INVESTIGATION OF γ-RAY EMISSION IN HEAVY ION INDUCED FISSION DURING THE CYCLOTRON BEAM-ON PERIODS*

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The delayed coincidence method with special reference to the in-beam experiments is considered as a means of identification and the lifetime measurements of isomeric states, as well as, the method of the investigation of radiations populating isomeric states. Isomers are detected and correlated with prompt events if they occur within a certain time of the prompt event. The $^{16}O + ^{208}Pb$ reaction was investigated using the OSIRIS-II and the EAGLE arrays at HIL-UW. About eighty nuclei were identified as fission fragments among the reaction products. Several known isomeric transitions associated with reaction products in neutron-rich nuclei region were detected, as well as some new candidates were observed.

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1. Introduction

The fusion-fission reaction ^{16}O + ^{208}Pb was used to produce excited fission fragments from the region of neutron-rich nuclei at the beam energies of 85 and 90 MeV. The 12–16 HPGe detectors in the OSIRIS-II and later in the EAGLE arrays, located at HIL-UW were employed. One of the ways to carry out spectroscopic studies of the neutron-rich systems is to analyze the prompt gamma rays from nascent fission fragments produced either in spontaneous fission or in heavy-ion-induced fission. After neutron emission, when the excitation energy is lower then their binding energy, the γ-ray cascade starts taking away remaining excitation energy. A prompt γ-ray emission competes with [1] or follows the last stages of prompt neutron emission. Typical γ-ray multiplicities of 7–10 photons/fission were observed. Because of the significant angular momentum of the fission fragments (7–12$\hbar$), photon emission can compete with neutron emission. The dependence of the number of emitted gamma rays from the fission fragments *versus* time has a complex character. One can distinguish a few time intervals, namely: (a) 10^{-12}–10^{-10} s, when appears the essential part of γ rays (more than 70% [2]) with energies of few MeV and low multipolarity *i.e.* E1, M1, E2 emitted from the fission fragments levels. Next time intervals are: (b) 10^{-10}–10^{-9} s, (c) 10^{-9}–10^{-7} s, during which about 20% of γ rays from the fission fragments is emitted. This radiation emerges due to the de-excitation of low energy states and/or isomeric states, and is characterized by high multipolarities, *i.e.* M2, E3, or even higher. Production of fragments with high spins after the neutron emission results in population of such states. Therefore, because of large spin differences the isomeric states may appear in fission fragments already during the cyclotron beam-on periods.

2. Experimental results

2.1. Observation of isomers during the cyclotron beam-on periods

Analyzing the in-beam γ–γ coincidences (during the cyclotron macro-pulse), one can often observe the appearance of various isomeric transitions over the course of the in-beam pulse. Setting gates at different positions within the in-beam macro-pulse the γ rays from a time region of several nanoseconds and/or few microseconds were detected in the obtained coincident spectra. This fact is illustrated (Fig. 1) with two formerly known isomers from the region of $80 < A < 130$, observed in the experiments performed at the HIL. A few other examples of γ-ray coincidences from fission fragments observed during the in-beam periods of the HIL cyclotron using ^{16}O + ^{208}Pb reaction are given in Table I. At the beam-off periods, these lines were not observed which means, that they are not originating from the β-decays. Among the γ rays listed in this table, there are also possible candidates (identified due to γ–γ coincidences based on known γ-ray transitions) in $^{95}_{40}Zr_{55}$ [3] and $^{108}_{45}Rh_{63}$ [4] nuclei which might be associated with the decay of unknown isomeric states. The further experiments verify these observation.

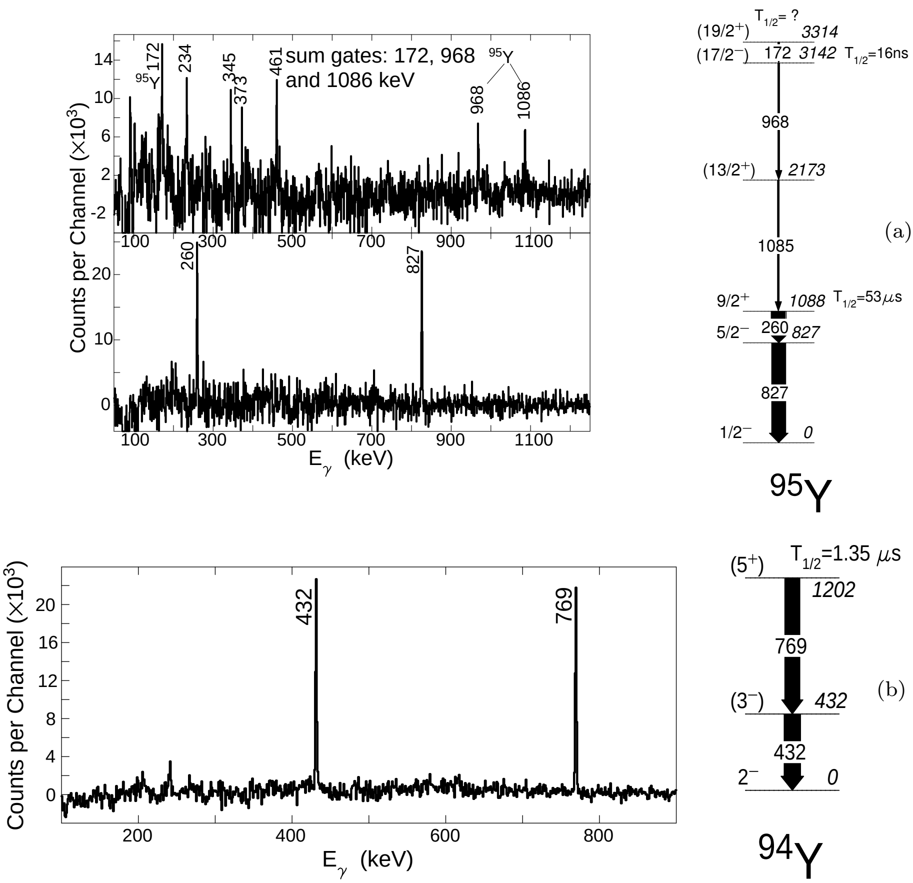

Fig. 1. The $\gamma\gamma$-ray coincidence spectra in ^{95}Y and ^{94}Y nuclei as observed during the cyclotron beam-on periods. In both cases, the respective transitions are related to known (Refs. [5] and [6]) isomers. (a) Upper part: Sum of the gates set on 172, 968 and 1086 keV γ lines. The lines 345 and 461 keV are feeding 2173 and 3314 keV levels, respectively. The 234 and 373 keV lines are due to random coincidences from other nuclei. (b) Sum of the gates set on 260 and 827 keV in^{95}Y nucleus. Lower part: Sum of the gates set on 769 and 432 keV lines in ^{94}Y nucleus.

TABLE I

The γ rays from fission fragments de-exciting the isomeric states in the nsec and few μsec regions, as observed in the in-beam mode using the ^{16}O + ^{208}Pb reaction.

Nucleus	Gate E_γ [keV]	γ rays in coincidence [keV]	$T_{1/2}$	Refs.
$^{94}_{39}Y_{55}$	769 (5^+)	432 (3^-)	1.35 μs	[6]
$^{95}_{39}Y_{56}$	261 ($9/2^+$)	827 ($5/2^-$)	53 μs	[5]
$^{95}_{40}Zr_{55}$	229 ($11/2^-$)	115 ($9/2^+$)	?	[3]
$^{99}_{42}Mo_{57}$	448 ($11/2^-$)	138 ($7/2^-$)	0.76 μs	[7]
$^{108}_{45}Rh_{63}$	142 (6^-)	102 (7^-)	?	[4]
$^{119}_{49}In_{70}$	152 ($25/2^+$)	218 ($21/2^+$)	240 ns	[9]
$^{123}_{51}Sb_{72}$	127 ($23/2^+$)	441 ($19/2^+$)	65 μs	[8]

2.2. Investigation of radiation populating isomeric states

As previously indicated, the prompt–delayed and/or delayed–prompt coincidence technique can be used to identify γ rays feeding the isomers in the heavy ion reactions in the in-beam mode. As an example, the 1.3 μs isomer in ^{94}Y is considered. A few of the prompt γ rays observed in the studied reactions were assigned to ^{94}Y as feeding the 5^+ isomer, *i.e.* the 188, 237, 742, 755, 891, 936 and 1171 keV lines, *cf.* Fig. 2 and Fig. 3. However, if 1171 keV transition is going from 2373 keV level to 1202 keV level, then spin of 2373 level must be higher than given in Ref. [6]. This information comes from the spectra measured taking advantage of natural high frequency beam bunching of the HIL cyclotron. It is based on coincidences between γ rays emitted in the prompt time range, *i.e.* during the beam micro-pulses with those emitted between them (the separation of two beam micro-pulses is given by the period $T = 1/f_{\rm RF}$. For ^{16}O^{+4}, the frequency is $f = 15.33$ MHz and $T = 65.3$ ns). Delayed–prompt coincident spectra which were created in this way include prompt γ-lines preceding (feeding) the isomers. In the off-line analysis, the sorting procedures were based on Kowalczyk multipurpose program [10], while multi-gated γ–γ-coincidence spectra were analyzed with Radware package [11].

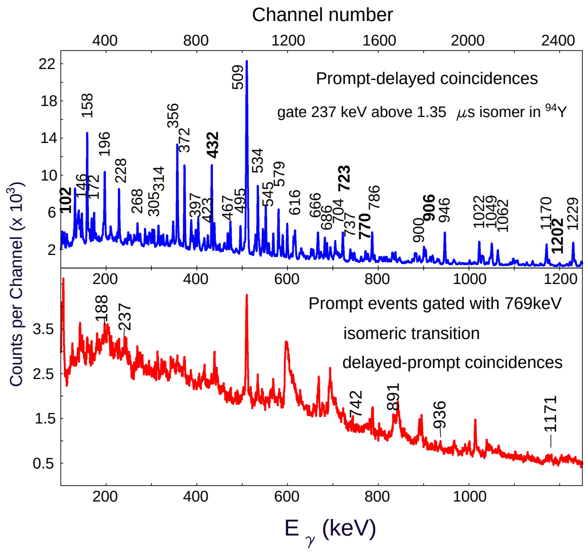

Fig. 2. The prompt–delayed and delayed–prompt coincidences in ^{94}Y during the cyclotron beam-on periods. In the upper spectrum, the numbers in bold are indicating transitions placed below 1202 keV isomer level as observed from prompt–delayed coincidences. The lower spectrum is obtained in the delayed–prompt coincidences, and numbers are indicating possible transitions feeding the (5^+) isomer, *i.e.* 188, 237, 742, 891, 936 and 1171 keV transitions (marked with dashed lines in Fig. 3).

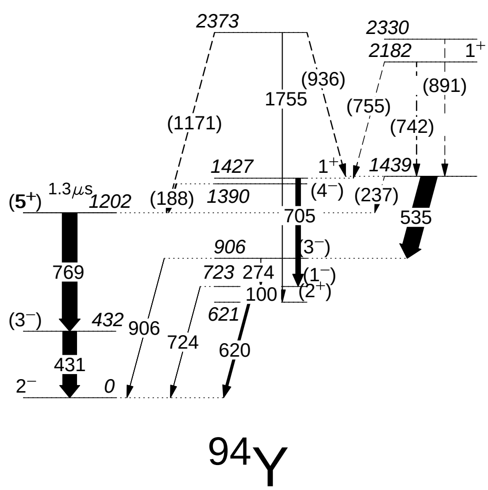

Fig. 3. The level scheme of ^{94}Y constructed based on Ref. [6] and tentatively placed lines as proposed in present work (marked with dashed lines).

3. Conclusion

The investigation of in-beam γ-ray emission can be useful in finding isomers in neutron-rich nuclei obtained in the heavy ion induced fission. Moreover, the prompt–delayed (and delayed–prompt) correlations can be studied, as well as the number of emitted γ rays *versus* time with respect to beam macro-pulses can be estimated from growing γ rays activities of activities before reaching the secular equilibrium. A rough $T_{1/2}$ estimation from the growing production rate of 1030 and 840 keV lines in ^{121}Sn was obtained. The $27/2^-$, 0.17 μs and $19/2^+$, 5 μs isomers in ^{121}Sn were reported formerly by Daly [12]. Our results were 0.16 μs and 3.2 μs, respectively. More results will be given in the forthcoming contribution.

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