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# ON THE POSSIBILITY OF POST-EQUILIBRIUM POLAR PARTICLE EMISSION IN HEAVY-ION INDUCED FUSION-FISSION REACTIONS

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## 1. INTRODUCTION

During the course of a fission process nonadiabatic effects in the coupling of internal and collective degrees of freedom can create nonequilibrated intrinsic states of the system. Due to decay of the system during this stage, emission of nucleons or preformed complex particles (d,t,$\alpha$) can contribute to light-particle yields from fission events. Such post-equilibrium components to multi-differential emission probabilities could exhibit features deviating from what is expected for evaporation from the compound nucleus before fission or from the excited fission fragments.

Two basic mechanisms for the appearance of post-equilibrium particles have been suggested:

i) Fast relaxation of shape degrees of freedom: A sudden collapse of the highly deformed prefragments after scission enables individual particles to acquire sufficient energy from the rapidly changing nuclear potential in the neck region to become unbound[1-4]. Using the simple slab geometry in a recent TDHF simulation of the fission process[3,4], it has been shown that the corresponding time scale might be as small as $10^{-22}$ s. It has been argued that, due to symmetry, the corresponding post-equilibrium particles should be sharply peaked around the fission axis. A similar post-equilibrium component has been obtained in the case of nuclear slab collisions[3] in addition to the well-known pre-equilibrium component.

ii) One-body dissipation : Due to the coupling of a particle to the moving potential wells during the separation and acceleration phases, it can appear in the continuum of the system and be emitted with a corresponding high probability[5]. Such a mechanism has recently been investigated[6] by extending the three-body model for the dynamics of heavy-ion collisions of refs.[7,8] to simulate spontaneous fission in three spatial dimensions. As a result of corresponding model calculations, the fast post-equilibrium particles are preferentially emitted in polar direction (fission axis). Opposite to case i) no drastically small time scales are needed to create fast polar particles.

There are some attempts to relate certain aspects of light charged particle emission in spontaneous and low-energy fission[9-11] or eventual deviations of the high-energy tail of the prompt-neutron spectrum in $^{252}Cf(s.f)$[12] from a Maxwellian to such mechanisms.

There are some qualitative and semiquantitative hints that the appearance of fast post-equilibrium particles could be enhanced in heavy-ion induced fusion-fission (FF) reactions compared to spontaneous fission (Sect.3). In Sect.2, we motivate a schematic proposal for a corresponding experiment.

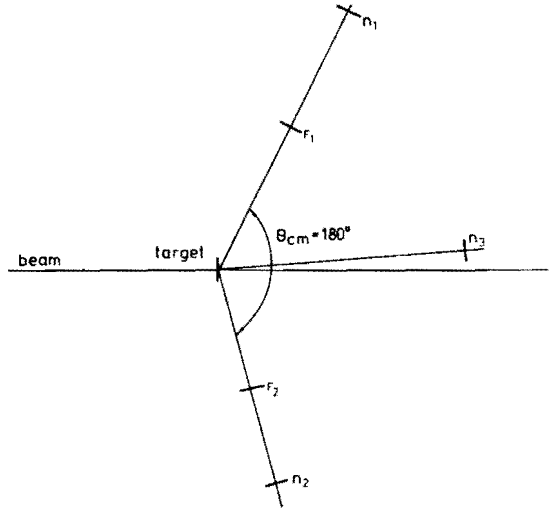
## 2. POST-EQUILIBRIUM POLAR FISSION NEUTRONS FROM THE $^{12}C+^{238}U \rightarrow$ FF REACTION ?

Since most of the existing indications for post-equilibrium fission particles concern spontaneous fission of Californium, it seems to be natural to investigate a reaction in which a Californium compound nucleus is formed. Stimulated by the investigations of ref.[12], we concentrate here on neutron emission although similar investigations would be highly interesting for light charged particles too (cf. ref.[9]). Despite a possibly enhanced emission of polar post-equilibrium neutrons (compared to s.f.), the following aspects require a careful choice of the experimental conditions, say for the $^{12}C + ^{238}U \rightarrow$ FF reaction: Due to the finite excitation energy of the fissioning $^{250}Cf$ nucleus, the neutron evaporation component is expected to be characterized by a higher effective temperature. Consequently the incident energy should be only slightly larger than the corresponding Coulomb barrier $V_c$ ( 64.5 MeV in the given case) in order not to cover the possible (in any case very small) effect by the high-energy



tail of the evaporation spectrum. Furthermore, since in such a type of reactions it is known that fast pre-equilibrium neutrons can be emitted, the incident energy should be small compared to the "threshold energy" for pre-equilibrium neutrons which according to the systematics of ref.[13] is about $(E_{c.m.}-V_c)/\mu \approx 3 \div 5$ MeV/A ( $\mu$ -reduced mass number). Even if this condition is fulfilled, the experimental set-up should allow one to decide whether a possibly obtained nonequilibrium component is post- or pre-equlibrium since the "threshold" for pre-equilibrium neutrons is probably not a sharp one and a very small pre-equilibrium component may be present even in the vicinity of the Coulomb barrier. All estimates and calculations in the present paper, therefore, are given for an incident energy as low as $E_{Lab}$ = 72 MeV (i.e. $(E_{c.m.} - V_c)/\mu$ = 0.394 MeV/A).

At this energy, the grazing angular momentum is as small as 18 $\hbar$ (compared to $L_{crit} \approx 64\hbar$ ). Therefore, the rotation of the system is negligible in our considerations: rotational energy for $L_{graz}$ $E_{rot}$ = 1.24 MeV, excitation energy for a central collision $E^*$ = 44 MeV, compound-nucleus temperature $T_{CN} \approx$ 1.2 MeV.




**F i g.** 1. Scheme of the proposed experimental set-up.

The experimental set-up we propose is schematically shown in Fig.1. Fast neutrons should be measured in coincidence with fission fragments (roughly **perpendicular** to the beam axis). Coincidence neutron spectra should be independently taken at positions $n_3$ (forward angle) as well as $n_1,n_2$ (along the scission axis). Deviations from Maxwellians would indicate pre-equilibrium emission in **detector** $n_3$ but post-equilibrium polar neutrons in detectors $n_1, n_2$ (if fission fragment masses are not determined, the spectra in $n_1$ and $n_2$ should be identical). A fourth neutron detector could be installed perpendicular to the reaction plane for control since it should not see neither pre- nor post-equilibrium neutrons. In any case, comparably large beam times are required for the measurements in order to get at least tens of events in the neutron energy region above 20 MeV. Superpositions of two lower-energy neutrons should be carefully excluded in-line.

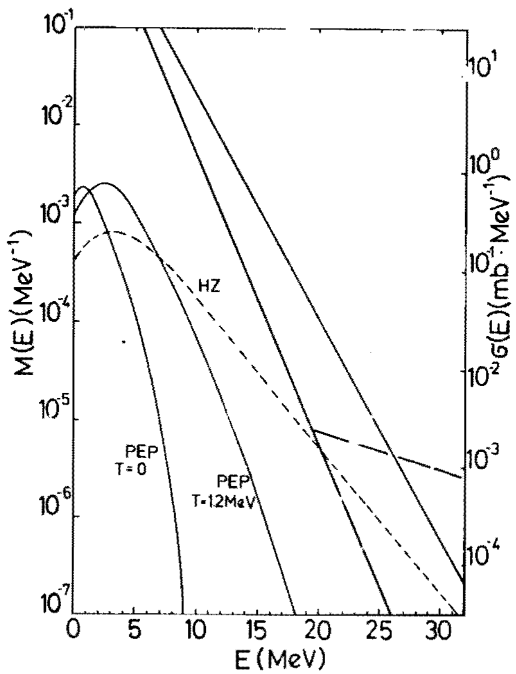



Fig. 2. Differential neutron multiplicities: Evaporation part for $^{252}$Cf (s.f.) -lower heavy full line. The level of the nonevaporative component obtained in /12/ is indicated by the heavy long-dashed line. Estimated evaporation contribution for the $^{12}$C + $^{238}$U, $E_{Lab}$ = 72 MeV reaction (for details, see **the** text) - upper heavy full line. Results of present calculations for the pre-equilibrium contribution: **within** the PEP model - thin full curves, within the **hot-zone** model of ref./14/ - thin dashed curve. The cross section scale to the right corresponds to the $^{12}$C + $^{238}$U reaction with $L_{grazing}$ = 18 $\hbar$ .

To get a more quantitative impression of the different neutron components met or to be expected in such an experiment, some estimates and model calculations for the differential (angle-integrated) neutron multiplicity are shown in Fig.2. To get an impression of the pre-equilibrium component (which would be peaked along the beam axis), we have performed calculations within the model of prompt emitted particles (PEP, for



details and references, see /14/) as well as within the hot-zone model of ref./14/. The result of a PEP-calculation introducing a finite ($T = T_{CN}$ = 1.2 MeV) temperature for the nucleonic momentum distribution is also shown in Fig.2. Despite the classical character (neglect of distortion effects) of the PEP-model the corresponding result probably represents an upper limit of the effect since there is no justification to introduce such a high temperature. Concerning the hot-zone calculation it is known that the model highly overestimates the high-energy part of the neutron spectra at incident energies close to the "threshold" for pre-equilibrium emission. So, although both models at the given very low incident energy, are surely not able to adequately discribe pre-equilibrium emission, by different reasons our calculations may serve as estimates for an upper limit of pre-equilibrium effects. If comparing these estimates with the evaporation components both for (s.f.) as well as for the fusion-fission reaction, it turns out that in the energy region $E_n \gtrsim$ 20 MeV pre-equilibrium effects should be quite small-possibly even smaller than the post-equilibrium component obtained in the case of $^{252}$Cf(s.f.) /12/ which we expect to be somewhat enhanced in the considered reaction. We emphasize, however, that the nonevaporative component obtained in /12/ is connected with quite large statistical errors and therefore, it is still impossible to accurately estimate its true magnitude.

The estimate for the evaporation component in the case of the fusion-fission reaction considered here, we have obtained as follows: From the temperature $T_{s.f.}$ = 1.42 MeV fitting the (s.f.) data up to about $E_n$ = 20 MeV a mean excitation energy of 31.3 MeV per fragment has been deduced. Then, **half** of the L-averaged compound nucleus excitation energy has been added to extract a new effective temperature for heavy-ion-induced first-chance fission: $T_{FF}$ = 1.84 MeV. To **fix** the **normalization** relative to the known (s.f.) spectrum, we have assumed that the total number of evaporated neutrons is proportional to the excitation energy. Finally, the spectrum shown in Fig. 2 has been obtained by adding incoherently 75% of the FF spectrum **and** 25% of the compound nucleus spectrum (T = 1.2 MeV) in accordance with the calculated /15/ $\Gamma_n / (\Gamma_n + \Gamma_f)$ ratio of $^{250}$Cf at several tens of MeV of excitation energy.

Finally, we mention a further way of discriminating pre- and post-equilibrium emission (provided deviations from Maxwellian spectra can be found): From the kinetic energy of the fragments it should be possible to get a rough estimate for the fragment masses. In coincidence with a nonevaporative high-energy component of the neutron spectra, two cases might occur:

i) All of the (probably, very few) fragments belong to asymmetric fission events. This would indicate that a comparably cold nucleus has fissioned. Hence, the fast coincident neutron was pre-equilibrium.

ii) Symmetric and asymmetric fission events are more or less equally frequent ; possibly, symmetric events dominate. This would be an indication for fission of a nucleus with several tens of MeV of excitation energy, i.e. for the coincident fast neutron to be post-equilibrium.

Note that in this connection an evaporated (low-energy) neutron before fission does not change the situation since after this more than 30 MeV excitation energy would still yield a quite small peak-to-valley ratio of the mass distribution (which must not be measured in detail).

Due to the probably very poor statistics in the energy region $E_n \gtrsim 20$ MeV, it might be advantageous to combine this method with the one described above (neutron coincidence spectra in detectors $n_1$, $n_2$, $n_3$).

## 3. SOME MODEL CONSIDERATIONS

In this section we give some arguments and estimates which possibly indicate an enhanced post-equilibrium neutron emission in heavy-ion induced fission compared to (s.f.).

i) In/3,4/ the spectrum of post-equilibrium particles which are due to a fast snatching of the neck stubes near scission has been calculated. In the energy region of interest (20-30 MeV), it turned out that the effect is about two orders of magnitude higher than obtained in the experiment/12/ (cf. Fig.2). Furthermore, it has been found that the effect is very sensitive to the time scale in which the snatching occurs. So, e.g., two-body correlations of the pairing type (not included in/3,4/) could stabilize the shape of the fissioning nucleus in the vicinity of the scission point and, consequently, lower the collective velocities involved. This would directly lead to a drastic reduction of the emission probability of fast post-equilibrium particles. This explanation of the large overestimation of the effect in/12/ seems to be reasonable since in the case of pre-equilibrium particle emission in heavy-ion collisions (where the influence of pairing correlations is expected to be smaller due to the high excitation energies involved) TDHF results obtained in the simple slab-geometry are close to the corresponding realistic TDHF calculations as well as to the experimental data/16/. Also, the time scales for the snatching of the neck stubes are nearly the same in slab collisions and 3-dimensional TDHF calculations (for the corresponding discussion, see refs./3,4/).

Since in the proposed fusion-fission reaction at scission the temperature is larger than 1 MeV, it might occur that post-equilibrium effects are much more pronounced than in the case of spontaneous fission due to the decreased influence of pairing correlations. Unfortunately, for such a mechanism there is no quantitative calculation (TDHFB-simulation of the fission process).

ii) More quantitative predictions are possible in the framework of the model of ref./6/ (one-body dissipation mechanism). In that model neutron emission in fission is treated by solving the time-dependent Schrödinger equation for a single nucleon in a mean field approximated by two one-term separable potentials, which initially have some overlap but then follow a given classical fission trajectory. In the initial state the neutron is bound in a two-centre state with a certain energy $E_B$. Numerical calculations give the following results/6/:

- The total emission probability is a few percent, nearly independent of the mass asymmetry of the fragments.

- The average energy of the emitted particles is in the range of a few MeV with high-energetic particles of about 20 MeV being decreased by a factor of $10^5$–$10^6$. The emission spectrum is hardened with increasing mass asymmetry.

- The particle emission along the direction of the light fragment is favoured by about one order of magnitude compared to the flight direction of the heavy fragment if high-energetic particles are concerned.

In order to investigate the possible dependence of the emission probability on the excitation energy, the influence of the initial bound-state energy $E_B$ of the neutron has been studied. This quantity has been varied between 8 and 1 MeV. In this range the total emission probability increases from 1% to 4% independently of the mass asymmetry $X = A_1/A_2$. The differential cross section $d\sigma/dE_n$ has been calculated for three neutron energies: $E_n$ = 5,15,25 MeV. In the table results are presented in ratio to $d\sigma/dE_n$ for the emission from a single state bound at $E_B$ = 8 MeV for various cases.

Table

| case \ En | | 5 MeV | 15 MeV | 25 MeV |
|---|---|---|---|---|
| a) | $X = \frac{126}{126}$ | 2.6 | 4.1 | 44.0 |
| | $X = \frac{110}{142}$ | 2.5 | 4.6 | 48.0 |
| b) | | 1.3 | 1.3 | 3.0 |
| c) | | 2.0 | 2.7 | 16.0 |

a) Emission from a single state at $E_B$ = 1 MeV for symmetric (X = 126/126) and asymmetric (X = 110/142) fission.

b) Total emission spectrum is computed as the incoherent sum of contributions resulting from emission from partially occupied s.p. states between $E_B$ = 8 MeV and 1 MeV; the occupation probabilities following a Fermi distribution with T = 1.2 MeV.

c) The same as b) but with equal occupation probabilities.



From these data, one can conclude that in the present model the emission of post-equilibrium particles should be enhanced in heavy-ion induced fission compared to spontaneous fission. This enhancement is most pronounced in the high-energy tail of the spectrum.

In conclusion, we state that there seems to be a chance to obtain fast post-equilibrium polar particles in heavy-ion induced reactions of the fusion-fission type, although the expected effect is still very small and its investigation requires quite a large beam time and a high precision in the registration and handling of the data.

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О возможности испускания полярных неравновесных частиц с тяжелыми ионами типа слияния-деления

Предлагается поиск быстрых полярных неравновесных частиц в процессе индуцированного тяжелыми ионами деления при начальных энергиях чуть выше кулоновского барьера. Обсуждаются возможная схема постановки эксперимента, а также два независимых метода дискриминации неравновесных компонент, возникших до и после формирования составного ядра. Некоторые модельные оценки указывают на возможное усиление эффекта в индуцированном делении по сравнению со спонтанным делением.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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On the Possibility of Post-Equilibrium Polar Particle Emission in Heavy-Ion Induced Fusion-Fission Reactions

We propose to search for fast polar post-equilibrium particles in heavy-ion induced fission at incedent energies slyghtly adove the Coulomb barrier. A possible schematic experimental set-up and two independent methods to discriminate pre- and post-equilibtium components are discussed. Some model estumates seem to indicate that the effect might be enhanced in heavy-ion induced fission compared to spontaneous fission.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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