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Fusion–fission is a new reaction mechanism to produce exotic radioactive beams

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Abstract

Pioneering in-flight fission experiments at GSI intensively explored neutron-rich isotopes with $Z = 28$–60. Elements with $Z > 60$ were weakly produced in these experiments. The alternative technique to produce these nuclei, fusion–fission reactions with heavy targets in normal kinematics, suffers from difficulties with fragment extraction from the target and their identification. In-flight fusion–fission could be a useful production method to enable a large number of experiments aimed to identify new neutron-rich isotopes and study their properties. In particular, the study of the beta decay properties of fission products and their lifetimes is of central importance to numerous applications in nuclear physics and related disciplines, such as astrophysics, particle physics and nuclear engineering. A fast analytical fusion–fission model has been developed in the `LISE++` framework to estimate the expected yields in in-flight fusion–fission experiments.
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1. The `LISE++` code

The program `LISE++`[1,2] is designed to predict intensities and purities for the planning of future experiments using radioactive beams with in-flight separators, as well as for tuning experiments where the results can be quickly compared to on-line data. Fast analytical calculations of fragment yield and transmission allow to quickly estimate expected fragment rates and purities comparing with Monte Carlo methods. The transport integral theory [3] is used for the estimation of the temporary evolution of distributions in the phase space. Recently, Monte Carlo methods have been developed as additional option in the code to calculate the production of fragments and their transmission. The program operates under the MS Windows environment, provides a highly user-friendly interface, and already includes configuration files for most of the existing fragment and recoil separators. Projectile fragmentation, fusion–evaporation, Coulomb fission, and abrasion–fission reactions, including the new reaction mechanism fusion–fission are modeled in this program and can be used as the production reaction mechanism to simulate experiments at beam energies above the Coulomb barrier.

2. The analytical fusion–fission reaction model

It is possible to distinguish the following principal directions in the development of the reaction mechanism in the `LISE++` framework:

- Production cross-section of fragments.
- Kinematics of reaction products.
- Spectrometer tuning to the fragment of interest optimized on maximal yield (or on good purification).

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A new model for fast calculations of fusion–fission fragment cross sections has been developed in `LISE++` based on previous `LISE++` analytical solutions: fusion–evaporation and fission fragment production models.

2.1. The fusion–evaporation model

The fusion–evaporation model `LisFus`[4] for fast analytical calculations of fusion residues cross sections is based on the Bass fusion cross-section algorithm [5], and the `LISE` evaporation cascade. The evaporation stage is treated in a macroscopic way on the basis of a master equation which leads to a diffusion equations as proposed by Campi and Hüfner [6], and reexamined lately by Gaimard and Schmidt [7] using level densities and decay widths from the statistical analysis of Iljinov et al. [8]. The `LISE` evaporation model works with probability distributions as function of excitation energy taking into account eight possible parent and daughter channels (n, 2n, p, 2p, d, t, ^{3}He, α), as well as including fission and breakup de-excitation channels, where the "break-up" channel is a simultaneous decay of a highly excited nucleus into many fragments when the nuclear temperature of the fragment exceeds the limiting temperature [9,10]. The fission width is calculated according to the article [8]. The influence of dissipation on the fission process [11] has been taken into account. Analytical solution of evaporation cascade was performed with the transport integral theory [3]. The main advantage of the `LISE` evaporation model is speed. Only such type of fast calculations is suitable for the low production nuclei. A disadvantage of this model is the fact that the code does not take into account the angular momentum of an excited nucleus.

2.2. The fission model

The fission fragment production model is the key to all fission reactions implemented in the `LISE++` code. Input parameters of this model are a fissile nucleus (A, Z), the fission channel cross section (σ_{fis}), excitation energy (E^*) as well as kinetic energy of the fissile nucleus which is used for fission fragment kinematics calculation to estimate transmission through a spectrometer.

Firstly, the code calculates an initial fission cross-section matrix of cross-sections of excited fragments using the semi-empirical model of Benlliure et al. [12]. This model has some similarities with previously published approaches [13,14], but in contrast to those, this model describes the fission properties of a large number of fissile nuclei at a wide range of excitation energies. The macroscopic part of the potential energy at the fission barrier as a function of the mass-asymmetry degree of freedom has been taken from experiment [14]. The code also takes into account unbound nuclei for this stage of the calculations.

The final stage is the post-scission nucleon emission. The use of the `LISE` evaporation model to define the number of post-scission nucleons is a big advantage of the program that allows one to observe shell effects in the *TKE* distribution, and enables the user to make a fast and qualitative estimate of the final fission fragment yield.

Two different methods for fission fragment kinematics are available in the `LISE++` code:

- The distribution method is the fast analytical method applied to calculate the fragment transmission through all optical blocks of the spectrometer.
- The Monte Carlo method for a qualitative analysis of fission fragment kinematics.

For more details of fission modes and the kinematic models see `LISE++` documentation [15,16].

Comparison between LISE calculations and experimental data [17] for the fusion–fission channel in the reaction ^{12}C + ^{238}U is shown in Fig. 1. The total fusion–fission cross sections are in excellent agreement with the simulation. But for simplicity of the calculations the code considers only fission of the compound nucleus and does not take into account sequential fission. As seen from the figure, this difference is not crucial for given case, and cross sections could be normalized manually.

3. Fusion–fission reactions with the ^{238}U beam on light targets

What happens to fusion–fission reactions when the primary beam properties are being kept constant and the target mass is increased? Then compound nucleus mass, energy in center-of-mass and compound excitation energy increase as well (see Table 1). But the probability of quasi-fission increases also, and quasi-fission becomes dominant under complete fusion later on with the target mass increase. This can be concluded from measurements

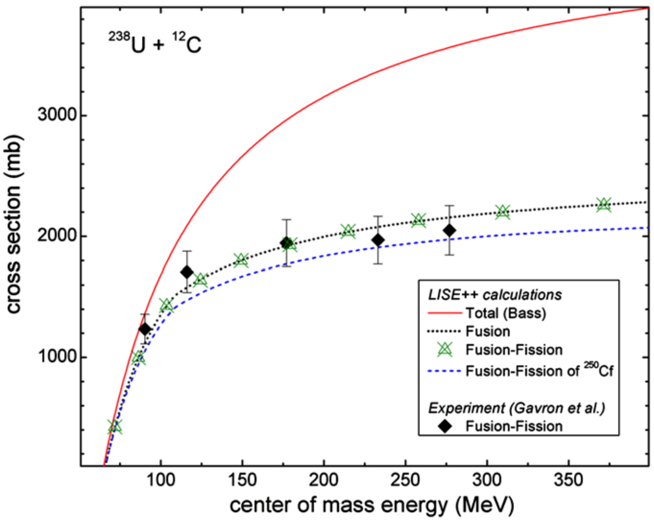

Fig. 1. Calculated total, fusion, fission, and experimental [17] fission cross sections for the reaction ^{12}C + ^{238}U as a function of center-of-mass energy.

Table 1
Fusion–fission reactions with the ^{238}U beam at energy 20 MeV/u, where $\sigma_{ff}^{\text{diss}}$ and σ_{ff}^{no} are first-chance-fission channels calculated by `LISE++` with and without taking into account dissipative effects

Target	E_{cm} (MeV)	B_{fus} (MeV)	E^* (MeV)	σ_{fus} (b)	$\sigma_{ff}^{\text{diss}}$ (b)	σ_{ff}^{no}(b)
^{1}H	20	26	25.4	3.4e–5	2.5e–5	2.8e–5
^{2}H	40	12.5	48.1	1.33	1.06	1.13
^{7}Li	136	33.0	137	2.05	1.73	1.86
^{9}Be	173	43.4	167	2.09	1.93	2.00
^{12}C	228	64.5	205	2.07	1.94	2.00
^{16}O	300	84.6	261	2.15	1.98	2.08
^{27}Al	485	133	404	2.40	2.31	2.36

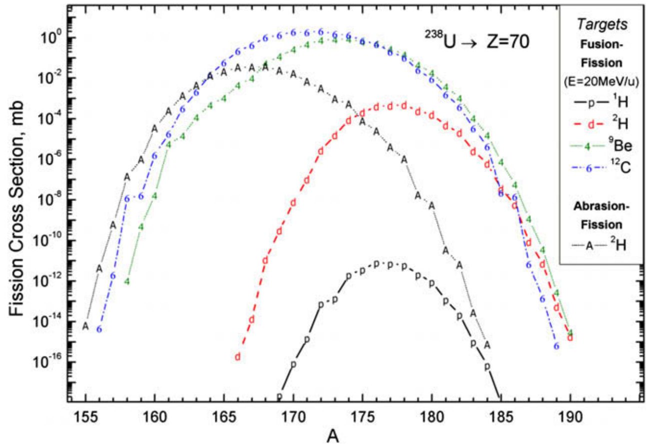

Fig. 2. Production fusion–fission cross section of Ytterbium isotopes calculated by `LISE++` for the ^{238}U beam at energy 20 MeV/u with different targets. Abrasion–fission cross sections for the ^{238}U + ^{2}H reaction are plotted for comparison.

and data interpretation in the works [17,18]. Increased excitation energy of the fissile nucleus leads to an increasing number of elements produced due to fission. On the other hand, the de-excitation break-up channels prevail under the fission channel with increased excitation energy of the compound nucleus. One sees from Table 1 that using light targets from hydrogen to oxygen can cover 25–260 MeV excitation energy. This means for the same primary beam it is possible to produce different fission fragment distributions by choosing targets corresponding to different excitation energy. Calculations show that the fusion–fission reaction mechanism has a very high production cross section for neutron-rich $Z = 70$ isotopes compared to abrasion–fission (see Fig. 2).

4. Towards the neutron drip-line

The `LISE++` fusion–fission model predicts the production of new isotopes of elements between neodymium and hafnium with the ^{238}U beam at energies 10–40 MeV/u on light targets (see Fig. 3). The region that we are particularly interested in a test experiment (neutron rich nuclei with $60 < Z < 75$) is more or less unexplored, although these nuclei are quite close to stability. Yet, this region is critical to test nuclear models and to understand the r-process abundance patterns of elements around lead. Advantages of in-flight fusion–fission to explore this region are the heavier fissile nuclei competing with abrasion–fission, and the higher excitation energy of a fissile nucleus competing with Coulomb fission of the ^{238}U primary beam.

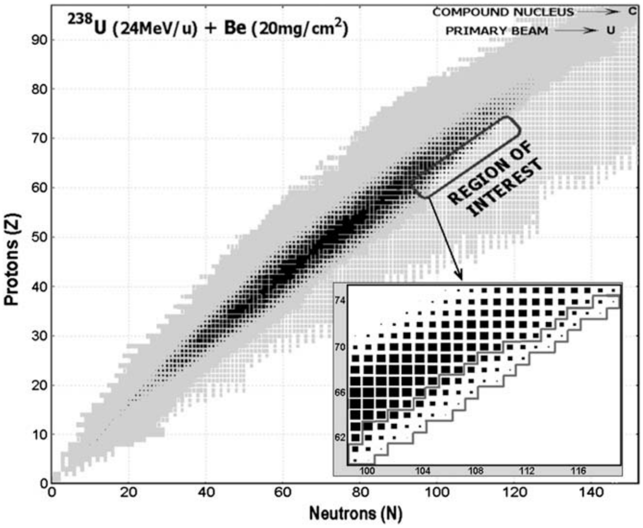

Fig. 3. Two-dimensional yield plot for fragments produced in the ^{238}U(24 MeV/u, 1 pnA) + Be(20 mg/cm^{2}) reaction and separated by the LISE spectrometer with horizontal and vertical angular acceptances ±19 mrad and momentum acceptance ±1.3%. The spectrometer was set on the ^{172}Tb^{60+} ion. Several tens new isotopes are expected for these settings. The total transmission of fragment of interest is about 1%. Isotopes with rate more than 1 particle per hour are shown.

5. Summary

In-flight fusion–fission can become a useful production method to identify new neutron-rich isotopes and study their properties.

The fusion–fission model developed and implemented in the `LISE++` package predicts the production of new isotopes in the region at $60 < Z < 75$ using the ^{238}U beam on light targets. A test in-flight fusion–fission experiment will be done at GANIL.

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