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THE EFFECT OF ELEMENTARY PARTICLES EMISSION AT THE HEAVY NUCLEI FISSION FRAGMENTS MASS DISTRIBUTION

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In the present work, we have shown that the suggested approach can account for the presence of the fission neutrons and describes the temperature dependence of the heavy nuclei fragment masses distribution. The capabilities of the theory are demonstrated at the example of a binary fission of the heavy nucleus with mass number A and charge Z. The data on the fission fragments mass distribution are presented for the ^{236}U and ^{232}Th nuclei.

Introduction

The investigation of the mass and charge distribution of the fission fragments (MCDF) for heavy nuclei is an important task of nuclear physics that allows the problems of nuclear matter stability to be studied, as a rule, the theoretical MCDF interpretation is based on the fission process dynamics and requires the introduction of fitting parameters that characterize their geometrical dimensions or one-particle nucleon state densities [1].

The statistical model of heavy nuclei fission has a long history [2] and start from the assumption on the thermodynamical equilibrium in the fission system for the time intervals before the compound-nucleus decay. In [3,4], the methods of statistical thermodynamics of condensed state were applied to describe the fission fragment system ordering. This has allowed one to describe MCDF from the first principles by using the binding energy of the fission fragments and the temperature (excitation energy) of the initial nucleus as the theory parameters. In the present paper, these studies are complemented by considering the effects related to the emission of elementary particles during the heavy nuclei fission.

Theory

The ensemble of two-fragment clusters produced at the heavy nucleus fission is considered by us [4] as the canonical one, whereas the total energy of the system is a motion integral. We assume the equality of nuclear temperatures T of the initial nucleus fission fragments with atomic mass A_0 and charge Z_0. The experimental facts related to that case could be found, e.g., in [5]. According to [6], due to the low number of particles forming the fragment nuclei $A \sim 50$-120 the notion of temperature for them is well defined in the case of $\Delta T/T \ll 1$, where

$$\Delta T/T = 2/\sqrt{AT} = (2\text{MeV}/AU)^{1/4} \quad (1)$$

where U is the internal energy of the nucleus. The estimate (1) was obtained within the framework of the Fermi-gas model whose critical discussion is given in [7].

If one neglects the effects related to the pressure produced by nucleons in the nucleus and the change of specific volume of nucleons in different nuclei, then the equilibrium ratios of masses and charges of the fission fragments as the functions of T are defined from the condition of minimum free energy of the nuclear matter in a form of an ensemble of the fission fragments:

$$F=U-TS \ . \qquad (2)$$

In our case U is equal to the binding energy of two fragments and has a discrete set of quantities (levels) $\{\varepsilon_i\}$. A rule of calculating the $\{\varepsilon_i\}$ spectrum can be written as:

$$\varepsilon_i=\sum_{j=1,2}\sum_{<N_p,N_n>_i}(U_j(N_p{}^{(i)},N_n{}^{(i)})+\Delta_j\times n_j)\quad(3)$$

where U_j is the binding energy of the j–th fragments, Δ_j is an average kinetic energy of the fission neutrons, $<..>_i$ is a symbol indicating than summation in (3) is taken over the i-th sets of nucleons $\{N_p{}^{(i)}, N_n{}^{(i)}\}$, obeying the equations:

$$\sum_{j=1,2}\{N_p{}^{(j)}+N_n{}^{(j)}+n_j\}=A_0$$

$$\sum_{j=1,2}\{N_p{}^{(j)}+e_j\}=Z_0 \qquad (4)$$

where, in the general case, we have included the number n_j ($e^{\cdot}_j$) of neutrons (electrons) emitted from the j-th fragment, j=1,2. The configuration entropy in (2) is defined by the number of possible realizations of the nuclear matter state with the energy U. The nucleons with different binding energies should be considered statistically non-equivalent. Then $S=\ln(\omega_i)$, where

$$\varpi_i=A!/(\prod_{j=1,2}(N_p{}^{(j)}!N_n{}^{(j)}!n_j!)_i \qquad (5)$$

$\prod_{j=1,2}x!=x_1!x_2!$, i is an index which indicates in (5) the above i-th set of nuclear fragments. It is easy to show that the entropy term in (2) is maximal if $N_p{}^{(J)}=N_n{}^{(J)}$, hence it is responsible for the symmetrization of the fission fragment masses with increasing T. The levels $\{\varepsilon_i\}$ are the energy spectrum of the ensemble of fission fragments, whereas ω_i in (5) is their degeneracy. In the general case, ε_i levels are not equidistant and the pair of fragments can occupy only one level of the $\{\varepsilon_i\}$ spectrum. The distribution function of the fragment pairs over the set $\{\varepsilon_i\}$, which defines FMD, can be written as:

$$f_i=\omega_i\exp(\varepsilon_i/T)/Z \qquad (6)$$

where Z is a partition function of the ensemble of fragment pairs and is determined from the normalization condition

$$\sum_{i=1,N}f_i=1\cdot$$

In general, we take into account the neutron emission under fission, then minimization of F (1) must be performed on 4D massive including the mass (charges) of the nuclear fragment A_i (Z_i) and n_i – number of neutrons, i=1,2.

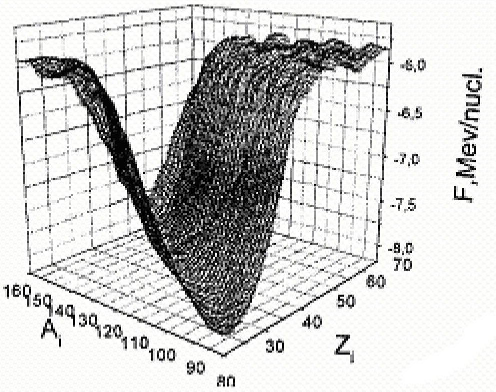

Fig. 1. Free energy F surface (in MeV/nucl.) for the ensemble of fragments of the Th-232 fission in the mass number and charge coordinates A_i, Z_i for one of the fission fragments. The initial nucleus temperature is T=1MeV.

In Fig.1 the F-dependence in the A_i, Z_i coordinates for the example of ^{232}Th fission is presented. As one can see, there is a curve of $(\tilde{A}_i,\tilde{Z}_i)$ pairs minimizing the free energy of fragment set. The neutron emission decreases the fragment pair total binding energy U (1) but increases their configuration entropy S (4). The neutron equilibrium number $\tilde{n}_i$ i=1,2 for every fragment ratio can also be determined from the condition of F minimum. The theory is able to obtain both neutron emission function for every fragments mass and average neutron number per fission. If the nuclei temperature T in (2) is increased or decreased, the shape of F- dependence (Fig.1) will be changed. In this way we can determine the equilibrium values of the total binding energy $\tilde{U}$, see (1), and other thermodynamic functions of the ensemble of the fragment pair.

The temperature dependence of ^{232}Th MCDF is shown in Fig.2. This dependence as well as the fragment charge distribution can be constructed from the distribution function f_i (5). One can see at sufficiently low T that MCDF is determined mainly by the contribution of the mass channels with magic neutron – 82 – and proton – 50 – numbers. If T rises, and the entropy term in (2) becomes more essential, MCDF (Fig.2) is getting more symmetrical.

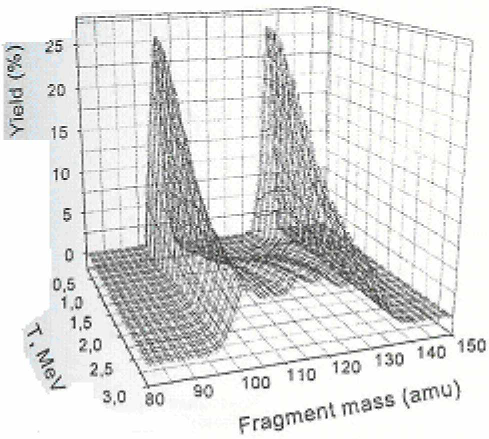

Fig. 2. Temperature dependence of MCDF at Th-232 fission. The calculation was performed with the allowance made for the fission neutrons.

The suggested theory has no fitting parameters since the binding energy of certain nuclei is either the tabulated quantity or could be calculated by using the mass formulae. However, just the first calculations have shown that deriving MCDF by formula (6) we overestimate the role of the effects related to the presence in the canonical ensemble of the fragment nuclei with even or magic proton (neutron) numbers.

The emission of elementary particles at the fission is related to the relaxation of the excitation of the heavy nuclei fission fragments or to the transition of the fragment nuclei isotopes to so-called beta or neutron stability isles, when we deal with the gain in the specific binding energy of the system. One may expect that this effect also affects MCDF.

Elementary particle emission at nuclear fission and MCDF

The further calculations will be performed for the example of ^{236}U isotope fission MCDF taking into account the availability of reliable experimental data for this isotope. In this case the ensemble of two-fragment ^{236}U fission fragments must be complemented by the fission neutrons, while electron and positron emission could be taken into account when assuming the preservation of the total charge in the nuclei fragment system with an accuracy up to the number of charged particles, the emission of which increases or decreases the charge of separate fission fragments. The emission of elementary particles results in the decrease of the nucleus binding energy and they carry out certain excitation energy. The latter fact limits the number of particles, which could be emitted at the fission. Thus, to obtain more realistic MCDF dependences one has to take into account the fission process energy balance.

It is known that the energy released at the heavy nuclei fission is spent to the kinetic energy and excitation energy of elementary particles. Due to the equality of the nuclear temperature of the fission fragments that is one of the postulates of the suggested theory, the fission energy may be redistributed between the kinetic energy of the fragment nuclei emitted at the fission, including the gamma-quanta. The following cases are available:

- The emission of elementary particles is not taken into account. The excess of the excitation energy may be carried out by the gamma-quanta. In that case the “null’ variant of the theory is realized, when there are no fitting parameters, and

MCDF is defined by the mass channels of yields stipulated by the pairing effects for outer shell nucleons and the fission fragments with the magic values of proton (neutron) numbers.

- The emission of fission neutrons and removal or conservation of an additional excitation energy are taken into account. The neutron number is defined by the condition of minimal specific binding energy of the final two-fragment cluster or by the energy balance in the system.
- Besides the availability of fission neutrons, the peculiarity of the distribution of fission fragment kinetic energies over their mass ration is taken into account, since, as is known, the maximal kinetic energy is reached in the case of the symmetric fission of the heavy nucleus. In that case the number of fission neutrons will be defined both by the fission process energy balance and the fragment mass ratio.
- The same effects should be considered in the case of the presence of the emission of charged particles (electrons, positrons).

According to [8], we shall present an estimation of the energy balance: in the case of ^{236}U the average fission energy is about 193 MeV, the average fission fragment kinetic energy is 166 MeV, while their excitation energy is 27 MeV. During ^{236}U fission 2.5 neutrons are emitted with the average kinetic energy of each of them (in the center-of-mass frame) being 1.5 MeV. The average energy of gamma-quanta per one fission is constant and less than the neutron binding energy, i.e ~4.5 MeV.

More complicated is the consideration of the energy balance at the beta-decay and positron emission. These processes belong to the weak interaction and are not directly related to the heavy nuclei fission physics. It has been found that the most apart from the stability domain fragments have the beta-decay energy of 8–10 MeV, while the half-decay period is about fractions of millisecond. With the approaching the beta-stability valley the beta-decay energy, as a rule, decreases, whereas the half-decay period increases.

The general regularity related to the emission of elementary particles at the fission has been found experimentally – their number is the maximal in the mass distribution maxima, i.e. at A~90–110 for light fragments and 130–150 for the heavy ones [9].

Figure 3 shows the results of calculation of the mass distribution of U-236 fission fragments at different initial nucleus temperatures with the inclusion of the fission neutron emission and with no such inclusion. It has been assumed that the average energy of neutrons is 1–1.5 MeV, and their number is defined by the condition of equality of the fragment nucleus excitation energy to that carried out by the fission neutrons. It is seen that the inclusion of the elementary particle emission indeed improves the agreement between the theoretical and experimental data for ^{236}U.

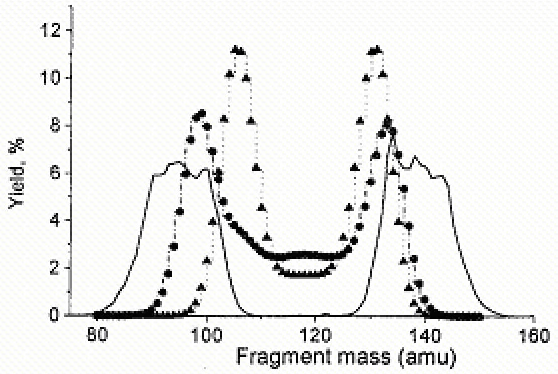

Fig. 3. MCDF at the ^{236}U fission: solid curve – experimental data for the spontaneous fission, triangles – calculation at T = 1 MeV with the fission particle emission being neglected. Circles – MCDF at T = 2 MeV with the inclusion of fission neutron emission.

Conclusions

Thus, the obtained results have testified the possibility of the improvement of the accuracy of the MCDF calculation for the heavy nuclei by taking into account the emission of elementary particles at the fission. The mechanism of this account within the framework of thermodynamical model is not clear yet, however, the comparison of the calculated and the experimental data may provide an interesting information on the nuclei fission mechanism.

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References

1. V.M.Strutinsky, *Nucl. Phys.* **122,** 1 (1968)
2. A.V.Ignatyuk, *Nucl. Phys.* **9**, 357 (1969)
3. V. Maslyuk, *Ukr. J .Phys.* **41**, 1029 (1996) [In Ukrainian]
4. V. Maslyuk, *Ukr. J .Phys.* **44**, 301 (1999) [In Ukrainian]
5. U. Facchini, G. Pierini, E. Saetta-Menichella, *Energia Nucleare* **20**, 667(1973)
6. H. Feshbach, *Physics Today*, **12**, 9(1987)
7. A. B.Migdal *The Theory of Finite Fermi Systems and Atomic Nuclei Properties* (Nauka, Moscow, 1983)
8. I. Chalpern *Nuclear Fission* (Fizmatgiz, Moscow, 1962) [In Russian]
9. Yu.P.Gangrsky, B.Dahsuren, B.N.Markov, *Nuclear fission fragments* (Energoatomizdat, Moscow, 1986) [In Russian]

ВПЛИВ ЕМІСІЇ ЕЛЕМЕНТАРНИХ ЧАСТИНОК НА МАСОВИЙ РОЗПОДІЛ УЛАМКІВ РОЗПАДУ ВАЖКИХ ЯДЕР

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Показано, що запропонований підхід може відповідати за присутність нейтронів розпаду і описує температурну залежність масового розподілу уламків важких ядер. Продемонстровано можливості теорії на прикладі бінарного розпаду важкого ядра з масовий числом A і зарядом Z. Подано дані з масового розподілу уламків розпаду для ядер ^{236}U і ^{236}Th.