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Why not: Prompt Fission Neutrons are Released at Scission

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Abstract

The main properties of the neutrons released during the neck rupture and emitted immediately thereafter are calculated for ^{236}U in the frame of a dynamical scission model. These properties are: the angular distribution with respect to the fission axis (calculated on spheres of radii R=30 and 40 fm and at time $T = 4\times10^{-21}$ sec), the distribution of the average energies of neutrons emitted from each state (calculated for durations of the neck rupture $\Delta T = 1$ and 2×10^{-22} sec) and the total neutron multiplicity (calculated for two values of the minimum neck-radius r_{min}=1.6 and 1.9 fm). They are compared with measurements of prompt fission neutrons during $^{235}U(n_{th}, f)$. The experimental trends are well reproduced, i.e., the focussing of the neutrons along the fission axis, the preference of emission from the light fragment, the range, slope and average value of the neutron energy-spectrum and the average total neutron multiplicity. The neutron emission during a non-adiabatic scission process is therefore a viable alternative to the evaporation (from fully accelerated fragments) hypothesis.

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The main characteristics of the prompt fission neutrons (PFN) (an emission along the fission axis and an exponential decreasing energy spectrum [Frazer (1952)]) led to the first guess about their origin: they are evaporated by the fission fragments when these fragments are fully accelerated. As a result, we observe a kinematic anisotropy in the laboratory system that originates from an isotropic center of mass (c.m.) emission, the exponential spectrum simply reflecting the fragments' temperature.

The emission is therefore supposed to occur long after the division of the fissioning system into two fragments: it takes $\approx 10^{-20}$ sec to reach 90% of TKE and $\approx 10^{-18}$ sec to evaporate a neutron if the temperature is $\approx$ 1 MeV. Comparing to a typical nuclear (Fermi energy) time-scale ($\approx 10^{-22}$ sec) these are long times. One may expect another type of emission to occur before. Moreover, deviations from a standard evaporation spectrum [Madland and Nix (1982), Litaize and Serot (2010), Talou et al. (2011)] or from an isotropic emission in the c.m. [Skarsvag and

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Bergheim (1963), Vorobyev et al. (2010)] have been constantly detected. In spite of this, the evaporation hypothesis has never been questioned, its simplicity prevailing any counter argument.

The possibility of an earlier (e.g., around scission) neutron emission of a different origin, that could likewise explain the observed PFN characteristics, was never brought up. However the existence of scission neutrons (SN) was not ignored [Petrov (2005)] but they were usually invoked only to explain the deviations (in certain energy or angular domains) from the predictions of the evaporation theory. Such a procedure led obviously to the conclusion that SN represent a small fraction of PFN.

The most accepted mechanism for SN emission is the nonadiabatic coupling between the neutron degree of freedom and the rapidly changing neutron-nucleus potential during the scission process (neck rupture at finite radius r_{min} and absorption of the neck stubs by the fragments) [Fuller (1962), Halpern (1964)]. This idea was recently developed quantitatively in the frame of a quantum-mechanical microscopic model. At the beginning the sudden approximation was used ([Carjan et al. (2007), Carjan and Rizea (2010), Carjan, Hambsch et al. (2012)]) assuming the scission process to happen infinitely fast (ΔT=0). Then the time dependence was introduced through the time-dependent Schrödinger equation with time-dependent potential. This allows a short but finite transition time ($\Delta T \neq 0$) to be considered [Carjan and Rizea (2012), Rizea and Carjan (2013)]. Realistic values for ΔT are around 10^{-22} sec. The neutrons present in the fissioning nucleus just before scission evolve in time and quickly find themselves in a postscission potential. They are described by wave packets with some components in the continuum. For $\Delta T \geq 6 \times 10^{-22}$ the adiabatic limit is reached and SN are no more emitted [Carjan and Rizea (2012)].

In this paper we use these unbound parts of the neutron wave packets in order to estimate, for ^{236}U, the angular distribution of the SN with respect to the fission axis, the distribution of the SN average energies and the total SN multiplicity. These estimates are compared with PFN data collected in the thermal-neutron induced fission of ^{235}U.

In our calculations the nuclear shapes just-before scission (two fragments connected by a thin neck) and immediately-after scission (two separated fragments) are described by Cassini ovals [Stavinsky et al. (1968)] with only one deformation parameter: $\alpha_i = 0.985$ (having $r_{min} = 1.6$ fm) and $\alpha_f = 1.001$ (having $d_{min} = 0.6$ fm) respectively. d_{min} is the distance between the surfaces of the two fragments along the z-axes. It is known that these ovals are very close to the conditional equilibrium shapes, obtained by minimization of the deformation energy at fixed value of the distance between the centers of mass of the future fragments [Strutinsky et al. (1963), Seregin (1992)]. To include asymmetric fission it is necessary to introduce a deviation from these ovals defined by a second parameter α_1 [Pashkevich (1971)]. It turns out that r_{min} and d_{min} are almost independent of α_1. The chosen value of the minimum neck radius (1.6 fm) is slightly lower than predicted by the optimal scission shapes [Ivanyuk and Pomorski (2009)]. One can also deduce an approximate neck radius by general considerations like the size of the alpha particle. These theoretical estimates are $\approx$ 2 fm. Our choice (1.6 fm) goes back to the first calculation of SN multiplicity ν_{sc} using the sudden approximation [Carjan et al. (2007)]. We found that using r_{min}=1.9 fm leads to a too large value of ν_{sc}, close to the total number of PFN detected. This result was in contradiction with the general point of view (that we shared at that time) that SN represents a small fraction of PFN. We therefore took a lower value and kept it.

Let us consider the neutron wave functions after scission (i.e. at $t = \Delta T$) $\hat{\Psi}^i(\Delta T)$, that correspond at $t = 0$ to the eigenstates $\hat{\Psi}^i$ that are occupied in the initial configuration α_i. Their distribution over the eigenstates of the α_f configuration is given by

$$a_{if} = \langle \hat{\Psi}^i(\Delta T) | \hat{\Psi}^f \rangle. \quad (1)$$

Convention: a wave function that doesn't show a t-dependence is an eigenstate i.e., a solution of the stationary equation. All wave functions have an implicit dependence on the cylindical coordinates (ρ, z). a_{if} is $\neq 0$ only if $|\hat{\Psi}^i\rangle$ and $|\hat{\Psi}^f\rangle$ have the same projection Ω of the total angular momentum along the symmetry axis.

$f^i = |\hat{\Psi}^i_{em}(t)\rangle$, the emitted part of $|\hat{\Psi}^i(t)\rangle$, is given by the contribution of the unbound states to the wave packet:

$$|\hat{\Psi}^i_{em}(t)\rangle = |\hat{\Psi}^i(t)\rangle - \sum_{bound\ states} a_{if} |\hat{\Psi}^f\rangle$$

The corresponding current density weighted by the occupation probability v_i^2 of the respective state i:

$$\bar{D}_{em}(\rho, z) = \frac{i\hbar}{\mu} \sum_i v_i^2 (f^i \bar{\nabla} f^{i*} - f^{i*} \bar{\nabla} f^i), \quad (2)$$