ. Отримані експериментальні дані та табличні дані з резонансної флюоресценції були проаналізовані і визначені інтегральні перерізи фото активаційних проміжних станів. Вони виявилися такими, що дорівнюють: 0.090, 0.009, 0.070 та (1.7 ± 0.5) еВ, відповідно.