USING OF CALCULATED NEUTRON MULTIPLICITIES FOR DETERMINATION OF THE EXCITATION ENERGY OF FISSION FRAGMENTS

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Study of excitation energy distribution of fission fragments as a function of its mass and charge is important for investigation of the fission process mechanism and useful for various applications. Direct measurement of excitation energy of primary fission fragments (before escape of neutrons) is very problematical. Method to obtain these excitation energies is considered using calculated neutron multiplicities and experimental values of differential yields of fragments pairs after emission of neutrons. We used code Empire II to calculate neutron multiplicities depending on various characteristics of nuclear structure, fission process and de-excitation of the fission fragments.

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1. INTRODUCTION

The study of fission characteristics like average number of prompt neutrons and fission fragments excitation energy distribution is very important for understanding of basic mechanisms of fission process and useful for various applications - nuclear power reactors, nondestructive analysis of nuclear materials, active and passive detection of special nuclear materials for nonproliferation application [1] etc. Information about primary fission fragments (before escape of neutrons) is desirable for accurate theoretical analysis of experimental data. Direct measurement of excitation energy for primary fragments before emission of neutrons is very difficult. Usually yields, kinetic energy, neutron multiplicity of fission fragments (integral values or mass distribution) after emission of all neutrons are measured. The neutron emission from fission fragments makes major contribution to total neutron multiplicity. Information about this emission is needed to obtain the excitation energy distribution for primary fission fragments.

Number of escaped neutrons depends from mass number and charge of the nucleus, total excitation energy of fission fragments, partitioning the total available excitation energy between light and heavy fragments, angular momenta of primary fission fragments (before escape of neutrons). Wide distribution of fission fragments pairs, difficulties for direct experimental obtaining of excitation energy, angular momenta of fragments and excitation energy partitioning - all these factors could significantly complicate theoretical and experimental study of neutron multiplicity. Therefore, first of all, averaged values are investigated in many cases.

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The neutron emission from fission fragments makes main contribution to total neutron multiplicity. Various theoretical approaches to study neutron emission are used [2] - Los Alamos Models, Dresden approach, Hauser-Feshbach statistical model approach and other studies with detailed calculation according to full scheme of excited fragment decay, taking into account consecutive escape of neutrons with competition between neutron emission and gamma-ray emission. It is believed that, ultimately, the Hauser-Feshbach approach will probably yield the most accurate results in the calculation of the prompt fission neutron spectrum and the average prompt neutron multiplicity. Essential advantage of such detailed approaches is an explicit treatment of each fragment in a relatively large number of fission-fragments pairs, accurate calculation is possible not only for integral (averaged) values, but for differential characteristics as well. Monte Carlo simulation of fission fragment statistical decay (Weisskopf-Ewing) by sequential neutron emission is developed in Los Alamos National Laboratory [3].

One can obtain not only integral values but also differential characteristics of fission process using calculation of characteristics for every fission fragment and comparing with corresponding differential experimental data. Experimental differential information for fission-fragments pairs is not very representative, but within last years interesting experimental results on neutron multiplicity and yields for selected fission-fragments pairs were obtained [4, 5, 6]. These experimental data can be very useful for deriving such important characteristics of fission process as total excitation energy and yield of primary fission fragments (before emission of neutrons).

2. CALCULATION SCHEME FOR CHARACTERISTICS OF PRIMARY FISSION FRAGMENTS

According to these experimental data we built up the equations set with expression for every cell (specified in the table 1 of ref. [4]) in the following way:

$$P^{exp}_{A1_f,A2_f} = \sum_{k=1}^{N} \sum_{i=A1_f}^{A-A2_f} Y^k_{i,(A-i)} \cdot Pj(Jj,Ej)^{A-i-A2_f}_{i,(A-i)} \cdot Pi(Ji,Ei)^{i-A1_f}_{i,(A-i)} \qquad (1)$$

where $P^{exp}_{A1_f,A2_f}$ - relative experimental probability of population the pair of final fission fragments with mass number $A1_f$ for the first fragment and mass number $A2_f$ for the second fragment, A – mass number of fissile nucleus (in this case ^{252}Cf); $\sum_{k=1}^{N} Y^k_{i,(A-i)}$- relative yield of primary fission fragments pair (before emission of neutrons) with mass number i for the first fragment (first subscript) and mass number $A-i$ for the second fragment (second subscript); $Pj(Jj,Ej)^{A-i-A2_f}_{i,(A-i)}$- relative probability of escaped number of neutrons $A-i-A2_f$ (superscript) for the second fragment of fragments pair $i,(A-i)$ (subscript); $Pi(Ji,Ei)^{i-A1_f}_{i,(A-i)}$ - relative probability of escaped number of neutrons $i-A1_f$ (superscript) for the first fragment of fragments pair $i,(A-i)$ (subscript). $Y^k_{i,(A-i)}$ - partial relative yield of primary fission fragments pair for total excitation energy bin (see Fig.1), where k - energy bin index, N - number of bins.

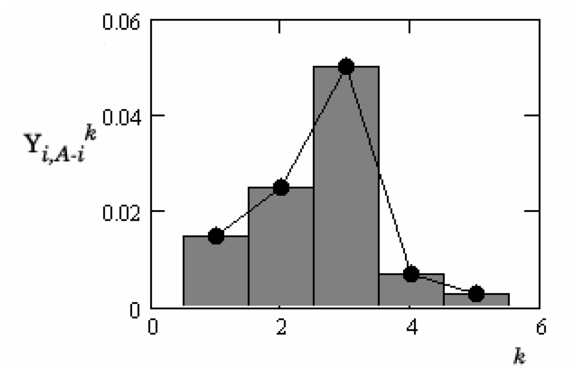


Fig.1. *Relative yield of primary fission fragments pair for total excitation energy (k-index of energy)*

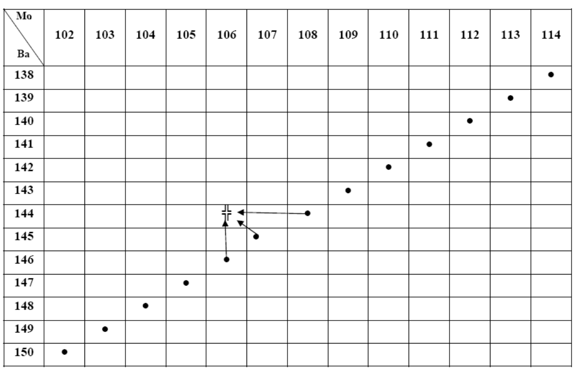


Fig.2. *Graphical illustration to equation (1)*

Relative probabilities of escaped number of neutrons $Pj(Jj,Ej)^{A-i-A2_f}_{i,(A-i)}$ and $Pi(Ji,Ei)^{i-A1_f}_{i,(A-i)}$ are calculated using Empire II code [7], and $Y^k_{i,(A-i)}$ - are derived from (1).

In Fig.2 one can see graphical illustration to equation (1) according yields data [4] of fragments pairs (barium-molybdenum) for spontaneous fission of ^{252}Cf. Admissible mass numbers (vertical and horizontal axes in Fig.2) of primary fission fragments are situated on the hypotenuse (part of diagonal with total mass number $A = 252$) of right-angled triangle for neutron emission transitions to fission fragments pair after escape of neutrons (vertex of right angle in triangle).

3. EMPIRE II CALCULATION OF NEUTRON MULTIPLICITY

Nowadays powerful and effective nuclear reaction codes for advanced modeling of nuclear reactions are developed. Such codes potentially allow to calculate in details a de-excitation of primary fission fragment before escape of neutrons to final nucleus-product of fission. One of these codes is Empire II code which uses various modern theoretical approaches, has an open source status, and some other important advantages [7]. We modified code Empire II and developed additional modules to study photofission reactions, isomer ratios, excitation energy and angular momentum dependencies of various reaction characteristics for fission fragments and other reactions products [8, 9]. It allows to calculate number of escaped neutrons versus spin and excitation energy of primary fission fragments. Using calculated distributions and mean values of escaped neutrons from primary fission fragments one can compare such results with experimental data and estimate relative yields of primary fragments and distribution of total excitation energy. We calculated relative probabilities of escape various number of neutrons from primary fission fragments of the spontaneous fission of ^{252}Cf. These data can be used for comparison with experimental data [4]. We studied fragments pairs - $^{138}Ba^{114}Mo$, $^{139}Ba^{113}Mo$, $^{140}Ba^{112}Mo$, $^{141}Ba^{111}Mo$, $^{142}Ba^{110}Mo$, $^{143}Ba^{109}Mo$, $^{144}Ba^{108}Mo$, $^{145}Ba^{107}Mo$, $^{146}Ba^{106}Mo$, $^{147}Ba^{105}Mo$, $^{148}Ba^{104}Mo$, $^{149}Ba^{103}Mo$, $^{150}Ba^{102}Mo$. The total excitation energy range was 25-55 MeV.

Example of calculation set (averaged values) of neutron multiplicities for primary fragments of ^{252}Cf fission (spin of primary fission fragments 4 or 4.5)

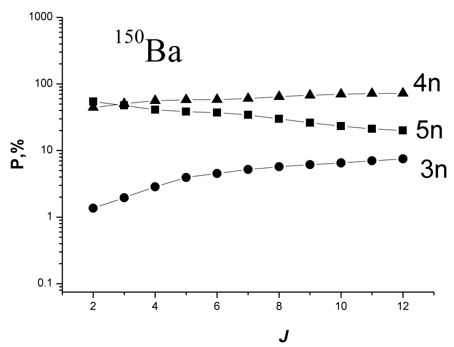
E^*, MeV	$^{138}Ba^{114}Mo$		$^{139}Ba^{113}Mo$		$^{140}Ba^{112}Mo$		$^{141}Ba^{111}Mo$		$^{142}Ba^{110}Mo$	
25	1.00	0.03	1.11	0.31	1.76	0.43	1.92	0.28	1.92	0.27
	1.95	0.22	1.67	0.47	1.65	0.48	1.35	0.48	1.15	0.36
	2.95	0.22	2.78	0.57	3.41	0.64	3.26	0.55	3.07	0.45
27	1.00	0.02	1.50	0.50	1.88	0.33	1.97	0.18	1.97	0.17
	1.98	0.13	1.84	0.37	1.88	0.33	1.70	0.46	1.64	0.48
	2.98	0.14	3.34	0.62	3.76	0.46	3.67	0.49	3.61	0.51
29	1.01	0.08	1.73	0.45	1.94	0.23	1.98	0.13	1.99	0.11
	1.99	0.09	1.93	0.25	1.95	0.22	1.86	0.34	1.85	0.36
	3.00	0.12	3.66	0.51	3.89	0.32	3.85	0.37	3.83	0.38
31	1.23	0.42	1.86	0.35	1.97	0.18	2.04	0.22	2.00	0.07
	2.00	0.09	2.04	0.31	1.98	0.15	1.95	0.22	1.94	0.24
	3.23	0.43	3.90	0.46	3.94	0.23	3.99	0.32	3.93	0.25
33	1.56	0.50	1.92	0.27	1.98	0.13	2.21	0.41	2.18	0.38
	2.08	0.28	2.29	0.47	1.99	0.09	2.00	0.23	1.94	0.24
	3.64	0.57	4.21	0.55	3.97	0.16	4.21	0.47	4.11	0.45
35	1.77	0.42	1.96	0.19	1.99	0.10	2.60	0.49	2.45	0.50
	2.32	0.47	2.49	0.51	2.00	0.06	2.00	0.23	1.97	0.16
	4.08	0.63	4.45	0.54	3.99	0.11	4.60	0.54	4.42	0.52
37	1.88	0.33	1.98	0.13	2.03	0.18	2.74	0.44	2.62	0.49
	2.48	0.50	2.70	0.46	2.00	0.06	2.18	0.41	1.99	0.10
	4.36	0.60	4.68	0.48	4.02	0.19	4.91	0.60	4.61	0.50
39	1.93	0.25	2.03	0.19	2.14	0.35	2.84	0.37	2.76	0.43
	2.64	0.48	2.70	0.46	2.05	0.23	2.38	0.50	2.00	0.07
	4.57	0.54	4.73	0.50	4.19	0.42	5.22	0.62	4.76	0.43

We supposed that both light and heavy fragments share the same temperature and level density parameter is proportional to mass number of nucleus. These conditions lead to partitioning of excitation energy between fragments proportionally its masses. Neutron multiplicities were calculated for spins of primary fission fragments 4 or 9/2 and default configuration options of Empire II code. Spin of every fragment was varied in the range 2 - 12 $\hbar$ for energy dependencies. Part of calculated data set (averaged values) is shown in table.

In the table 1: E^* - the total excitation energy of fragments; υ_1, υ_2, υ_{1+2} - average neutron multiplicity for the first primary fragment, for the second primary fragment, and total average number of neutrons; σ_1, σ_2, σ_{1+2} - standard errors of υ_1, υ_2, υ_{1+2}.

E^*, MeV	$^{138}Ba^{114}Mo$	
25	υ_1	σ_1
	υ_2	σ_2
	υ_{1+2}	σ_{1+2}

One can see some results of these calculations in Fig.3,4. Spin dependencies of relative neutron yield from primary fragments ^{138}Ba and ^{150}Ba for various number of neutrons (total excitation energy $30\,MeV$) and spin are shown in Fig.3.



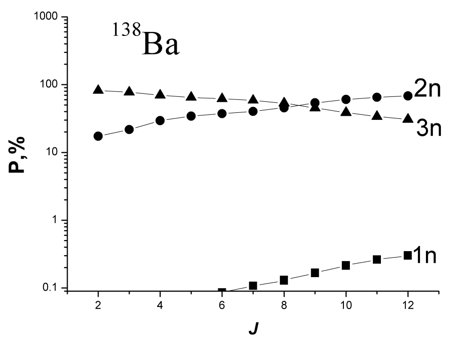


Fig.3. *Spin dependencies of relative neutron yield (P) from primary fragments ^{138}Ba and ^{150}Ba for various number of neutrons (total excitation energy 30 MeV) and spin (J)*

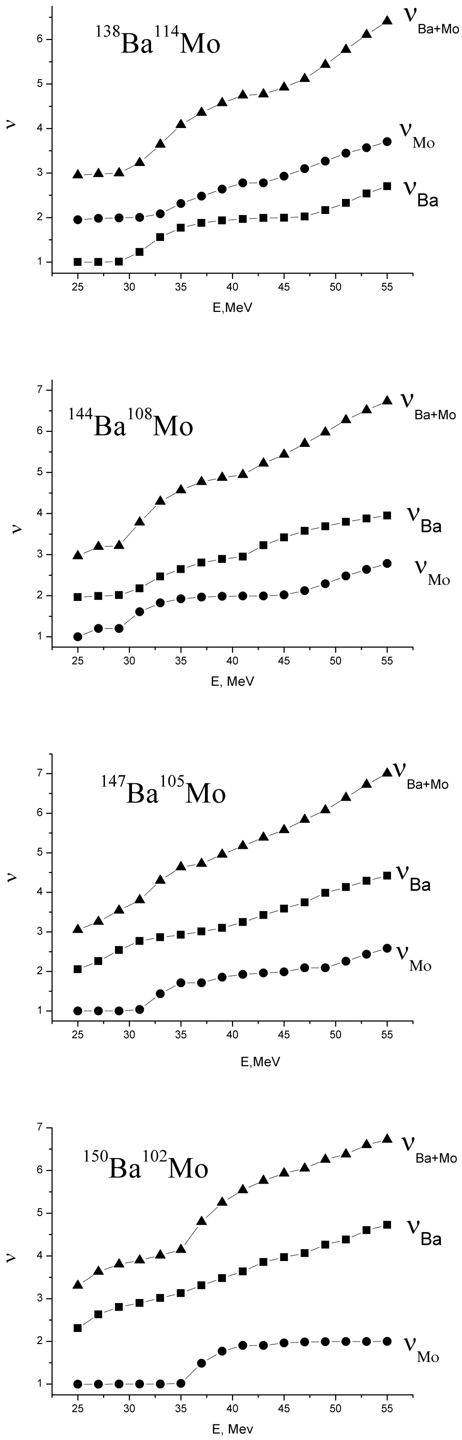


Fig.4. *Neutron multiplicities (υ) versus total excitation energy (E) of fragments (spin of primary fission fragments 4 or 4.5)*

Neutron multiplicities (υ) versus total excitation energy of fragments are shown in Fig.4.

One can see that spin dependence of multiplicities is not very strong. As a rule the escape probability of more number of neutrons decreases with spin increasing. Neutron multiplicity dependencies have some peculiarities for different fragment pairs. It is necessary to take into account these differences. Calculated data allow more accurate studying the characteristics of primary stages for fission process.

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ОПРЕДЕЛЕНИЕ ЭНЕРГИИ ВОЗБУЖДЕНИЯ ОСКОЛКОВ ДЕЛЕНИЯ С ИСПОЛЬЗОВАНИЕМ РАССЧИТАННЫХ МНОЖЕСТВЕННОСТЕЙ НЕЙТРОНОВ

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Изучение распределения энергии возбуждения осколков деления как функции массы и заряда осколков может дать важную информацию о механизмах процесса деления и быть полезным для целого ряда приложений. Прямое экспериментальное определение энергии возбуждения осколков деления сталкивается с целым рядом проблем различного характера. Рассмотрен подход для определения энергии возбуждения осколков деления с использованием рассчитанных множественностей нейтронов и экспериментальных величин дифференциальных выходов пар осколков после вылета из них нейтронов. Для расчетов множественностей нейтронов использовался программный код Empire II.

ВИЗНАЧЕННЯ ЕНЕРГІЇ ЗБУДЖЕННЯ УЛАМКІВ ПОДІЛУ З ВИКОРИСТАННЯМ РОЗРАХОВАНИХ МНОЖИННОСТЕЙ НЕЙТРОНІВ

О.А. Безшийко, Л.О. Голінка-Безшийко, І.М. Каденко, Р.С. Джигадло

Дослідження розподілу енергії збудження уламків поділу як функції їх маси та заряду може надати важливу інформацію про механізми процесу поділу та може бути корисним для вирішення цілого ряду прикладних задач. Пряме експериментальне визначення енергії збудження уламків поділу зіштовхується з цілим рядом проблем різного характеру. Розглянуто підхід для визначення енергії збудження уламків з використанням розрахованих множинностей нейтронів та експериментальних величин диференційних виходів пар уламків після вильоту з них нейтронів. Для розрахунків множинностей нейтронів використовувався програмний код Empire II.