

New ²⁰⁹Bi photodisintegration data and physical criteria of data reliability

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Abstract. The well-known problem of noticeable disagreements between photoneutron cross sections from various experiments was discussed in detail for ²⁰⁹Bi. Data for partial photoneutron reactions cross sections obtained at Livermore (USA) using quasimonoenergetic annihilation photons and the method of neutron multiplicity sorting were analyzed using the objective physical criteria and the experimental-theoretical method for evaluation. Because of significant systematic uncertainties involved in the method for determining the neutron multiplicity, experimental data do not satisfy the criteria of reliability and differ noticeably from the evaluated data. The new experimental data for ²⁰⁹Bi (γ, in) reactions with $i = 1-4$ were obtained using quasi-monochromatic laser Compton-scattering (LCS) γ -ray beams at the NewSUBARU synchrotron radiation facility and the novel technique of direct neutron-multiplicity sorting with a flat-efficiency detector. It was found that new $\sigma(\gamma, 1n)$, $\sigma(\gamma, 2n)$, and $\sigma(\gamma, 3n)$ contradict noticeably to the Livermore data. It was shown that at the same time the new ²⁰⁹Bi photoneutron cross-sections are in good agreement with data evaluated using experimental-theoretical method and assuring the reliability of those.

1 Introduction

The major part of experimental data for the total and partial photoneutron reaction cross sections consists of those from Livermore (USA) and Saclay (France), which were obtained by the quasimonoenergetic annihilation photons and the photoneutron multiplicity sorting technique [1]. For 19 nuclei from ⁵¹V to ²³⁸U investigated at both laboratories significant disagreements were found [2, 3]. Those are definitely systematic: as a rule $\sigma(\gamma, 1n)$ have larger values at Saclay but $\sigma(\gamma, 2n)$ vice versa at Livermore. Over the 19 nuclei mentioned above the ratio $\sigma_S^{int}/\sigma_L^{int}$ of integrated cross sections fluctuates between 0.76 and 1.34 for the ($\gamma, 1n$) cross-section and between 0.71 and 1.22 for the ($\gamma, 2n$) cross-section and reaches the averaged values $\langle \sigma_S^{int}/\sigma_L^{int} \rangle = 1.07$ and 0.84, correspondingly. It is obvious that the discrepancy between the Livermore and Saclay data could not be removed by applying a constant normalization factor. It was shown [4–14] that the reasons are the definite shortcomings of neutron multiplicity-sorting method based on the idea that energies of neutrons from the partial reactions are noticeably different and neutron multiplicities could be deduced from its measured kinetic energies.

The experimental-theoretical method for evaluation the partial reaction cross sections was developed [4] in order to resolve these problems. The experimental neutron yield

cross-section,

$$\sigma^{exp}(\gamma, Sn) = \sigma^{exp}(\gamma, 1n) + 2\sigma^{exp}(\gamma, 2n) + 3\sigma^{exp}(\gamma, 3n) + \dots \quad (1)$$

not dependent on the experimental neutron multiplicity sorting because includes all outgoing neutrons was decomposed into the partial reaction cross sections,

$$\sigma^{eval}(\gamma, in) = F_i^{theor} \times \sigma^{exp}(\gamma, Sn) \quad (2)$$

using the transitional neutron multiplicity functions,

$$F_i(\gamma, in) = \sigma(\gamma, in) / \sigma(\gamma, Sn) \quad (3)$$

calculated within the framework of the Combined photonucleon reaction model (CPNRM) [15] for the partial reactions (γ, in) with definite neutron multiplicity factors $i = 1, 2, 3, \dots$. The ratios $F_i^{exp}(\gamma, in)$ (3) were proposed as the objective physical criteria of experimental partial photoneutron reaction cross-section data reliability. Follow definitions (3) positive F_i^{exp} could not have values higher than 1.00, 0.50, 0.33, 0.25, ... correspondingly for $i = 1, 2, 3, 4, \dots$. The larger F_i^{exp} values mean that experimental cross sections are not reliable because contain significant systematic uncertainties.

Using the experimental-theoretical method for evaluation of partial photoneutron reaction cross sections for many nuclei (^{63,65}Cu, ⁸⁰Se, ^{91,94}Zr, ¹¹⁵In, ¹¹²⁻¹²⁴Sn, ¹³³Cs, ¹³⁸Ba, ¹⁵⁹Tb, ¹⁸¹Ta, ¹⁸⁶⁻¹⁹²Os, ¹⁹⁷Au, ²⁰⁸Pb, ²⁰⁹Bi and some others) it was found [4–14] that in many cases the experimen-

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tal cross sections do not satisfy the proposed data reliability criteria and are noticeably different from the evaluated cross sections. The main reason of disagreements between the data obtained at Livermore and Saclay is the difference of procedures used to separate counts into 1n and 2n events leading to unreliable transmission of neutrons from one partial reaction to another.

The systematic uncertainties could be connected with noticeable difference in efficiency of detection one, two or three neutrons dependent on neutron energy. Therefore the new measurements of partial photoneutron reaction cross sections for ^{209}Bi were carried out using the novel technique of direct neutron-multiplicity sorting with a flat-efficiency detector. It was found that newly partial $\sigma(\gamma, 1n)$ and $\sigma(\gamma, 2n)$ experimental cross sections for ^{209}Bi are significantly different from Livermore cross sections but at the same time agree with data evaluated using experimental-theoretical method, described above.

2 Experimental partial photoneutron reaction cross sections reliability

Data for partial photoneutron reactions ($\gamma, 1n$) and ($\gamma, 2n$) for ^{209}Bi were obtained at Livermore [16]. Both F_1^{exp} and F_2^{exp} obtained in [12] are presented in figures 1a and 1b, correspondingly. It was shown [12] that $\sigma(\gamma, 1n)$, $\sigma(\gamma, 2n)$ [16] are not reliable: one can see many negative F_1^{exp} values, corresponding to negative ($\gamma, 1n$) reaction cross-section values in Fig 1a and many unreliable values of F_2^{exp} larger than physically possible top limit 0.50 in Fig. 1b.

Both F_1^{exp} and F_2^{exp} [16] are compared with the ratios $F_{1,2}^{exp}$ for new data [17] obtained using quasi-monochromatic laser Compton-scattering (LCS) γ -ray beam and the novel technique of direct neutron-multiplicity sorting with a flat-efficiency detector (look further) for four particle reactions. $F_{3,4}^{exp}$ [17] are also presented. One can see that ratios $F_i^{exp}(\gamma, in)$ obtained using new novel technique for all partial reactions satisfy the data reliability criteria: all of those are positive, all $F_i^{exp}(\gamma, in)$ values are smaller than 1.00, 0.50, 0.33, 0.25, correspondingly for $i = 1, 2, 3, 4$.

3 Partial photoneutron reaction cross sections for ^{209}Bi evaluated using the experimental-theoretical method

Using the experimental-theoretical method for evaluation of partial photoneutron reaction cross sections described above, the ($\gamma, 1n$) and ($\gamma, 2n$) reaction cross sections were obtained in accordance with data reliability criteria using data for neutron yield cross-section (I) obtained at Livermore [16] and F_i^{theor} calculated in the CPNRM [15]. The evaluated $\sigma^{eval}(\gamma, 1n)$ and $\sigma^{eval}(\gamma, 2n)$ together with for total photoneutron reaction (γ, tot) cross-section,

$$\sigma^{eval}(\gamma, tot) = \sigma^{eval}(\gamma, 1n) + \sigma(\gamma, 2n) + \sigma(\gamma, 3n) + \dots \quad (4)$$

are presented in figure 2 in comparison with data from the experiment [17] (look further). The evaluated $\sigma(\gamma, 1n)$

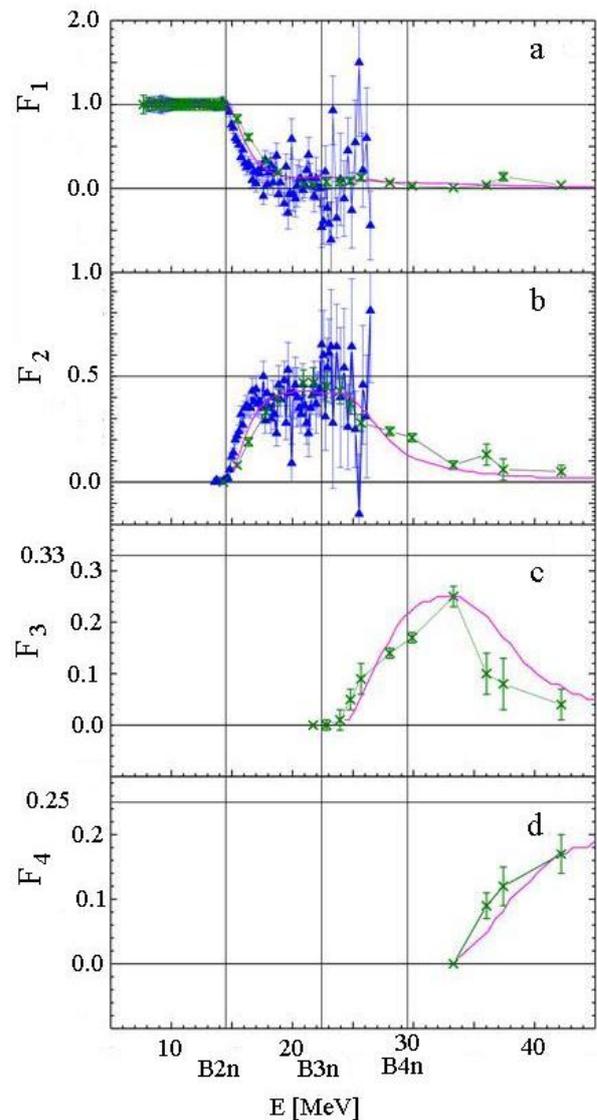


Figure 1. F_i^{exp} data for ^{209}Bi using the data obtained at Livermore ([16] - triangles) in comparison with calculated F_i^{theor} ([15], lines). Crosses present data obtained using the novel technique of flat-efficiency detector (look further) [17]. Data are presented for reactions ($\gamma, 1n$) - a, ($\gamma, 2n$) - b, ($\gamma, 3n$) - c, and ($\gamma, 4n$) - d.

proves to be substantially larger than the respective experimental Livermore cross-section, while the evaluated $\sigma(\gamma, 2n)$ is substantially smaller than its experimental counterpart.

It is noteworthy that the cross sections evaluated for the ($\gamma, 1n$) and ($\gamma, 2n$) reactions agree well with yields measured for the respective reactions in the activation experiment [18]. Reactions were identified by the final-states ^{208}Bi and ^{207}Bi nuclei produced in, respectively, the ($\gamma, 1n$) and ($\gamma, 2n$) reactions. Therefore this method give to one opportunity for reliable separation of reactions with different numbers of outgoing neutrons measured independently. Absolute yields and integrated cross sections of multiparticle reactions ($\gamma, 2n - 6n$), ($\gamma, 4n1p$), and ($\gamma, 5n1p$) were obtained using the spectra of induced gamma-ray activity of the irradiated bismuth tar-

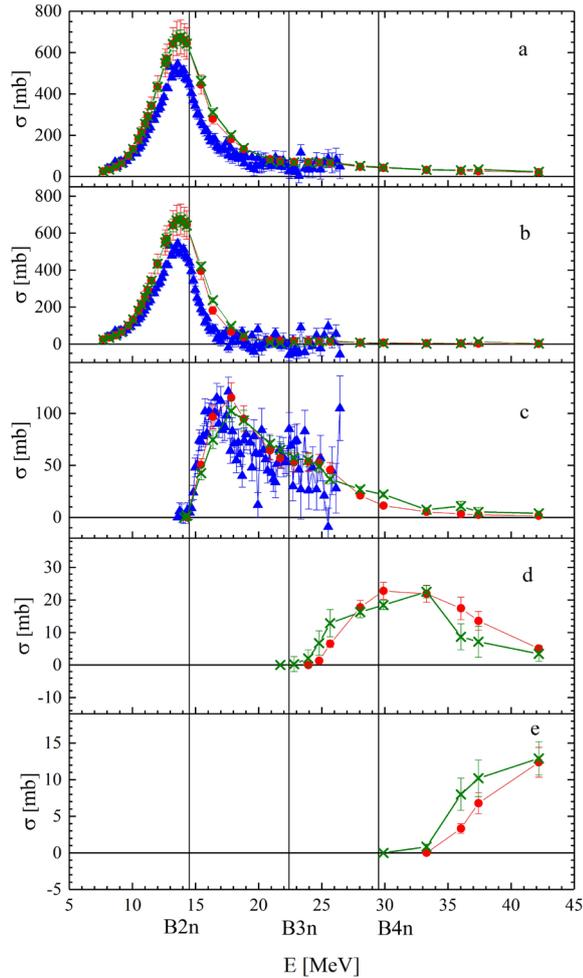


Figure 2. ^{209}Bi experimental cross sections obtained at Livermore ([16] - triangles) in comparison with the evaluated one ([12], circles). Crosses present data obtained by the novel technique of flat-efficiency detector (look further) [17]: (a) $\sigma(\gamma, \text{tot})$, (b) $\sigma(\gamma, 1n)$, (c) $\sigma(\gamma, 2n)$, (d) $\sigma(\gamma, 3n)$, (e) $\sigma(\gamma, 4n)$.

get [18]. The main conclusion [18] was that evaluated cross sections are in agreement with the results of a photon activation experiment, while the experimental cross-section of the $(\gamma, 2n)$ [16] is apparently overestimated. This conclusion was supported by the results of comparison of evaluated data with experimental once obtained using bremsstrahlung beams and activation method for ^{181}Ta [19] and ^{197}Au [20].

4 Partial photoneutron reaction cross sections for ^{209}Bi measured using the technique of direct neutron multiplicity sorting with a flat efficiency detector.

As it was mentioned above the experimental partial photoneutron reaction cross sections were found to be noticeably different from evaluated cross sections for many nuclei because the shortcomings of procedures used to separate counts into 1n and 2n events. Data presented in figures 1 and 2, show that procedures to separate counts into

1n and 2n events used at Livermore for ^{209}Bi are not reliable because of large systematic uncertainties depending noticeably of difference in efficiency of one, two, three or four neutrons detection.

The new measurements of partial photoneutron reaction cross sections for ^{209}Bi performed at the NewSUBARU synchrotron radiation facility were carried out using the quasi-monochromatic laser Compton-scattering (LCS) γ -ray beams [21, 22] and the novel technique of direct neutron-multiplicity sorting with a flat-efficiency detector [17, 23].

Partial $\sigma(\gamma, in)$ with the neutron-multiplicity i ($i = 1, 2, 3, 4, \dots$) can be determined from the number N_i of (γ, in) reactions as,

$$N_i = N_\gamma N_T \sigma(\gamma, in), \quad (5)$$

where N_γ is the number of γ -rays incident on a target with number N_T nuclei per unit area. In fact N_i is not a direct experimental observable. Because the neutron detection efficiency of neutron detector depends on the neutron kinetic energy, the ring ratio (RR) technique was developed at Livermore [24] to determine the average neutron energy. However, the RR technique can be applied not to N_i but only to experimental observable, multi-neutron coincidence events. This may be a source of uncertainties involved in experimental Livermore cross sections and investigated for many nuclei [4–14].

A novel technique was developed [23] to overcome shortcomings of the RR method, in which for neutron detection at the photon energies E between $(\gamma, 3n)$ and $(\gamma, 4n)$ thresholds, the number N_s of single neutron event corresponds to observing only one neutron during an interval of two successive γ -ray pulses there contains three contributions from $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ reactions,

$$N_s = N_1 \varepsilon(E_1) + N_{22} C_1 \varepsilon(E_2) (1 - \varepsilon(E_2)) + N_{33} C_1 \varepsilon(E_3) (1 - \varepsilon(E_3)). \quad (6)$$

The first term means that one neutron emitted in the $(\gamma, 1n)$ reaction with detection efficiency $\varepsilon(E_1)$ for neutron kinetic energy E_1 is observed, the second term means that one of two neutrons emitted in the $(\gamma, 2n)$ reaction with detection efficiency E_1 for neutron kinetic energy E_2 is observed and the other neutron with unobserved efficiency $(1 - \varepsilon(E_3))$ is unobserved.

As was mentioned above, there is no way to know E_1 , E_2 , and E_3 because the RR technique is applied not to individual N_1 , N_2 , and N_3 but to the experimental observable N_s . Furthermore, the neutron kinetic energy depends on the order of neutron emission from an excited nucleus. Therefore, the second term of Eq. (6) should be re-written as $N_2 \varepsilon(E_{21})(1 - \varepsilon(E_{22})) + N_2 \varepsilon(E_{22})(1 - \varepsilon(E_{21}))$, using kinetic energies E_{21} and E_{22} of the first and the second neutron emitted, respectively. The concept of the novel technique is to make the detection efficiency independent of neutron kinetic energy. Thus, using a constant efficiency ε , the single neutron event N_s , the double N_d and triple N_t neutron coincident events are,

$$N_s = N_1 \varepsilon + N_{22} C_1 \varepsilon (1 - \varepsilon) + N_{33} C_1 \varepsilon (1 - \varepsilon), \quad (7)$$

$$N_d = N_2 \varepsilon_2 + N_{22} C_2 \varepsilon_2 (1 - \varepsilon), \quad (8)$$

$$N_i = N_3 \varepsilon^3. \quad (9)$$

So the partial $\sigma(\gamma, 1n)$, $\sigma(\gamma, 2n)$, and $\sigma(\gamma, 3n)$ can be obtained from the events N_1 , N_2 , and N_3 which are the solutions of a set of equations (7-9) with known ε .

The newly experimental cross sections for (γ, tot) , $(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, and $(\gamma, 4n)$ reactions are presented in figure 2. Those are noticeably different from the Livermore data but agree with data evaluated using experimental-theoretical method in accordance with physical criteria of data reliability. It means that using the new experimental method based on the technique of flat-efficiency neutron detector the reliable partial reaction cross-section data could be obtained. This conclusion is supported by the data for $F_i^{exp}(\gamma, in)$ presented in figure 1.

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