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ANALYSIS OF MULTIPLE-DIFFERENTIAL EMISSION CROSS SECTIONS OF NEUTRONS FROM SPONTANEOUS FISSION OF ^{252}CF

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Abstract

The prompt neutron emission in the spontaneous fission of ^{252}Cf is studied in the framework of the cascade evaporation model (CEM) for specified scission configurations. In addition to the analysis presuming the main emission mechanism, i.e. evaporation from fully accelerated fission fragments, the energy and angular distributions of neutrons evaporated during fragment acceleration (NEDFA) as well as of neutrons coming from the decay of ^5He nuclei (HEN) are estimated on the base of theoretical data on post-scission dynamics and experimental results on ^5He emission in Cf fission respectively. It is shown that scission neutrons should be attributed to single-particle excitations which occur due to rapid changes of nuclear potential close to scission.

1. Introduction

According to several experimental and theoretical studies made in the last decades (compare the references reviewed in the papers[1,2]) the predominant mechanism of fission neutron emission is the evaporation from fully accelerated fragments which obtain their excitation energy (on an average of about 20 MeV per fragment) due to the dissipation of collective energy (fragment deformation at scission) mainly. A small fraction of fission neutrons - the so-called scission neutrons - are emitted close to the scission point. Their angular distribution seems to be nearly isotropic[3]. On the base of poor experimental data, the term "scission neutrons" is defined roughly. Possible emission mechanisms have been considered[4,5,6,7,8], but estimations are quite uncertain. Up to now, the partial spectra and angular distributions of the different eventual kinds of scission neutrons have not been deduced theoretically.
Fission is a rather complex process characterized by an occurance probability distribution P with nucleon number, excitation energy, fragment kinetic energy, nuclear spin etc. as arguments. P itselves depends on the features of the fissioning nucleus. The dynamics of the fission process - the time dependence of the nuclear potential especially - is connected with the final scission configuration specified by elongation, i.e. the total kinetic energy TKE of the fission fragments, as well as asymmetry, i.e. the fragment mass number ratio A_L/A_H. Therefore, the mechanism of fission neutron emission should be studied in dependence on A_L/A_H and/or TKE experimentally. Hitherto existing results are contradictory[9,10,11]. Compare review[2] also.
A comprehensive analysis of fission neutron emission should include all essential mechanisms. As a first step, we study the laboratory system (l.s.) double-differential emission cross sections $N(E,\Theta;A_L/A_H,TKE)$ for fixed asymmetry and elongation of the scission configuration in the framework of the CEM[2,12] (E,Θ - l.s. neutron energy and emission angle with reference

to the light fragment direction). Preliminary results and essential conclusions are discussed in addition to earlier publications[2,12,18]. Furthermore, we estimate the influence of NEDFA (compare the treatment of Pik-Pitchak[6]) on $N(E,\Theta)$ on the base of new theoretical results about the post-scission dynamics[13]. This component may simulate scission neutron emission. Another possible fraction of neutrons with a relatively low yield is attributed to the decay of n-unstable light nuclei emitted at scission in equatorial direction mainly due to the repulsion in the Coulomb field of the fission fragments. Hence, such neutrons are directed close to the 90 deg-plane with reference to the fission axis. We estimate the l.s. emission distribution in the case of the ^5He decay studied experimentally[14]. Intercomparisons between the results of the CEM calculations and available experimental data as well as the influence of both the NEDFA and HEN component are discussed with regard to the totality of fission neutron emission.

2. Calculations in the framework of the CEM

The CEM calculations described in detail in the references[2,12] were based on realistic initial distributions of excitation energy deduced from experimental data on neutron and γ-ray emission as a function of both A and TKE. For fixed A, the consideration of the dependence on TKE results in a modification of $N(E,\Theta:A_L/A_H)$ at high emission energies especially[2,12]. In the case of $A_L/A_H = 108/144$, the differences between the exact calculation and the approximation for an average TKE are about 1 % (10 %) at 1 MeV (10 MeV).
The shape of $N(E,\Theta:A_L/A_H,TKE)$ depends on the ratio between the average excitation energies of the complementary fragments mainly. As discussed in ref.[12], this quantity is determined by A dependent shell effects at scission modified by intrinsic temperature and deformation. Fig. 1 illustrates the stated assertion and represents calculated $N(E,\Theta:A_L/A_H)$ for typical fragment mass number ratios at E = 2 MeV.

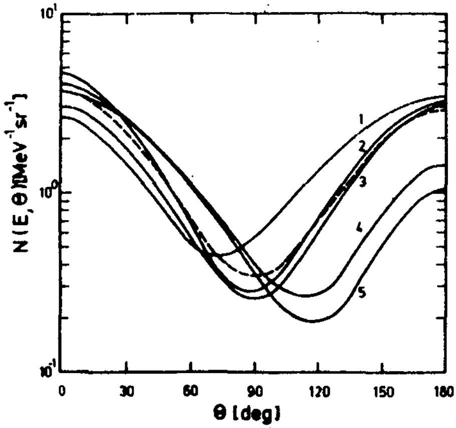


Fig. 1.
The angular distribution of Cf-252 fission neutrons at E = 2 MeV for selected fragment mass number ratios (1 - 90/162, 2 - 108/144, 3 - 126/126, 4 - 120/132, 5 - 123/129, dashed line - weighted average)

The energy spectrum of the scission neutron component is usually approximated by the simple equation

$$N_{sc}(E) \sim E \cdot \exp(-E/T_{sc}) \qquad (1)$$

in which T_{sc} is the "temperature" (spectrum hardness) parameter. Considering the published yields $\bar{\nu}_{sc}$ and average emission energies of scission neutrons from ^{252}Cf(sf) (compare review of ref.[2]) one finds $T_{sc,1} \approx (1.0 - 1.2)$ MeV and $\bar{\nu}_{sc}/\bar{\nu}_{total} \approx 0.1$.
By a comparison of experimental 90 deg spectra of refs.[3,16] with the CEM calculation, we deduced a second, harder central component characterized by $T_{sc,2} \approx (2.0 - 2.5)$ MeV and $\bar{\nu}_{sc,2}/\bar{\nu}_{total} \approx (0.001 - 0.01)$. The measured high-energy end of the Cf spectrum[18] corresponds to the given result (Fig. 2, 3) However, the differential data of refs.[3,16] were not confirmed by Riehs[17]. It seems to be necessary to measure at least the 90 deg spectrum accurately to draw certain conclusions about the second component of scission neutrons. In ref.[12], we have discussed the hard emission component as a consequence of non-equilibrium effects.

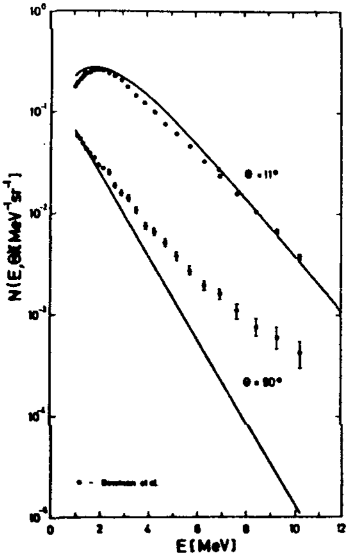


Fig. 2

The calculated A integrated differential energy spectra for Θ = 11 deg and 90 deg in comparison with experimental results 3).

Using the CEM in a complex form it was possible to describe the general features of fission neutron emission. This concerns the integral energy spectrum N(E) (compare Fig. 3) up to about 20 MeV especially. The angular distributions cannot be deduced satisfactorily because of the existence of scission neutrons. It is indicated that this component should be subdivided into two parts of different hardness and yield.

The calculated average c.m.s. emission energies as a function of A contradict to experimental data in the region around 132 considerably. This fact was interpreted as a consequence of the possibly A dependent scission neutron yield (refs.[12,18]).

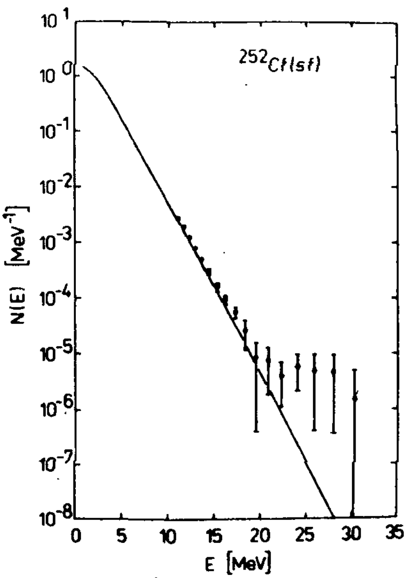


Fig. 3
The Cf-252 fission neutron spectrum calculated in the framework of the complex CEM in comparison with experimental data on its high-energy end 12,18).

3. Estimation of NEDFA emission cross sections

Pik-Pitchak had discussed the appearence NEDFA as a possible "source" of scission neutrons[6]. Obviously, neutron evaporation until about $2 \cdot 10^{-20}$ s after scission modifies the angular distribution of fission neutrons to a certain degree and may simulate the actual scission neutron emission. Samanta et al.[13] have recently published theoretical results on post-scission dynamics. They investigated the dissipation of deformation energy after scission in the case of symmetric fission especially. Wc have combined these results with the treatment of Pik-Pitchak, but in the c.m.s. by a modification of the CEM, and deduced time-dependent emission cross sections which have been transformed into the l.s. using the time-dependent kinetic energy of the fission fragments. The emission probability was deduced on the base of the equilibrium temperature T_{eq} according to the Fermi gas model (T_{eq} amounts to around 1.0 MeV). Fig. 4 represents the NEDFA angular distribution at 1 MeV for selected times t after scission. The average excitation energies at 0.25, 0.5, 1.5 and 2.5 · 10^{-20} sec amount to about 44, 51, 73 and 96 % respectively with reference to the final value. The corresponding relative kinetic energies are 34, 60, 87 and 94 % respectively.

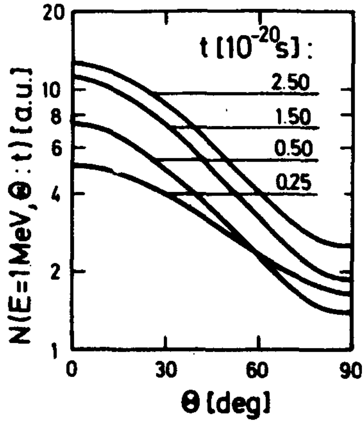


Fig. 4
Estimated NEDFA angular distributions for symmetric fission at E = 1 MeV and selected times (curve parameter) after scission.

Fig. 4 indicates that the shape of the angular distribution varies as a function of t up to about 1 · 10^{-20} s mainly. In this time interval, the neutron yield is at maximum 3 % of $\bar{\nu}_{total}$. Comparing the NEDFA with the final double-differential emission cross sections and considering the other fragment mass splits roughly we found that NEDFA may simulate a central component with a yield not higher than 0.1 % of $\bar{\nu}_{total}$. Higher values of about 10 % were only deduced for a non-realistic value of T_{eq} (about 2 MeV) which, in fact, simulate non-equilibrium. A further analysis for other fragment mass splits seems to be useful.

4. HEN emission in Cf fission

It is expected that neutrons from the decay of ^{5}He nuclei[14] are predominantly directed around the 90 deg (equatorial) plane. Hence, such neutrons may probably influence the angular distribution of ordinary fission neutrons in this angular range. The double-differential emission cross sections of HEN were estimated on the base of the following assumptions and considerations:

i) Isotropic decay of ^{5}He nuclei (about $3 \cdot 10^{-4}$ per fission) in the c.m.s. with a half life of $8 \cdot 10^{-22}$ s[14].

ii) Time-dependent distribution of ^{5}He kinetic energies according to ref.[14].

iii) Angular distribution of ^{5}He emission with reference to the fission axis.

iv) Angular resolution (for the comparison of calculated and measured[14] HEN energy spectra).

The model parameters as far as not known from ref.[14] were fixed by the intercomparison of the calculated and the measured HEN spectrum considering item iv (Fig. 5). Calculated doublo-differential emission probabilities N(E,Θ) (normalized to the yield of HEN) are represented in Fig. 6 as well as in Fig. 7 in comparison with N(E,Θ) calculated in the framework of the CEM.

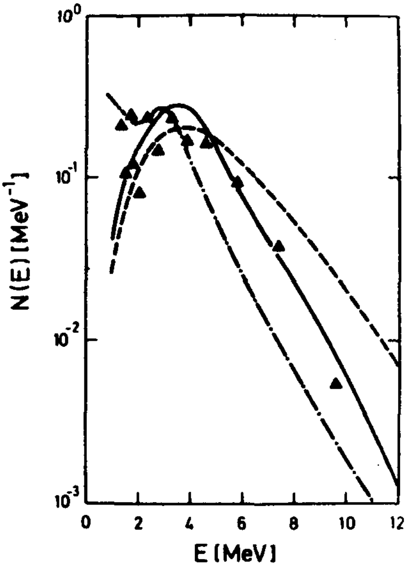


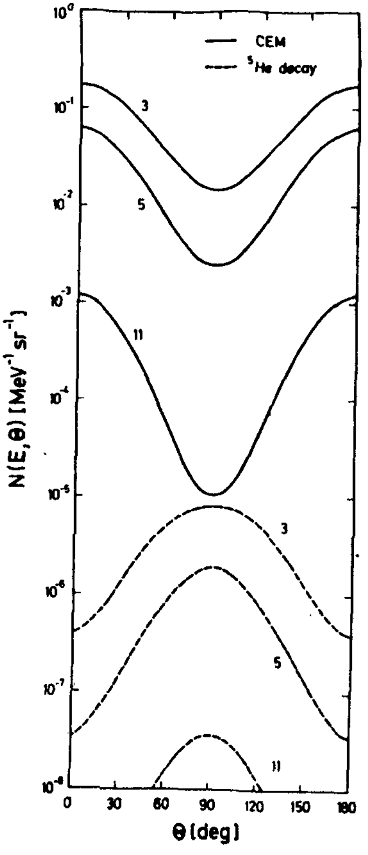
Fig. 5

Calculated HEN energy spectra in comparison with experimental data of Cheifetz et al. 14) (dashed line - calculated spectrum at 0 deg with reference to the He-5 direction, dashed-dotted line - calculated spectrum at 90 deg with reference to the fission axis, continious line - calculated energy spectrum around 90 deg with reference to the fission axis for an angular resolution of 40 deg). All spectra are normalized to the yield of HEN.
The experimental spectrum is not corrected for neutron detection efficiency.

Obviously, the HEN $N(E,\Theta=90deg)$ is lower than 1 % with reference to the CEM. However, it may be possible that this portion is higher in the case of special scission configurations.
The described study shows that scission neutron emission should not be attributed to the low-yield HEN component.
A more detailed analysis, i.e. for specified scission configurations, is not possible up to now.

Fig. 6

Calculated HEN angular distributious for selected emission energies (parameter in MeV).



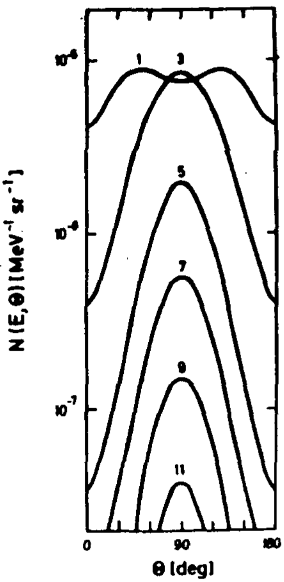


Fig. 7

Comparison of calculated angular distributions of HEN and ordinary fission neutrons (CEM) for selected emission energies (parameter in MeV).

5. Summary. Conclusions

Besides the application of the complex CEM for the analysis of the main mechanism of fission neutron emission, we studied two neutron components which may simulate actual scission neutron emission: NEDFA and HEN. Essential conclusions are summarized in the following items:

i) More detailed experimental and theoretical investigations are necessary to clarify our knowledge about the nature of scission neutron emission. This concerns the measurement of $N(E,\Theta:A_L/A_H,TKE)$ especially, but one should analyse the results carefully regarding data corrections and reference calculations on the base of evaporation models.

ii) According to the presented study, NEDFA is indicated as an appearance of minor importance. To obtain sufficiently high emission probabilities within about $2 \cdot 10^{-20}$ s after scission it is likely that one has to introduce non-equilibrium effects during the energy dissipation process.

iii) In the analysis of the ^5He decay after scission, we reproduced the measured HEN spectrum and estimated the double-differential emission cross section. HEN emission should modify the fission neutron spectrum at 90 deg to in maximum of 1 %.

iv) The problem of single-particle excitations due to the rapid changes of nuclear potential (descent of the fissioning nucleus from saddle to scission point[5,7], transition of strongly deformed fragments into their equilibrium shape[8]) is still a challenge for theoreticians. More detailed measurements may give some clues.

v) It is indicated that scission neutrons should be subdivided into a weak and a hard component with a yield of 10 % and (0.1 - 1) % respectively. This result has to be confirmed by more accurate measurements.

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