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Neutron-induced Fission

F. Gönnenwein, Univ. Tübingen, Germany

THE FISSION PROCESS

Discovery of fission

In fission a heavy nucleus decays into two fragments of comparable mass. Most studies were performed for actinide nuclei bombarded by neutrons, protons, heavy ions or gammas. The decay of nuclei by fission was discovered in reactions induced by neutrons in uranium.

How nuclear fission is coming about

The pioneers of fission were O. Hahn (experiment, Dec. 1938), L Meitner (interpretation), Jan 1939), N. Bohr and J.A. Wheeler (theory, June 1939). The seminal Bohr-Wheeler theory is up to nowadays the basis for understanding the process. In the frame of the Liquid Drop Model it is argued that any excitation energy may be converted into deformation energy of the nucleus as a whole. For small deformations the energy of stable nuclei increases with deformation. However, at a critical deformation, the “saddle point”, the energy no longer increases but instead decreases. Beyond the critical deformation the long-range repelling Coulomb forces overcome the short-range attractive nuclear forces and the nucleus breaks into pieces.

Neutron-induced fission

By far the best studied nuclear reaction is fission induced by neutrons. The reasons for that are manifold. First, most of the basic properties of fission have been scrutinized and discovered in (n,f) reactions. Second, the energy set free in fission is transformed in power plants producing electricity on a large-scale. Third, the economic impact of this source of energy is enormous.

Cross sections of (n,f) reaction in U-isotopes

Fission cross sections in (n,f) reactions are vastly different for odd and even U-isotopes. For odd isotopes $B_n > B_f$ and σ_{fi} is huge (“fissile” ^{235}U) while for even isotopes $B_n < B_f$ and σ_{fi} is negligibly small (“fertile” ^{238}U). Most reactors therefore require fuel enriched in ^{235}U.

PROPERTIES OF FISSION FRAGMENTS

Mass and charge distributions

A salient feature in fission of actinides at low excitation energies is the asymmetric division of mass. For example in fission of uranium the most probable mass split is for a light fragment with mass $A \approx 100$ and a heavy fragment with $A \approx 140$. Only at higher excitation the symmetric split is catching up. The phenomenon is traced to the extra stability of the magic ^{132}Sn cluster favoring asymmetric nuclear shapes already at the saddle point.

The distributions of nuclear charges Z of fragments follow closely the mass. However, the Z-distributions exhibit a pronounced even-odd staggering with the yields for even Z-nuclei being enhanced compared to odd Z-yields. The e-o effect is understood as a reminiscence of the cold fully paired superfluid nucleus at the saddle point. In the evaluation of the effect the intrinsic excitation energy already present at scission is derived.

Energy distributions

By far most of the energy Q set free in fission goes into the kinetic energy of fragments. An example: for $^{235}U(n_{th},f)$ the average Q-value is $\langle Q \rangle = 195.3$ MeV, while the average total kinetic energy release is $\langle TKE \rangle \approx 170.5$ MeV. Since Q is feeding both, total kinetic TKE and total excitation energy TXE, the average TXE in fission of ^{235}U is $\langle TXE \rangle = 24.8$ MeV.

Neutrons and gammas from fission

The sizable excitation energy of fragments is exhausted by neutrons and gammas. Average multiplicities for $^{235}U(n,f)$ are $\nu = 2.43$ for neutrons and $M_\gamma \approx 7.0$ for gammas. Neutrons are emitted within $4 \cdot 10^{-14}$ s while emission times for gammas can be several μs. A characteristic feature is the saw-tooth shape of the plot for multiplicity vs. fragment mass. Neutron energy spectra are well described by a Maxwellian with average energy $\langle E_n \rangle \approx 2$ MeV while gamma spectra follow an exponential decrease with average energy $\langle \varepsilon_\gamma \rangle \approx 1$ MeV.

Note that the neutrons produced in the process of fission allow for chain reactions as exploited in nuclear power plants