ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА 2010, т. 11, № 3, с. 246 - 250

УДК 539.172.4

SPECTRA OF GAMMA-RAYS IN (n, xγ) REACTIONS ON FERRUM AND BISMUTH NUCLEI

© 2010 V. M. Bondar, O. M. Gorbachenko, I. M. Kadenko, B. Yu. Leshchenko, Yu. M. Onishchuk, V. A. Plujko

Nuclear Physics Department, Taras Shevchenko National University, Kyiv

The results of the gamma-ray spectra measurements for (n, xγ) reactions induced by 14.1 MeV neutrons on iron and bismuth are presented. Time-of-flight method based on pulse neutron generator was applied. Measurement results are compared with theoretical calculations performed assuming gamma-emission from compound nucleus as well as preequilibrium emission. Calculations were performed by the use of EMPIRE and TALYS codes. Sensitivity of the calculations to characteristics of excited nuclei was analyzed.

Keywords: neutron induced reactions, time-of-flight method, gamma-spectra, Hauser - Feshbach statistical model, radiative strength function, nuclear level densities.

Introduction

Precise experimental cross section data for (n, xγ) reactions induced by fast neutrons are of considerable interest for the development of the advanced reactor technologies as well as for investigations of the different nuclear reaction mechanisms in the neutron induced reactions, characteristics of excited nuclear states and its decay. The experimental measurements are usually performed with 14.1 MeV neutrons due to the possibility of using neutron generators based on DT-reaction, but the experiments in which γ-spectra was obtained in full energy range (from extremely low to the highest possible excitation energy) are practically absent. In this contribution we present results of the investigation of the γ-spectra within the energy interval from 2 to 18 MeV. Differential cross sections of the (n, xγ) reactions for iron and bismuth were unfolded from amplitude instrumental spectra and cross sections uncertainties are estimated. The experimental cross sections are compared with theoretical calculations.

Method of experimental measurements

The measurements of γ-spectra are performed using scintillation γ-spectrometer based on 15 × × 10 cm NaI(Tl) detector. Time-of-flight method based on pulse neutron generator was applied for separation of prompt γ-rays from source neutrons, background and rescattered γ-rays. Reaction $T(d, n)^4He$ in Ti-T target was used as neutron source. Deuterons were accelerated by low-voltage accelerator with klystron bunching of deuteron beam and finally deuteron energy was 130 KeV. Pulse generation frequency was equal to 7.25 MHz, average neutron intensity ~ 10^7 s^{-1}. The geometry of the experiment is presented on Fig. 1.

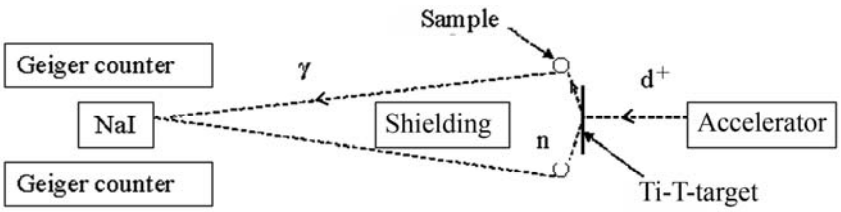


Fig. 1. Geometry of the experiment.

Measurements have been performed in circular geometry. Ring samples of iron and bismuth with mean radius 16 cm were placed on minimal distance from the neutron target. It provides optimal sample irradiation by 14.1 MeV neutrons. Geiger counters applied in anti-coincidence ($\tau \approx 10^{-6}$ s) with spectrometer signals were used in order to reduce the influence of cosmic rays.

Flight path between the neutron source and 15×10 cm NaI(Tl) detector was equal to 172 cm which provides reliable separation of prompt γ-rays from neutron and γ-ray background. Prompt γ-rays selection was performed by differential discriminator.

Relation between amplitude spectra $U(V, \Delta V, \theta_\gamma)$ and differential cross section $\sigma_\gamma(E_\gamma, \theta) = d^2\sigma_\gamma(\theta_\gamma) / dE_\gamma d\Omega$ is given by the expression

$$U(V,\Delta V,\theta_\gamma)=\int_0^{E_{max}} dE_\gamma\cdot\sigma_\gamma(E_\gamma,\theta_\gamma)\int_{V-\Delta V/2}^{V+\Delta V/2} dV\cdot G\alpha(E_\gamma)\,\varepsilon(V,E_\gamma)=\int_0^{E_{max}} A(V,E_\gamma)\sigma_\gamma(E_\gamma,\theta_\gamma)\cdot dE_\gamma. \quad (1)$$

where V is signal amplitude; ΔV - signal amplitude width; θ_γ - scattering angle; E_γ - γ-ray energy; G - geometry factor; $\alpha(E_\gamma)$ - energy-depended coefficient of the γ-ray self-absorption by sample detector; $\varepsilon(V, E_\gamma)$ - detector response function and $A(V, E_\gamma)$ is total response function. Double differential cross section $\sigma_\gamma(E_\gamma, \theta_\gamma)$ have been measured at θ_γ = 90°. Weak angle dependence of the cross section allows estimating energy spectra $\sigma(E_\gamma)$ in the following way

$$\sigma(E_\gamma)\equiv\frac{d\sigma(E_\gamma)}{dE_\gamma}=4\pi\cdot\sigma_\gamma(E_\gamma,\theta_\gamma). \quad (2)$$

The expression for the detector response function $A(V, E_\gamma)$ was taken from Ref. [1]. It is based on analytical approximation of the bremsstrahlung experiment with correction on Monte Carlo simulations as well as on detection of 4.43 MeV γ-rays from neutron inelastic scattering on carbon. More details concerning experiment can be found in Refs. [2, 3].

Data analysis

According to the Eqs. (1) and (2), the following Fredholm integral equation of the first kind should be solved to unfold cross section $\sigma(E_\gamma)$ from amplitude spectrum *U (V)*

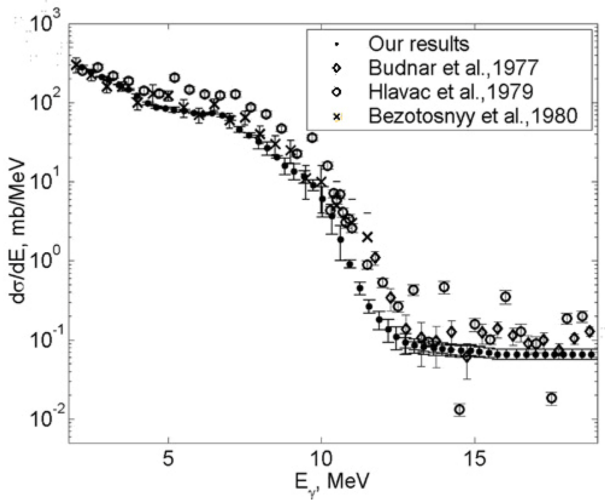
$$\int_0^{E_{max}} A(V,E_\gamma)\sigma(E_\gamma)dE_\gamma=U(V)\,. \quad (3)$$

There are problems in solving Eq. (3) due to instability of unfolded spectra to the experimental data uncertainties (so called ill-posed [4]). To find cross section $\sigma(E_\gamma)$ from inverse solving Eq. (3), an algorithm on the compact set of limited variations [4] was used. Uncertainties of the cross sections were estimated in assumption that the amplitude spectrum is distributed with Gauss distributions due to the large number of external factors. The uncertainties of the amplitude spectra were estimated as

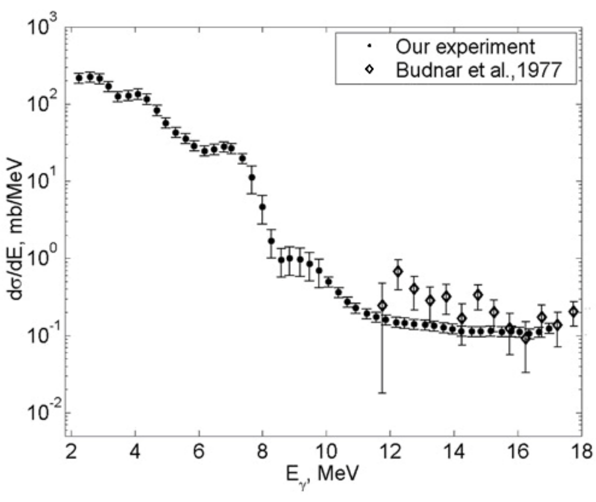
$$\sigma_i=\sqrt{D_i+D_i^b}\ , \quad (4)$$

where σ_i – standart deviation of the number of counts N_i; i – number of channel; D_i – variance of the number of counts N_i; D_i^b – variance of the number of counts N_i^b corresponding to background measurements (without sample). The following values were used: $D_i = N_i, D_i^b = N_i^b$.

Experimental values of the unfolded differential cross sections and their uncertainties are shown in Fig. 2. As one can see, stable solution is obtained for the cross sections of the ^{nat}Fe(n, xγ) and ^{nat}Bi(n, xγ) reactions. Set of monotonically decreasing functions were used. Rather good agreement of obtained cross sections with experimental results of other authors is obtained.



a



b

Fig. 2. Differential cross sections of the reactions ^{nat}Fe(n, xγ) (*a*) and ^{nat}Bi(n, xγ) (*b*) obtained using regularization algorithm on the compact set of limited variations: points – results of our experiment, diamonds – experimental data from [5], circles – [6], crosses – [7].

Calculations and discussions

Experimental results were compared with theoretical calculations performed considering gamma-emission from compound nucleus (CN) as well as preequilibrium emission. Calculations assuming CN emission were performed using the Hauser - Feshbach statistical model. Within the framework of this model cross section of the reaction in the channel b is given by

$$\sigma_b(E,J,\pi)=\sigma_a(E,J,\pi)\frac{\Gamma_b(E,J,\pi)}{\Sigma_e\Gamma_e(E,J,\pi)}, \qquad (5)$$

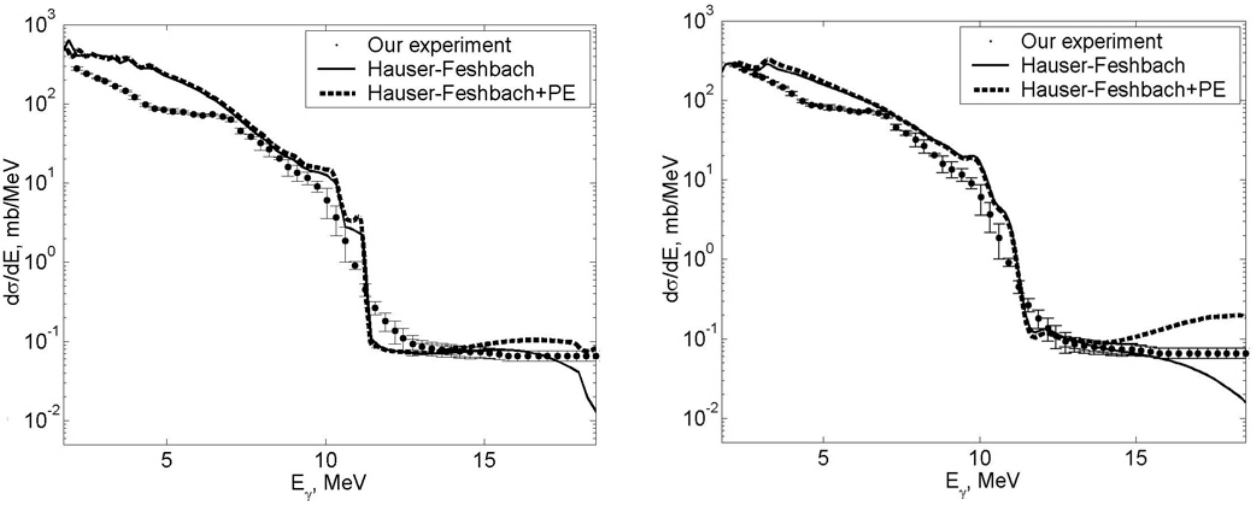
where σ_a – cross section of the compound nucleus production; E – excitation energy; J – spin; π – parity; Γ_b – width in the channel b; $\Sigma_e\Gamma_e$ – total width

$$\Gamma_e(E,J,\pi)=\frac{1}{2\pi\rho_{CN}(E,J,\pi)}\times$$

$$\times\sum_{J=0}^{\infty}\sum_{\pi}\sum_{j=J'-J}^{J'+J}\int_0^{E-B_e}\rho_e(E',J,\pi)T_e^{l,j}(E-B_e-E')dE', \qquad (6)$$

B_e is the separation energy of the particle e in the CN, ρ is the level density and $T_e^{l,j}$ stands for the transmission coefficient for particle e with channel energy $\varepsilon = E - B_e - E'$ and defined through radiative strength function (RSF). Cross section of CN production σ_a is calculated using optical model. The calculations of differential cross sections were performed using the EMPIRE [8] and TALYS [9] codes. Calculations have been performed with and without taking into account preequiliblirum emission.

Fig. 3 shows experimental differential cross sections of the reactions $^{nat}Fe(n, x\gamma)$ in comparison with theoretical calculations performed using EMPIRE [8] and TALYS [9] codes. Default sets of input parameters were used.



a *b*

Fig. 3. Differential cross sections of the reactions $^{nat}Fe(n, x\gamma)$ performed using EMPIRE *(a)* and TALYS *(b)* codes: points – our experimental results, solid curve – calculations within Hauser - Feshbach statistical model, dashed curve – calculations within Hauser - Feshbach statistical model with taking into account preequilibrium emission (PE).

As one can see from Fig. 3, the good agreement of the theoretical calculations with experimental data is obtained for the $^{nat}Fe(n, x\gamma)$ reactions almost in all energy range accept intervals below 7 MeV and above 17 MeV. Calculations within Empire and Talys codes are in rather good agreement. It can be concluded that for such energies preequilibrium processes should be taking into account in the calculations.

As it was mentioned above (see first paragraph of this section, (5) - (7)), the optical potential, RSF and nuclear level density are required in order to calculate the cross sections. Sensitivity of the calculated cross sections to these quantities was analyzed. The result of the analysis is given below (Figs. 4 and 5). Fig. 4 demonstrates the cross sections obtained by the use of different optical potentials taken from [10 - 12]. It can be seen from Fig. 4 that results of the calculations are quite sensitive to the optical potential. The results obtained using Koning - Delaroche potential (global one) gives best agreement with the experiment.

The RSF can be calculated with using different models. To check sensitivity of the cross sections to the RSF, we performed calculations by the use the following models: Standart Loretzian (SLO), Enchanced Generalized Loretzian (EGLO), different kinds of modified Loretzian (MLO), Generalized Fermi liquid (GFL) model. For the calculations of nuclear level densities we used Enhanced Genera-

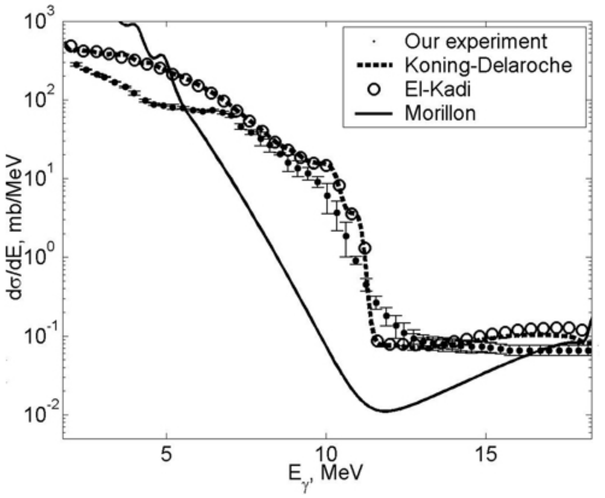
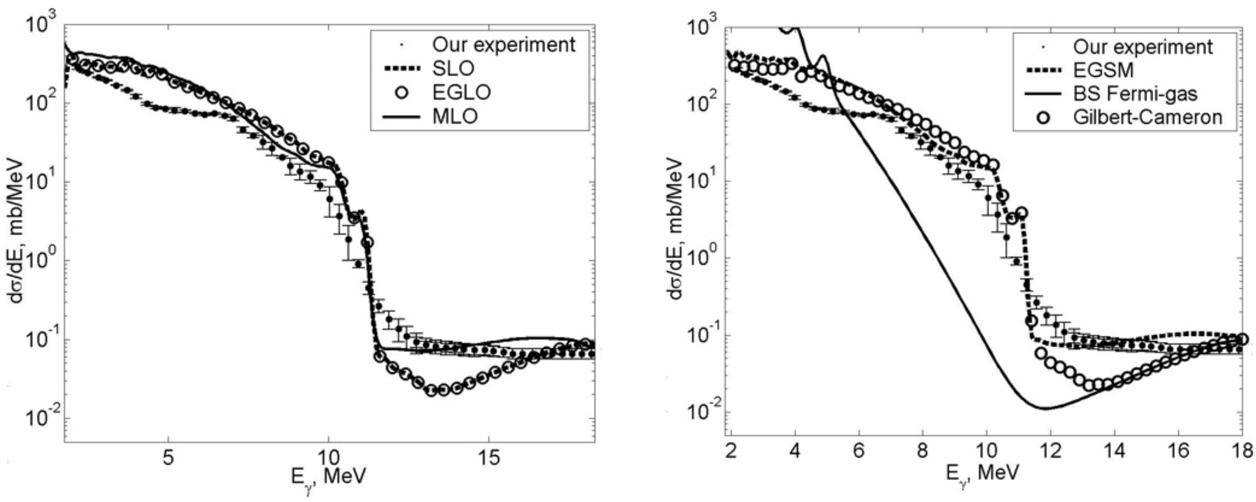


Fig. 4. Differential cross section of the reactions ^{nat}Fe(n, xγ) calculated with EMPIRE code using different optical potentials: dashed curve – Koning - Delaroche potential [10], circles – El-Kadi potential [11], solid curve – Morillon potential [12].

lized Super-Fluid Model (EGSM), Back-Shifted Fermi-gas model and Gilbert-Cameron approach. More detailed description of the models mentioned above can be found in Ref. [13].

Fig. 5, *a* demonstrates the example of the RSF dependence of ^{nat}Fe(n, xγ) reaction cross sections calculated by the use of EMPIRE code. As one can see, the best agreement with the experiment is obtained in case of using MLO model. For the nuclear level densities the best agreement can be achieved using EGSM model (Fig. 5, *b*). Similar results were obtained for ^{209}Bi(n,xγ) reactions.

From the results presented in Fig. 5, one can conclude that the best agreement of the theoretical calculations with experimental results can be obtained in the case of simultaneous changes of the models both the radiative strength function and the nuclear level density.



a *b*

Fig. 5. Differential cross sections of the ^{nat}Fe(n, xγ) reactions calculated with EMPIRE code using different models for the RSF *(a)*: dashed curve – SLO model, open circles – EGLO, solid line – MLO; and cross sections calculated by the use of different models for the nuclear level densities within MLO model for RSF *(b)*: dashed curve – EGSM model, solid line – BS Fermi-gas model, open circles – Gilbert - Cameron. Experimental results are shown by points.

It was also checked that calculated cross sections are insensitive to the high values of the γ-ray transition multipolarity that is caused by the fact that number of the nuclear levels is large and electric dipole transitions are dominated.

Conclusions

Differential cross sections of ^{nat}Fe(n, xγ) and ^{209}Bi(n, xγ) reactions were measured using time-of-flight technique. The algorithm on the compact set of limited variations was used in order to obtain the cross sections values.

Theoretical calculations of the cross sections are performed considering gamma-emission from compound nucleus as well as preequilibrium emission. Results of the calculations within EMPIRE and TALYS codes are rather in good agreement and general behaviour of the theoretical results is in agreement with experimental ones.

In order to obtain the best agreement of calculated cross sections with experimental results, the optimal set of models for RSF, nuclear level densities and optical potential should be used. According to our analysis, using of MLO RSF model with EGSM model for the nuclear level densities in the calculations of the cross sections of ^{nat}Fe(n, xγ) and ^{209}Bi(n, xγ) reactions gives the best agreement with experimental results.

REFERENCES

1. *Gurevich G.M., Mazur V.M., Solodukhov G.V.* Apparatus function of scintillation γ-spectrometer based on large NaI(Tl) detector // Instruments and Experimental Techniques. - 1975. - Vol. 2. - P. 59 - 62 (in Russian).
2. *Prokopets G.O., Leshchenko B.Yu., Onishchyk Y.M., Basenko V.K.* Differential cross sections of prompt γ-rays in reactions produced by 14 MeV neutrons // Bulletin of the Kiev University. Physical and mathematical Science. - 1997. - Vol. 3. - P. 423 - 434 (in Ukrainian).
3. *Bondar V.M., Kadenko I.M., Leshchenko B.Yu. et al.* Differential cross sections of prompt γ-rays irradiation produced by 14 MeV neutrons on iron // Nuclear Physics and Atomic Energy. - 2008. Vol. 1(23). - P. 16 - 23.
4. *Tikhonov A.N., Goncharsky A.V., Stepanov V.V., Yagola A.G.* Numerical methods for the solution of ill-posed problems. - Moscow, 1990. - 286 p. (in Russian).
5. *Budnar M., Clevbar F., Hodgson E. et al.* Prompt γ-Ray Spectra and Integrated Cross Sections for the Radiative Capture of 14 MeV Neutrons for 28 Natural Targets in the Mass Region from 12 to 208 // Nuclear Instrum. and Methods in Physics. - 1977. - Vol. 44. - P. 59 - 62.
6. *Hlavac S., Oblozinsky P.* On gamma-decay of high lying states produced in the interaction of 14.6 MeV neutrons with ^{56}Fe // 2^{d} Symp. on Neutron Induced Reactions. - Smolenice, 1979. - Vol. 6. - 395 p.
7. *Bezotosnyi V.M., Gorbachev V.M., Efimova M.A. et al.* Cross sections of γ-rays in inelastic scattering produced by 14 MeV neurtons on different nuclei // Atomic Energy. - 1980. - Vol. 4. - P. 239 - 242.
8. *Herman M., Capote R., Carlson B. V. et al.* EMPIRE: Nuclear Reaction Model Code System for Data Evaluation // Nucl. Data Sheets. - 2007. - Vol. 108. - P. 2655 - 2719.
9. *Koning A.J., Hilaire S., Duijvestijn M.C.* In TALYS-1.0 // Proc. of the Int. Conf. on Nuclear Data for Science and Technology, ND2007. (Nice, France, April 22 - 27, 2007). - Nice, 2007. - P. 211 - 214.
10. *Koning A.J., Delaroche J.P.* Local and global nucleon optical models from 1 keV to 200 MeV // Nucl. Phys. - 2003. - Vol. A713. - P. 231 - 310.
11. *El-Kadi S.M., Nelson C.E., Purser F.O. et al.* Elastic and inelastic scattering of neutrons from 54, 56Fe and 63, 65Cu. Measurements from 8 to 14 MeV and a spherical optical model analysis // Nucl. Phys. - 1982. - Vol. A390. - P. 509 - 540.
12. *Morillon B., Romain P.* Bound single-particle states for neutrons from a global spherical optical model // Phys. Rev. - 2006. - Vol. C74. - P. 014601.
13. *Parameters* for calculation of nuclear reactions of relevance for energy and non-energy nuclear applications / *R. Capote., M. Herman., P. Oblovzinsky, P.G. Young, S. Goriely, T. Belgya, A.V. Ignatyuk, A.J. Koning, S. Hilaire, V.A. Plujko, M. Avrigeanu, O. Bersillon, M.B. Chadwick, T. Fukahori, Ge Zhigang, Han Yinlu, S. Kailas, J. Kopecky, V.M. Maslov, G. Reffo, M. Sin., E. Sh. Soukhovitskii, P. Talou* // Nucl. Data Sheets. - 2009. - Vol. 110. - P. 3107 - 3214; http://www-nds.iaea.org/RIPL-3/.

СПЕКТРИ ГАММА-КВАНТІВ У (n, xγ) РЕАКЦІЯХ НА ЯДРАХ ЗАЛІЗА ТА ВІСМУТУ

В. М. Бондар, О. М. Горбаченко, І. М. Каденко, Б. Ю. Лещенко, Ю. М. Оніщук, В. А. Плюйко

Представлено результати вимірювань гамма-спектрів (n, xγ) реакцій при взаємодії нейтронів енергії 14,1 МеВ з ядрами заліза та вісмуту. Було використано метод часу прольоту на основі імпульсного нейтронного генератора. Результати вимірювань порівнюються з теоретичними розрахунками, виконаними в припущенні перебігу реакції через складене (компаунд) ядро, а також із врахуванням вильоту частинок на передрівноважних стадіях. Розрахунки було виконано з використанням кодів EMPIRE та TALYS. Проаналізовано чутливість теоретично розрахованих результатів до зміни характеристик збуджених станів ядер.

Ключові слова: реакції з нейтронами, метод часу прольоту, гамма-спектри, статистична теорія Хаузера - Фешбаха, радіаційна силова функція, густини ядерних рівнів.

СПЕКТРЫ ГАММА-КВАНТОВ В (n, xγ) РЕАКЦИЯХ НА ЯДРАХ ЖЕЛЕЗА И ВИСМУТА

В. М. Бондар, О. Н. Горбаченко, И. Н. Каденко, Б. Е. Лещенко, Ю. Н. Онищук, В. А. Плюйко

Представлены результаты измерений гамма-спектров (n, xγ) реакций при взаимодействии нейтронов энергии 14,1 МэВ с ядрами железа и висмута. Был использован метод времени пролета на основе импульсного нейтронного генератора. Результаты измерений сравниваются с теоретическими расчетами, выполненными в предположении протекания реакции через составное (компаунд) ядро, а также с учетом предравновесных процессов. Расчеты выполнены с использованием кодов EMPIRE и TALYS. Проанализирована чувствительность теоретически полученных результатов к изменению характеристик возбужденных состояний ядер.

Ключевые слова: реакции с нейтронами, метод времени пролета, гамма-спектры, статистическая теория Хаузера - Фешбаха, радиационная силовая функция, плотность ядерных уровней.

Received 07.06.10,
revised - 03.11.10.