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Physics Procedia 64 (2015) 19 – 27

Physics
Procedia

Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3

Inclusion of angular momentum in `FREYA`

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Abstract

The event-by-event fission model `FREYA` generates large samples of complete fission events from which any observable can extracted, including fluctuations of the observables and the correlations between them. We describe here how FREYA was recently refined to include angular momentum throughout. Subsequently we present some recent results for both neutron and photon observables.

Peer-review under responsibility of the European Commission, Joint Research Centre – Institute for Reference Materials and Measurements

Keywords: Fission modeling; prompt neutrons; prompt photons; angular momentum; fluctuations; correlations; Monte Carlo simulation.

1. Introduction

`FREYA` (Fission Reaction Event Yield Algorithm) was developed to produce large samples of complete fission events from which any desired fission observable can subsequently be extracted [Randrup and Vogt (2009)]. Each fission event is characterized by full information about the two product nuclei and the emitted neturons and photons:

$A_{\rm L},\ Z_{\rm L},\ \boldsymbol{P}_{\rm L},\ \boldsymbol{S}_{\rm L}$: mass & charge number and linear & angular momentum of the light product nucleus, (1)
$A_{\rm H},\ Z_{\rm H},\ \boldsymbol{P}_{\rm H},\ \boldsymbol{S}_{\rm H}$: mass & charge number and linear & angular momentum of the heavy product nucleus, (2)
$\boldsymbol{p}_n,\ n=1,\dots,\nu$: momenta of the ν neutrons, (3)
$\boldsymbol{q}_m,\ m=1,\dots,N_\gamma$: momenta of the N_γ photons. (4)

It is straightforward to obtain any observable, including fluctuations and correlations, and detection cuts and acceptances can readily be incorporated. Furthermore, because the event generation is very fast, it is practical to incorporate `FREYA` into existing transport codes.

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Peer-review under responsibility of the European Commission, Joint Research Centre – Institute for Reference Materials and Measurements
doi:10.1016/j.phpro.2015.04.003

2. FREYA without angular momentum

To facilitate the later discussion, we first describe how FREYA works without consideration of angular momentum. More complete descriptions have been given by Randrup and Vogt (2009); Vogt *et al.* (2009, 2011, 2012); Vogt and Randrup (2013); Randrup and Vogt (2014).

The excitation energy of the initial fissionable nucleus is determined from the energy of the incoming neutron, or specified explicitly (as is useful when addressing photon-induced fission leading to excitations below the neutron separation energy). Sequential pre-fission evaporation is considered in competition with fission according to a simple model for $\Gamma_{\rm n}/\Gamma_{\rm f}$ [Vogt *et al.* (2012)].

Once the mass number A_0, charge number Z_0, and excitation energy E_0 of the fissioning nucleus have been determined, the first task is to select the mass partition, *i.e.* the mass numbers of the two primary fission fragments, $A_{\rm L}$ and $A_{\rm H}$. This is done by sampling one of them from a specified mass distribution based on experimental data and then obtaining the other one by baryon number conservation, $A_{\rm L} + A_{\rm H} = A_0$. Subsequently, the fragment charge numbers $Z_{\rm L}$ and $Z_{\rm H}$ are obtained by sampling one of them from a distribution of the form $P(Z_i; A_i) \sim \exp(-(Z_i - \overline{Z}_i)^2/2\sigma_Z^2)$ with $\overline{Z}_i = (Z_0/A_0)A_i$, as suggested by experiment [Reisdorf *et al.* (1971); Lemaire *et al.* (2005)] and then getting the other one by charge conservation, $Z_{\rm L} + Z_{\rm H} = Z_0$.

The fragments are emitted back-to-back in the frame of the fissioning nucleus and their total kinetic energy TKE is determined in several steps. For the given mass split, the average value of the total kinetic energy is taken as $\overline{\rm TKE}(A_f) = {\rm TKE}_{\rm exp}(A_f) - d{\rm TKE}(E_0)$, where the (relatively small) shift away from the data is adjusted so that the resulting overall mean neutron multiplicity $\bar{\nu}$ matches the experimental value at the given energy E_0. The mean total fragment energy of the two fragments, $\overline{E}^*$, then follows from energy conservation,

$$\overline{E}^* = \overline{E}^*_{\rm L} + \overline{E}^*_{\rm H} = Q_{\rm LH} + E_0 - \overline{\rm TKE} \,. \tag{5}$$

Here $Q_{\rm LH} = M(A_0, Z_0) - M(A_{\rm L}, Z_{\rm L}) - M(A_{\rm H}, Z_{\rm H})$ is the Q-value for the particular mass-charge split. In thermal equilibrium the mean excitations of the individual fragments are in proportion to their respective heat capacities, which, in the simple Fermi-gas model, in turn are proportional to the level-density parameters $a_i = A_i/e_0$, where $e_0 \approx 10\,{\rm MeV}$ is taken as a somewhat adjustable parameter. The corresponding common temperature T is given by $\overline{E}^* = (a_{\rm L} + a_{\rm H})T^2$. But because the light fragment tends to acquire more than its “fair share” of the excitation, we adjust these averages by means of the adjustable parameter x, taking the individual fragment excitations to be

$$\overline{E}^*_{\rm L} = x\,\frac{a_{\rm L}}{a_{\rm L} + a_{\rm H}}\,\overline{E}^*,\;\; \overline{E}^*_{\rm H} = \overline{E}^* - \overline{E}^*_{\rm L} \,. \tag{6}$$

Subsequently we sample the fluctuations in excitation, $\delta E^*_{\rm L}$ and $\delta E^*_{\rm H}$, using that the equilibrium variance in E^*_i is given by $\sigma^2(E^*_i) = 2\overline{E}^*_i T$ and we thus obtain the actual fragment excitations as $E^*_i = \overline{E}^*_i + \delta E^*_i$. The total kinetic energy is then adjusted correspondingly,

$$\mathrm{TKE} = \overline{\rm TKE} - \delta E^*_{\rm L} - \delta E^*_{\rm H} \,. \tag{7}$$

The direction of the relative fragment motion is sampled isotropically and the individual fragment momenta $\boldsymbol{P}_{\rm L}$ and $\boldsymbol{P}_{\rm H}$ then follow by energy and momentum conservation.

The fully accelerated fragments undergo sequential neutron evaporation as long as it is energetically possible and the resulting product nuclei subsequently dispose of their excitation by sequential emission of photons. At each step for both processes, the maximum possible temperature in the daughter nucleus is calculated, $T_{\rm max}$, and the kinetic energy of the ejectile is then sampled from a simple black-body spectral profile. The non-relativistic form is used for neutrons while the ultra-relativistic form is used for photons,

$$dN_{\rm n}/d\epsilon_{\rm n} \sim \epsilon_{\rm n} \exp(-\epsilon_{\rm n}/T_{\rm max}) \,,\;\; dN_\gamma/d\epsilon_\gamma \sim \epsilon_\gamma^2 \exp(-\epsilon_\gamma/T_{\rm max}) \,, \tag{8}$$

where the kinetic energies are $\epsilon_n = |\boldsymbol{p}_n|^2/2m$ for the ν neutrons and $\epsilon_m = |\boldsymbol{q}_m|$ for the N_γ photons. All ejectiles are emitted isotropically in the respective emitter frame and the nuclear momentum recoils are taken into account after each individual emission.

It is possible to generate one million complete fission events in about ten seconds on a standard laptop computer.