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IMPACT OF GAMMA-DECAY DESCRIPTION ON NUCLEAR REACTION CHARACTERISTICS

The results of the study of gamma-transition description in fast neutron capture and photofission are presented. Recent experimental data were used, namely, the spectrum of prompt gamma-rays in the energy range 2÷18 MeV from 14-MeV neutron capture in natural Ni and isomeric ratios in primary fragments of photofission of the isotopes of U, Np and Pu by bremsstrahlung with end-point energies E_e =10.5, 12 and 18 MeV. The data are compared with the theoretical calculations performed within EMPIRE 3.2 and TALYS 1.6 codes. The mean value of angular momenta and their distributions were determined in the primary fragments ^{84}Br, ^{97}Nb, ^{90}Rb, ^{131,133}Te, ^{132}Sb, ^{132,134}I, ^{135}Xe of photofission. An impact of the characteristics of nuclear excited states on the calculation results is studied using different models for photon strength function and nuclear level density.

Keywords: photon strength function, nuclear level density, photofission, fast neutrons, isomer ratios, gamma-ray spectrum

Introduction

Nuclear reactions with different projectiles provide information on properties of the excited nuclear states and nuclear reaction mechanisms. They are also required in different applications. Specifically, data of (n,xγ) reactions with any outgoing particle (x) and gamma-rays for atomic nuclei of the reactor materials and photofission reactions are needed for estimations of energy release, γ-ray shielding and radiation swelling of the reactor pressure vessel internals. Photofission reactions are also essential to an explanation of nuclear fission dynamics.

Here, we consider the reliability of description of gamma-transitions in (n,xγ) reactions and photofission by the use of simple closed-form expressions [1] for photon strength function (PSF) and nuclear level density (NLD). We use our recent experimental data, namely, the spectrum of prompt gamma-rays in the energy range 2÷20 MeV from 14 MeV neutron capture of ^{nat}Ni and isomeric ratios in primary fragments of photofission of isotopes U, Np and Pu by bremsstrahlung with end-point energies E_e = 10.5, 12.0 and 18.0 MeV. These data are compared with the theoretical calculations performed within EMPIRE 3.2 and TALYS 1.6 codes [2,3]. An impact of shapes of electric dipole PSF and NLD on accuracy of cross section description and determination of mean angular momenta in primary fragments are analyzed.

Experimental data

Fig. 1 demonstrates comparison of our recent experimental data [4] for γ-spectrum from (n,xγ) reactions on ^{nat}Ni with the earlier data from EXFOR database [5-8]. The amplitude spectrum of gamma-rays was measured in a circular geometry using time-of-flight technique based on pulse neutron generator of neutrons with energy 14.1 MeV (NPG-200), designed and manufactured at Nuclear Physics Department of Taras Shevchenko National University of Kyiv (Ukraine). All experiment and calculation details can be found in Refs. [4,9].

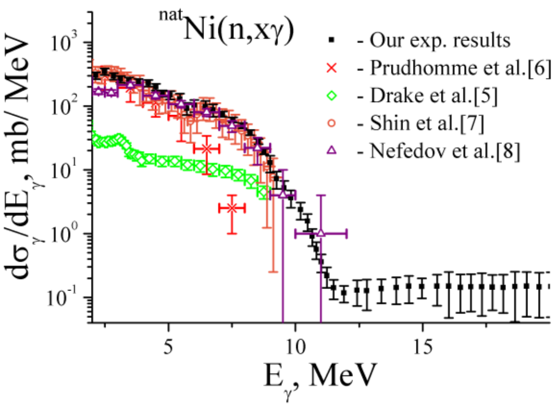

Fig. 1. The measured gamma spectrum from fast neutron capture in ^{nat}Ni in comparison with experimental data from Refs.[5-8].

One can see in Fig.1, that for the gamma-ray energy interval 2÷6 MeV, our experimental results are in rather close agreement with the data from EXFOR database. Gamma-ray spectrum smoothly decreases with gamma-ray energy. For higher energy range of 12÷18 MeV, the differential cross section $d\sigma_\gamma(E_\gamma)/dE_\gamma$ has almost constant value.

In this study of PSF and NLD, we use also our recent experimental data [10,11] for isomeric yield ratios in primary fragments of photofission of isotopes U, Np and Pu by bremsstrahlung with different end-point energies E_e.

These measurements were performed using the bremsstrahlung induced by electron beam from the M-30 microtron at the Laboratory of Photonuclear Reactions of the Institute of Electron Physics (Uzhgorod, Ukraine). The activation method was applied with direct spectrometry of irradiated samples for further identification of the radioactive products. Isomeric ratios were calculated as ratio of the yields of the reactions, leading to formation of final nuclei in the metastable and ground states $R_Y = Y_m / Y_g$. All other details can be found in [10-12]. The results are presented in Table 1.

Table 1.

Isomeric yield ratios and mean angular momentum $\bar{J}$ of photofission primary fragments calculated within EMPIRE 3.2 code with default inputs

Fragment	Target nucleus	Energy E_e, MeV	Isomeric ratio R_Y	$\bar{J}/\hbar$
^{84}Br	^{235}U	18	0.14±0.01	1.8±0.5
^{84}Br	^{237}Np	18	0.15±0.01	1.9±0.5
^{84}Br	^{239}Pu	18	0.118±0.006	1.7±0.5
^{90}Rb	^{237}Np	18	1.2±0.2	2.2±0.6
^{90}Rb	^{239}Pu	18	1.0±0.2	1.8±0.6
^{97}Nb	^{235}U	10.5	0.7±0.09	1.4±0.6
^{97}Nb	^{238}U	12	0.75±0.09	1.4±0.6
^{97}Nb	^{238}U	18	3.8±0.6	5.0±0.7
^{131}Te	^{235}U	18	2.6±0.5	6.8±0.8
^{131}Te	^{237}Np	18	1.9±0.3	5.8±0.7
^{131}Te	^{239}Pu	18	3.2±0.6	7.4±0.8
^{132}Sb	^{235}U	18	1.46±0.22	8.0±0.7
^{132}Sb	^{237}Np	18	1.01±0.12	6.9±0.6
^{132}Sb	^{239}Pu	18	1.48±0.16	8.1±0.6
^{132}I	^{235}U	18	2.2 ±0.4	9.6±0.9
^{132}I	^{237}Np	18	0.95±0.15	6.7±0.7
^{132}I	^{239}Pu	18	0.51±0.06	5.2±0.6
^{133}Te	^{235}U	18	4.3±0.3	7.6±0.6
^{133}Te	^{237}Np	18	9.0±0.9	10.6±0.7
^{133}Te	^{239}Pu	18	5.3±0.3	8.4±0.5
^{134}I	^{235}U	18	0.58±0.09	5.6±0.6
^{134}I	^{239}Pu	18	1.26±0.25	7.7±0.8
^{135}Xe	^{235}U	18	0.056±0.007	1.4±0.5
^{135}Xe	^{237}Np	18	0.041±0.006	1.2±0.5
^{135}Xe	^{239}Pu	18	0.066±0.007	1.4±0.5

Theoretical calculations

Theoretical calculations of cross-sections and mean angular momentum are performed using EMPIRE 3.2 and TALYS 1.6 codes. Comparison with experimental data is made in two steps. At first we use estimations obtained with default parameters and then we use results of calculations within EMPIRE code with different shapes of PSF and NLD [13-15].

Default expressions for PSF and NLD are the following ones: MLO1 variant of the Modified Lorentzian model (MLO) for the electric dipole PSF with Enhanced Generalized Super-Fluid Model (EGSM) for NLD in Empire code, and Enhanced Generalized Lorentzian (EGLO) for PSF with Gilbert-Cameron approach (GC) for NLD in TALYS code. Calculations were performed with allowance for outgoing particles and gamma-rays at equilibrium (HF denotations in the figures) and from pre-equilibrium states (HF+PE denotations with parameter PCROSS = 1.5 for EMPIRE). Global optical potential given by Koning – Delaroche [16] was adopted as a default in the calculations within two codes.

For calculations of considered characteristics, we use expressions presented in Refs. [4, 11, 12]. The cross section of the target with natural elements was taken as a sum of the cross-sections for each isotope of the target weighted with the abundances of the isotope, and the cross section of gamma-ray emission for isotope was a sum of the cross-sections for all possible reactions with any outgoing particle and gamma-rays.

Measured isomeric ratio R_Y for primary fission fragment (A_f, Z_f) was used to obtain its mean angular momentum $\bar{J}$. Initially the spin distribution of primary fission fragments may be deduced from theoretical and experimental isomeric ratios comparison. The theoretical values of the isomeric ratios are determined by the generalized Huizenga-Vandenbosh statistical model [10-12]. Populations of ground and metastable states of given nuclide (A_f, Z_f) after decaying of (A_f+i, Z_f) isotope with larger number of neutrons $(i \le i_m = 2)$ were also taken into account. The probabilities of populations of ground and metastable states by cascades of gamma-rays and neutrons were calculated using EMPIRE 3.2 and TALYS 1.6 codes. The probabilities of deexcitation and population of discrete levels were taken from the RIPL-3 library [1].

Figure 2 shows comparison between experimental data and calculations within EMPIRE and TALYS codes of cross-section for (n,xγ) reaction on ^{nat}Ni.

It can be seen from Fig. 2 that in the gamma-ray energy interval 2÷10 MeV the results of calculations are in rather good agreement with experimental data and a role of preequilibrium emission is small. For high energy range 10÷20 MeV, contribution of the preequilibrium processes is more important.

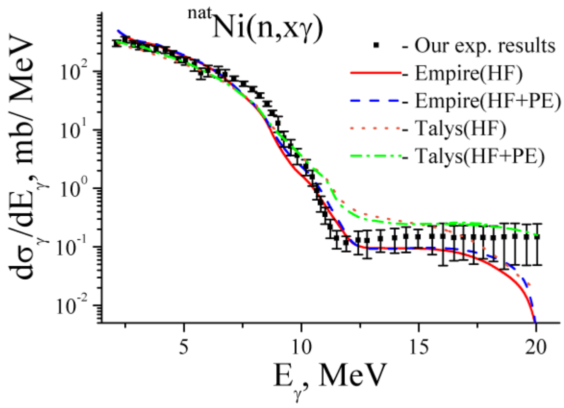

Fig. 2. Comparison of the experimental and theoretical gamma spectrum from fast neutron capture in ^{nat}Ni. Calculations were performed using EMPIRE and TALYS codes with default parameters

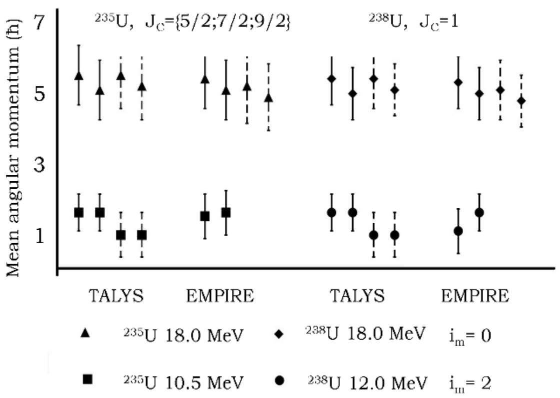

Fig. 3. Comparison of theoretical calculations of mean angular momentum of ^{97}Nb performed using EMPIRE and TALYS codes with default parameters

The table 1 lists the values (in a unit of $\hbar$) of mean angular momentum $\bar{J}$ obtained with default parameters for primary fragments ^{84}Br, ^{90}Rb, ^{97}Nb, ^{131,133}Te, ^{132}Sb, ^{132,134}I, ^{135}Xe of photofission by bremstrahlung. Populations were calculated within EMPIRE code. Figure 3 demonstrates comparison between values of mean angular momentum obtained within

EMPIRE and TALYS codes for ^{97}Nb in photofission of ^{235}U and ^{238}U by bremsstrahlung with end-point energies of 10.5, 12 and 18 MeV. One can see that calculation results with use of different codes are in close agreement.

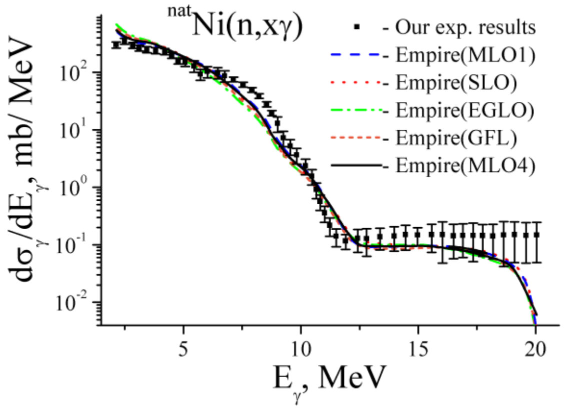

Fig. 4. The gamma spectrum from fast neutron capture in ^{nat}Ni calculated within EMPIRE 3.2 code with different models for the PSF

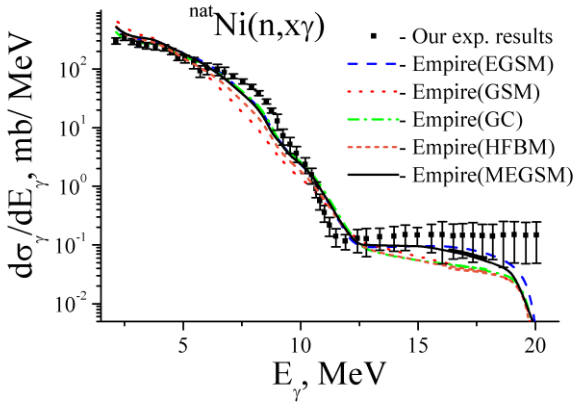

Fig. 5. The gamma spectrum from fast neutron capture in ^{nat}Ni calculated within EMPIRE 3.2 code with different models for NLD

Figures 4-7 demonstrate results of calculations within EMPIRE code (PCROSS=1.5) with different shapes of PSF and NLD [13-15]. For the PSF, we used the EGLO model, MLO1 and MLO4 variants of MLO approach, Standard Lorentzian model (SLO) and Generalized Fermi Liquid (GFL) model. For the NLD, we applied the EGSM, Generalized Superfluid Model (GSM), Gilbert and Cameron (CG) model (from EMPIRE 2.18), microscopic combinatorial level densities within Hartree-Fock-Bogoliubov method (HFBM) and Modified Generalized Super-Fluid Model with Bose attenuated numbers for vibrational enhancement factor (MEGSM) [1,15].

One can see from Figs. 4,5 that difference between calculated gamma spectra with different PSF and NLD shapes is small. The best agreement with the experiment was obtained in case of using MLO1 or MLO4 for the PSF and EGSM or MEGSM for the NLD.

Figures 6,7 show that values of mean angular momentum of primary fission fragments are unaffected by PSF and NDL models.

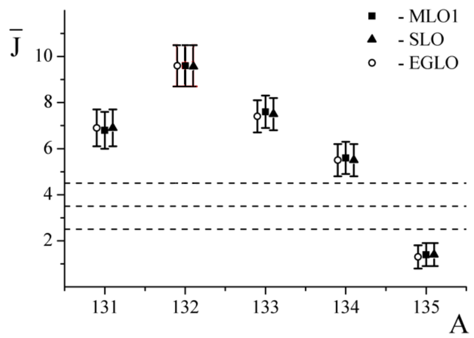

Fig. 6. Mean angular momentum of primary fragments ^{131}Te, ^{132}I, ^{133}Te, ^{134}I, ^{135}Xe calculated by EMPIRE 3.2 code with different PSF models

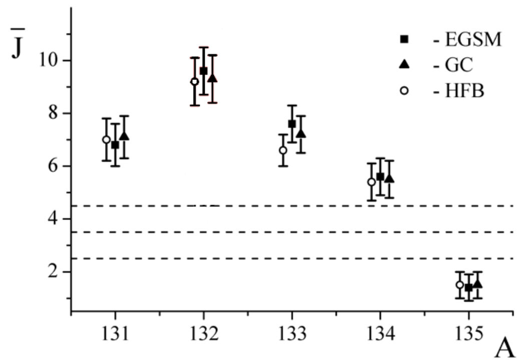

Fig. 7. Mean angular momentum of primary fragments of ^{131}Te, ^{132}I, ^{133}Te, ^{134}I, ^{135}Xe calculated with EMPIRE 3.2 code with different shapes of NLD

Conclusions

The theoretical calculations of gamma-spectrum from (n,xγ) reaction and mean angular momentum of primary fragments were performed. New experimental data were used for (n,xγ) cross-sections on ^{nat}Ni induced by 14 MeV neutrons and for isomeric ratios in primary photofission fragments (^{84}Br, ^{90}Rb, ^{97}Nb, ^{131,133}Te, ^{132}Sb, ^{132,134}I and ^{135}Xe).

For two different quantities, i.e. cross-sections and mean angular momentum, the comparison between calculations within

EMPIRE and TALYS codes shows small impact of shapes of RSF and NLD on the results.

Comparisons of the experimental data with their theoretical values also demonstrate high reliability of the calculations with the use of the EMPIRE and TALYS codes with the default sets of the input parameters for estimations of both the gamma-ray spectrum in reactions induced by fast neutrons and determination of mean angular momentum in primary fission fragments.

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ВПЛИВ МЕТОДІВ ОПИСУ ГАММА-ПЕРЕХОДІВ НА ХАРАКТЕРИСТИКИ ЯДЕРНИХ РЕАКЦІЙ

Представлено результати дослідження різних методів теоретичного опису гамма-переходів у процесах поглинання швидких нейтронів та фотоподілі. Використовуються недавні експериментальні дані, а саме спектр миттєвих гамма-квантів у енергетичному діапазоні 2÷18 МеВ від поглинання нейтронів з енергією 14-МеВ ізотопами Ni та ізомерні відношення у первинних фрагментах фотоподілу ізотопів U, Np та Pu гальмівним випромінюванням із граничними енергіями E_e=10.5, 12 та 18 МеВ. Експериментальні дані порівнюються з теоретичними розрахунками, виконаними за допомогою кодів EMPIRE 3.2 та TALYS 1.6. Розраховано розподіли кутових моментів та середні значення кутових моментів у первинних фрагментах ^{84}Br, ^{97}Nb, ^{90}Rb, ^{131,133}Te, ^{132}Sb, ^{132,134}I, ^{135}Xe. Досліджено вплив характеристик збуджених станів ядер, а саме різних моделей фотонних силових функцій та густин ядерних рівнів, на результати розрахунків.

Ключові слова: фотонні силові функції, густина ядерних рівнів, фотоподіл, швидкі нейтрони, ізомерні відношення, гамма-спектр

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ВЛИЯНИЕ МЕТОДОВ ОПИСАНИЯ ГАММА-ПЕРЕХОДОВ НА ХАРАКТЕРИСТИКИ ЯДЕРНЫХ РЕАКЦИЙ

Представлены результаты исследования надежности различных методов теоретического описания гамма-переходов в процессах захвата быстрых нейтронов и фотоделении. Используются недавние экспериментальные данные, а именно спектр мгновенных гамма-квантов в энергетическом диапазоне 2÷18 МэВ в реакции захвата нейтронов с энергией 14 МэВ изотопами Ni и изомерные отношения в первичных фрагментах фотоделения изотопов U, Np и Pu тормозным излучением с граничными энергиями E_e =10.5, 12 и 18 МэВ. Экспериментальные данные сравниваются с теоретическими расчётами, выполненными с помощью кодов EMPIRE 3.2 та TALYS 1.6. Вычислены распределения угловых моментов и средние значения угловых моментов в первичных фрагментах ^{84}Br, ^{97}Nb, ^{90}Rb, ^{131,133}Te, ^{132}Sb, ^{132,134}I, ^{135}Xe. Исследовано влияние характеристик возбужденных состояний ядер, а именно различных моделей описания фотонных силовых функций и плотности ядерных уровней, на результаты расчётов.

Ключевые слова: фотонные силовые функции, плотность ядерных уровней, фотоделение, быстрые нейтроны, изомерные отношения, гамма-спектр