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Prompt Neutron Emission in Nuclear Fission

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Abstract: Experimental results obtained in recent fragment-neutron correlation measurements are the basis for a detailed analysis of neutron emission characteristics in conjunction with several statistical-model approaches:

(i) temperature distribution model (applied calculations).

(ii) standard evaporation theory I (Weisskopf-Ewing approach extended by a rough angular momentum correction term),

(iii) standard evaporation theory II (Hauser-Feshbach type calculations including angular momentum effects),

(iv) statistical multistep compound theory (closed-form description including equilibrium as well as non-equilibrium emissions).

All emission models account for an intricate fragment occurrence probability distribution in nucleon numbers, excitation energy, kinetic energy, and (excepting models (i and (iv)) angular momentum. They have been used to predict yields, energy and angular distributions as well as representative c.m.s. spectrum shape parameters in the case of 252-Cf spontaneous fission in order to study the mechanisms of prompt fission neutron emission and several features of statistical emission. Model (iv) describes the development of the fragment compound system as a stochastic process starting at scission point and, hence, considering emission processes during fragment acceleration. The results of all model calculations indicate a clear predominance of the evaporation mechanism. The possible role of secondary mechanisms and difficulties in deducing informations about them are discussed. The present paper gives a review on all four models. Results obtained within standard evaporation theory II (full-scale Hauser-Feshbach calculation) are discussed in more detail.

1. INTRODUCTION

In the eighties, several experimental /1-5/ as well as theoretical /6-14/ investigations resulted in new insights in the mechanism of prompt fission neutron (PFN) emission and further clues for the development of corresponding models. These studies have shown (in contrast to earlier results obtained in the sixties and seventies) that at least 95% of PFN are released due to de-excitation of fragments in a time scale 10^{-20} - 10^{-16} s after scission. Much effort has also been devoted to theoretical models for the prediction of PFN data (multiplicities, energy spectra, angular distributions) for practical applications, since empirical relations do not meet all present requirements in the fission data field. In spite of sophisticated investigations based on experiment in comparison with theory, the role of secondary mechanisms /9/ of PFN emission (scission neutron ejection /13,14,9/, emission during fragment acceleration including non-equilibrium processes /12/, neutron release due to the decay of n unstable nuclei produced in ternary fission /9/) have not yet been clarified in sufficient detail. However, the bulk of experimental data can be understood in the framework of evaporation models adopted to the diversity of fragment configurations. Non-adequate simplifications of PFN evaporation theory have been shown to be the reason for wrong conclusions about PFN emission mechanisms /9/. As a matter of principle, emission models for the description of PFN evaporation from fully accelerated fragments, i.e. asymptotic approximation concerning dissipation of fragment deformation energy as well as equilibration, should include:

(i) consideration of an intricate fragment distribution $P(A,Z,E^*,$ $TKE,J)$ in mass and charge number, excitation energy (asymptotic value), total kinetic energy (asymptotiv value), and angular momentum,

(ii) an evaporation spectrum ansatz in the center-of-mass system (CMS) $\varphi(\varepsilon,\vartheta:A,Z,E^*,J)$, where the dependence on emission energy ε and angle ϑ (due to J) is important,

(iii) a reliable description of neutron transmission coefficients (optical model) and level density of rest nuclei (with account of shell and pairing effects in the whole A scale),

(iv) a procedure to account for cascade evaporation of neutrons in competition to the emission of γ-rays and other particles (as protons),

(v) exact transformation into the laboratory system (LS) based on the actual kinetic energy of the fragment.

This idealized scheme of a statistical model approach (SMA) involves several obvious sources of uncertainties. Together with the experimental ones, they restrict the possibilities to deduce informations about PFN emission mechanisms on the basis of a comparison between SMA calculations and experimental data (in particular, energy and angular distribution $N(E,\theta)$ in LS in correlation to fragment variables). There are further reasons rendering more difficult in solving the puzzle of PFN studies, namely the superposition of all distributions corresponding to the mechanisms mentioned above and the clear predominance of evaporation neutrons over secondary neutrons (which are, of course, of special interest in studying fission dynamics). In particular, the angular distribution of neutrons emitted close to scission point is probably non-isotropic /13,14/ and exhibit some similarities to distributions of PFN evaporated from rapidly moving fragments. Further, the energy and angular distribution of PFN emitted during fragment acceleration is strongly influenced by the time characteristics of dissipation /12/.

Only in the case of "abrupt" dissipation, the emission probability is enhanced in equatorial direction (i.e. θ = 90 deg with reference to fission axis). Therefore, it is not justified to account for scission neutrons as a "central" (i.e. isotropic in LS) component. A limitation of the theoretical analysis to the main evaporation mechanism is far from simplicity. Whereas the statistical model for the description of emission spectra for a given excited-nucleus state is well established (within the uncertainties in describing transmission coefficients and level density), fission theory fails in reproducing the whole fragment distribution $P(A,Z,E^*,TKE,J)$ with sufficient accuracy and completeness. In particular, the overlap of different fission modes may result in rather complicated fragment distributions. Hence, the assumption of simple Gaussian distributions (with averages and widths deduced from experimental data) might be a too strong simplification (cf. ref. /15/).

The present review includes a brief description of several models developed at T.U. Dresden. Some of the earlier results have been published at the other conferences devoted to the fiftieth anniversary of the discovery of nuclear fission. Summarizing some of the conclusions drawn in these works /16,19,20/ we focus on new calculations performed in the framework of a full-scale Hauser-Feshbach model.

2. PFN EMISSION MODELS

2.1. Temperature distribution model /16/

The Madland-Nix Model /6/ is based on the assumption of an idealized temperature distribution P(T) of triangular shape. Its maximum value is related to $\overline{E}^*$. The original model version (MNM) has been applied to a representative fragment pair for the fission reaction studied, i.e. P as a very complex distribution is reduced drastically. The Madland-Nix model has been generalized in ref. /10/ by considering the dependence on mass number. This version (GMNM) requires the description of the fragment energies $\overline{E}^*(A)$ and $\overline{TKE}(A_1/A_2)$ as well as mass yield curves P(A). A scission point model based on semi-empirical. temperature-dependent shell energies and a 5-Gaussian approximation to P(A), respectively, are used for this purpose. As described in ref. /16/, some further refinements have been introduced:

(i) realistic P(T) distribution deduced from an initial $P(E^*)$ distribution with account of cascade emission,

(ii) reliable choice of level density parameter as function of A,

(iii) CMS-LS transformation considering CMS anisotropy as a consequence of fragment spin (semiclassical approach),

(iv) consideration of neutron/γ competition during fragment de-excitation (rough approach via setting a T bias).

The temperature distribution model (code FINESSE) can be used to describe multiplicities, energy and angular distributions of PFN from any fission reaction. In the case of induced fission reactions, the angular distribution of PFN is also calculated with reference to incidence beam direction (DDX). FINESSE is now the basis of PFN data systematics. First results were published in ref. /17/. Note that FINESSE reproduces PFN data in a wide energy range (E = 0 ... 20 MeV).

2.2 Cascade evaporation model (CEM)

Starting with an initial distribution in E^* as function of A and TKE, i.e. $P(E^*:A,TKE)$, and considering $P(Z:A)$ and $P(J:A)$ a complex model for the description of PFN spectra was applied /8/. It is based on the Weisskopf-Ewing ansatz for the prediction of CMS energy spectra at given E^*. The level density is described by considering microscopic effects (shell, pairing). The optical model is used to calculate inverse cross sections of compound-nucleus formation. Cascade evaporation is considered exactly. Based on a semi-classical approach, CMS anisotropy of PFN emission has been involved. Due to the consideration of the full dependence on A and TKE, the CMS-LS transformation can be done exactly. The influence of the input data on PFN energy and angular distributions has been studied carefully /9/ giving an impression about the sensitivity of calculations in regard of input parameter variations. The CEM has succesfully been applied for the interpretation of new experimental $N(E,\theta)$ data /4,5/ for $^{252}Cf(sf)$ in ref. /11/. Due to some further model refinements as

- account for neutron/γ competition on the basis of statistical theory and
- spin correction to the spectrum ansatz /19/

the energy and angular distribution of Cf PFN could be well reproduced. CEM results were considered as a theoretical reference for the Cf standard neutron spectrum /18/. The CEM is also suitable to describe differential distributions und the multiplicity of protons released in Cf fission, whereas the α particle yield is strongly underestimated (showing that they are released in ternary fission) /19,20/.

2.3. Hauser-Feshbach calculation (HFC)

The whole scheme of CEM has recently been modified to account for the Hauser-Feshbach spectrum ansatz in describing $\varphi(\varepsilon:A,\bar{Z}(A),E^*,J)$, i.e.

the dependence of CMS spectrum shape on fragment angular momentum is involved. As in the CEM, the CMS angular dependence is described semi-classically. Applying standard evaporation theory to cascade particle emission by steps i (including γ emission) from a fragment for given initial distribution $P_0(E^*)$, i.e. A, Z, and TKE are fixed, we can describe the CMS spectrum of partcle π as

$$\varphi_\pi(\varepsilon_\pi) = \sum_i \int dE^* \sum_J P_i(E^*,J) \frac{\Gamma_\pi(\varepsilon_\pi,E^*,J)}{\sum_{\pi'} \Gamma^{tot}_{\pi'}(E^*,J) + \Gamma^{tot}_\gamma(E^*,J)}, \quad (1)$$

where

$$\Gamma_\pi(\varepsilon_\pi,E^*,J) = (2\pi\ \rho(E^*,J))^{-1} \sum_{J'} \rho^\pi(U_\pi,J') \sum_{l_\pi,s_\pi} T^\pi_l(\varepsilon_\pi), \quad (2)$$

$$U_\pi = E^* - B_\pi - \varepsilon_\pi, \qquad \vec{J} = \vec{J}' + \vec{l}_\pi + \vec{s}_\pi \quad (3)$$

(Γ - emission width, Γ^{tot} - total decay width, ε_π - CMS emssion energy of particle π, $\rho(E^*,J)$ - nuclear level density, B_π - separation energy, U_π, J' - rest-nucleus excitation energy and angular momentum, respectively, l_π - orbital momentum, s_π - spin of particle π).
Transforming the CMS emission distribution into the LS considering CMS anisotropy one obtaines the LS emission probability $N_\pi(E,\theta:A,Z,TKE)$. The total distribution is given by

$$N_\pi(E,\theta) = \sum_{A,Z} \int dTKE\ N_\pi(E,\theta:A,Z,TKE)\ P(A,Z,TKE). \quad (4)$$

In the calculations performed, the full dependence on Z hasn't yet been considered. However, it has been involved to obtain average nuclear structure data (level density /21/, binding energies) and averaged transmission coefficients (optical model accepting potential given in ref. /22/) for fixed A. The transmission coefficients for γ-ray emission have been calculated as in ref. /23/, where a first Hauser-Feshbach calculation of the $^{252}Cf(sf)$ neutron spectrum (based on an initial $P(E^*,J:A)$ distribution) was presented. Our new results of HFC energy and angular distribution of Cf PFN are represented and discussed below.

2.4. Statistical multistep-compound theory (SMC)

Based on the fundamental ideas of Agassi et al. /24/, Feshbach et al. /25/, and Zhivopistsev et al. /26/, a new statistical multi-step reaction theory including direct (collective as well single-particle) and compound processes has been proposed in ref. /27/. This SMD/SMC model was derived from Green's function formalism /26/ and random matrix physics /24/. The SMC approach involves a closed-form solution of the master equation describing the transitions between the states classified by exciton number n (damping widths) as well as emission processes (escape widths for exciton number changes Δn = 0 and -2). The main sources of the "asymptotic" excitation energy of a fragment are its deformation energy at scission E_{def} as well as a certain part of the excitation energy of the scissioning nucleus E^*_{sc}. Therefore, the master equation is solved for an initial distribution in n consisting of two parts. The first one simulates doorway states of E_{def} dissipation assuming low-order exciton configurations starting with n = 2. The second part accounts for scission point excitation energy for equilibrium $n = \bar{n}$. The weight of both contributions are estimated on the basis of E_{def}/E^*_{sc} ratio obtained within a scission point model /16/. In the framework of this stochastic model, the CMS-LS transformation is approximatively done for each exciton class of given lifetime separately. The corresponding average TKE values are calculated by solving the Coulomb problem with account for pre-scission kinetic energy: It has been shown recently /20/ that the equilibrium approximation of SMC (account for neutron emission from fully accelerated fragments, i.e. first contribution to the initial distribution in n is neglected) is also successful in describing energy and angular distributions of PFN from ^{252}Cf(sf). The calculations were performed for an initial fragment distribution $P(E^*:A)$, $\bar{Z}(A)$, $\overline{TKE}(A_1/A_2)$. The consideration of the non-equilibrium component appearing during fragment acceleration leads to minor changes of the energy spectrum. A significant enhancement of the emission probability is only observed at equatorial direction (θ = 90 deg) and high energy ($E \geq 8$ MeV). The experimental data /1,5/ show a similar trend compared to SMA calculations (CEM, FINESSE, HFC). However, the experimental uncertainties are rather high even in this region as a consequence of the low emission probability.

3. HFC RESULTS

As described in paragraph 2.3, the Hauser-Feshbach approach to neutron emission from highly excited, fully accelerated fragments with account of the diversity of fragment configurations and cascade emission has been used to calculate N(E,θ) and several CMS spectrum parameters of PFN from spontaneous fission of ^{252}Cf. Due to the uncertainties in predicting $\Gamma_{\gamma}(E^{*},J)$, a scaling parameter has been introduced to simulate the lower limit, the most probable value, and the upper limit of the γ-ray emission width (versions 1, 2, and 3, respectively). Only version 2 gives the correct neutron multiplicity of Cf fission neutrons. HFC results are represented in the figures 1 - 4. In general, there is rather good agreement between experiment and theory (in particular, version 2). However, compared to CEM the HFC energy spectrum is "softer" than the experiment leading to an underestimation of the emission probability at high E. Further studies will show if a

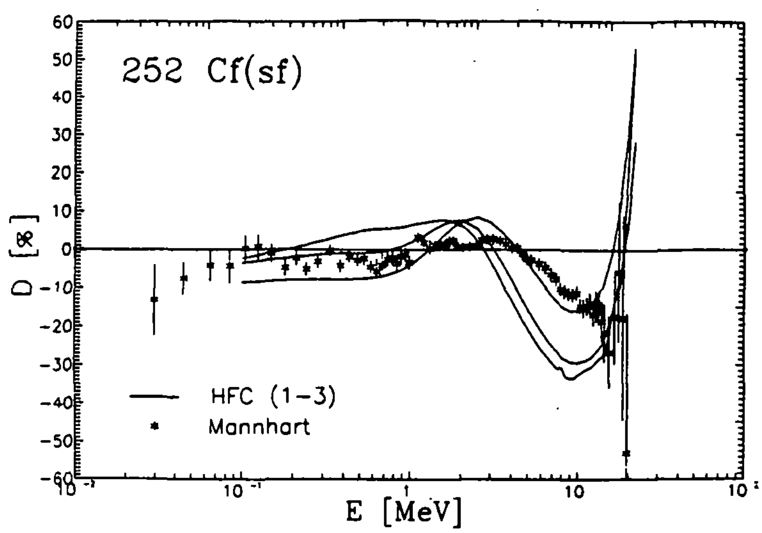

Fig. 1 The energy spectrum of Cf neutrons represented as percentage deviation from a Maxwellian with a 1.42 MeV "temperature" parameter. HFC results for the versions 1 -3 indicating the strength of γ-ray emission are compared with a recent evaluation by Mannhart /18/

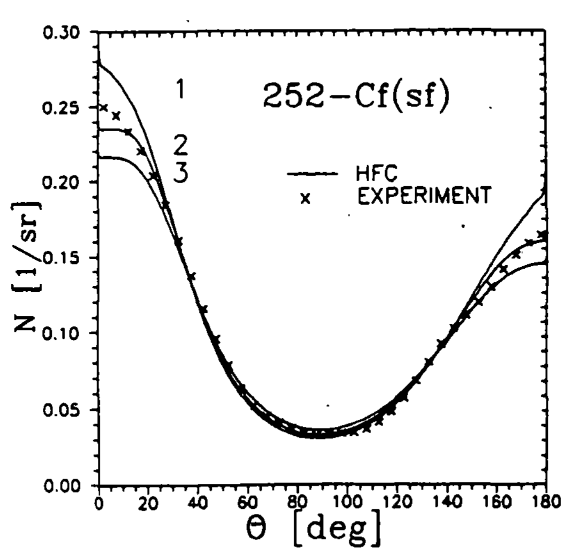

Fig. 2 Total angular distribution of Cf fission neutrons: HFC results in comparison with experimental data /5/

perfect agreement between experimental data and HFC results (including angular distributions) can be obtained for reliable choices of level density description and global optical potential. The present results were obtained on the basis of the Holmqvist potential /22/ which was found to be best in describing N(E,θ) of Cf PFN in the framework of CEM /17/.

Whereas the energy and angular distributions of Cf fission neutrons agree with experiment (version 2), the average CMS emission energy depending on fragment mass number A cannot be reproduced by HFC in the A range 125 - 138. In ref. /8/, this has been interpreted as a possible influence of scission neutrons. Recently, more detailed investigations of the fragment distribution in E^* in the framework of a macroscopic-microscopic scission point model with energy balance consideration /15/ has shown that this effect is due to the appearance of further fission modes causing a more complex $P(E^*:A,TKE)$ distribution than considered in the present HF calculation.

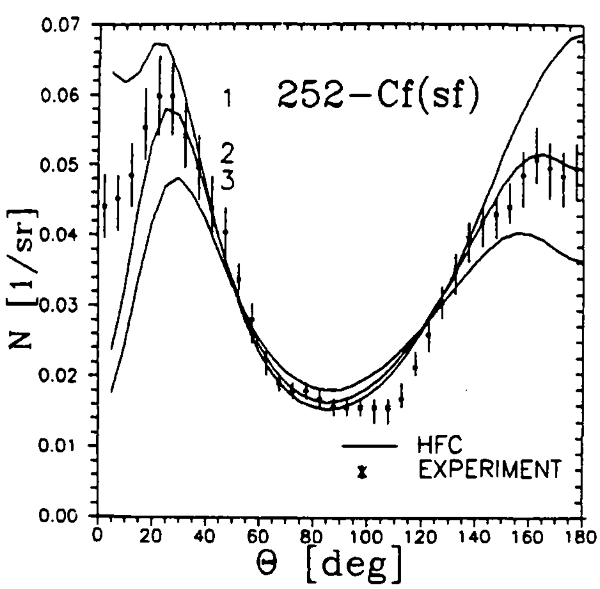

Fig. 3 The angular distribution of Cf neutrons for 1.0 MeV LS energy (experimental data: ref. /5/)

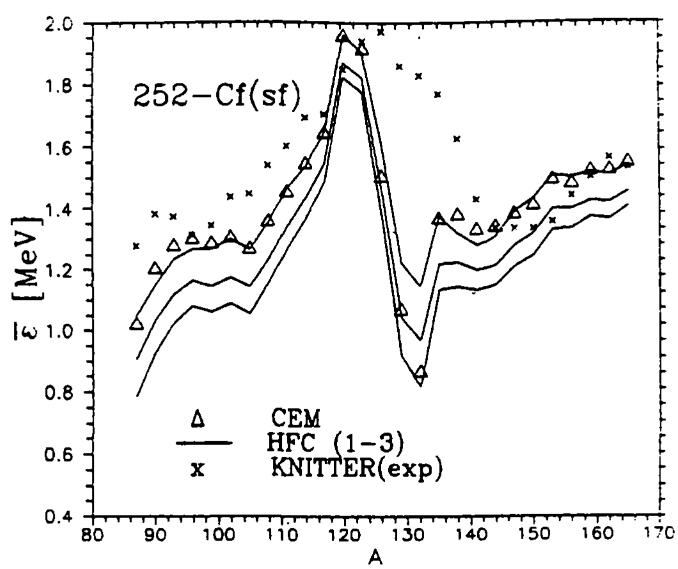

Fig 4 Average CMS PFN energy as function of mass number A (experiment: ref. /1/)

4. SUMMARY

All currently available statistical theories of neutron emission have been adopted to formulate corresponding PFN models. The brief review presented in this paper (concerning CEM, FINESSE, and SMC) as well as new results obtained within a full-scale Hauser-Feshbach calculation have confirmed that all features of neutron emission can be understood in the framework of a SMA (based on the assumption that all PFN are evaporated from fully accelerated fragments). The earlier study of fission neutron emission during fragment acceleration within the CEM

/12/ has been improved by applying a stochastic model describing the dynamics of dissipation adjoint with pre-equilibrium emission processes /20/. There is a weak indication that such a pre-equlibrium component exists really. All recent studies of PFN emission mechanisms /1,2,8,9,19,20/ justify the application of a pure SMA for practical applications /6,10,16/.

The present work has also shown the difficulties in realizing a full-scale SMA because of limited knowledge of the corresponding fragment distribution. The necessity in considering the influence of all fission modes has been pointed out (cf. ref. /15/).

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