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Development of the program LISE: application to fusion–evaporation

O.B. Tarasov [a,b,*], D. Bazin [a]

[a] National Superconducting Cyclotron Laboratory, Michigan State University, 164 S. Shaw Lane, East Lansing, MI 48824-1321, USA
[b] Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia

Abstract

A new fusion–evaporation model LisFus for fast calculation of fusion residue cross-sections has been developed in the framework of the code LISE. This model can calculate very small cross-sections quickly due to its compared to programs using the Monte-Carlo method. Such type of fast calculations is necessary to estimate fusion residue yields. Using this model the program LISE has now the possibility to calculate the transmission of fusion residues through a fragment separator.

It is also possible to use fusion residues cross-sections calculated by the program PACE, which has been incorporated in the LISE package. The code PACE is a modified version of JULIAN- the Hillman–Eyal evaporation code using a Monte-Carlo code coupling angular momentum. A comparison between PACE and the LisFus model is presented.
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1. Introduction

The program LISE [1] is intended to calculate the transmission and yields of fragments produced and collected in a fragment separator. It allows one to fully simulate the production of radioactive beams, from the parameters of the reaction mechanism to the detection of nuclei selected by the fragment separator. Among the goals of this program is a highly user-friendly environment, designed not only to forecast intensities and purities for planning experiments, but also as a tuning tool during experiments where its results can be quickly compared to on-line data.

So far the only the production mechanism used in the program was projectile fragmentation. Further development of the program is directed towards lower energies down to the Coulomb barrier, and involves other types of reactions. With the occurrence of new facilities producing high-intensity radioactive beams of low energies (for example SPIRAL [2] and the DRIBs project [3]) a fast calculation of reaction-product transmission through a fragment separator at these energies (in particular for fusion–evaporation reactions) has

* Corresponding author. Tel.: +1-517-333-6396; fax: +1-517-353-5967.
E-mail address: tarasov@nscl.msu.edu (O.B. Tarasov).

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become necessary. To fulfill this need a new model with a fast algorithm for calculating residue formation cross-sections must be built. More problematic is the question of calculating cross-sections of nuclei far from stability, since programs based on the Monte-Carlo method such as PACE or CASCADE are very time consuming. To avoid this problem the LisFus model using an analytical approach was developed within the framework of the program LISE. The basic principles of model, as well as its advantages and disadvantages are given in the following section.

The program LISE offers the possibility to compare the LisFus model with the program PACE ported to Windows from FORTRAN to C++, and incorporated in the LISE package under the name PACE4. The code projection angular-momentum coupled evaporation (PACE) [4] is a modified version of JULIAN the Hillman–Eyal evaporation code using a Monte-Carlo code coupling angular momentum. In the LISE framework the program PACE4 has several new features:

- A user-friendly interface, where the user can enter information in dialogs, in which the explanation for each parameter is displayed. A convenient output of results is available too;
- Possibility to plot the calculated cross-sections using the LISE tools;
- A database of recommended values for binding energies [5] was added into the program.

2. LisFus: fusion residue cross-section fast calculations

The new fusion–evaporation model LisFus is based on the Bass fusion cross-section algorithm [6], the evaporation cascade algorithm of the Abrasion–Ablation model [7], and the LISE code mathematical apparatus of probability distributions using the transport integral theory [8]. 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 [9], and lately reexamined by Gaimard and Schmidt [7]. For each i-point of excitation energy (E_i) distribution (P) of parent nucleus, the LisFus model calculates the probabilities (W_k) of 8 possible decay channels (n, 2n, p, 2p, d, t, ^{3}He, α), and a daughter excitation energy distribution function D_kE_i. Using these definitions it is possible to express the i-segment of the parent excitation function as follows:

$$\int_{E_i}^{E_{i+1}} P(E)\mathrm{d}E = \sum_{k=1}^{8} W_k(E_i)D_k(E_i).$$

The fast speed of the LisFus calculations allows one to quickly build and inspect fusion residue excitation functions. The analytical approach of this model permits to calculate the cross-section for nuclei far from stability. However, the model

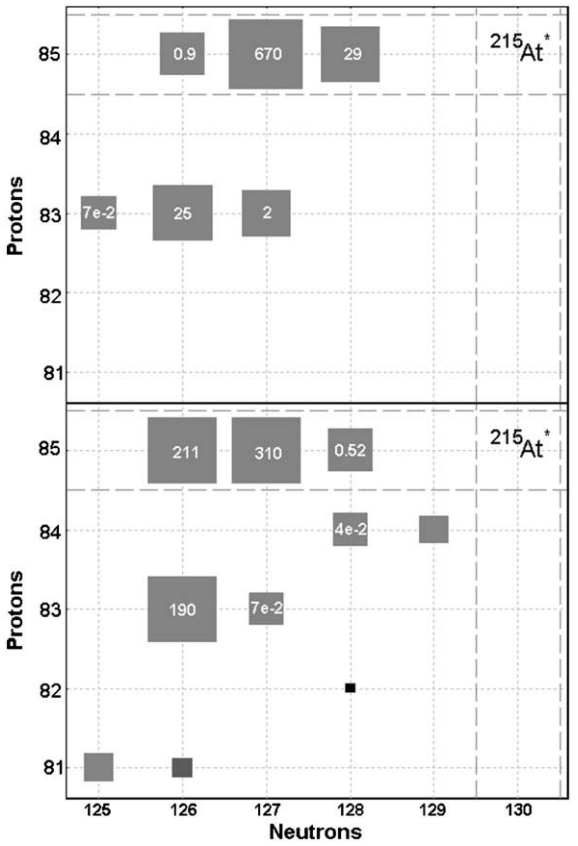

Fig. 1. Evaporation products following the fusion $^6\mathrm{He} + {}^{209}\mathrm{Bi}$ for a center-of-mass energy of 25 MeV. The PACE 4 calculations are shown in the upper frame, the LisFus calculations on the bottom frame. Cross-section values [mb] are shown inside squares.

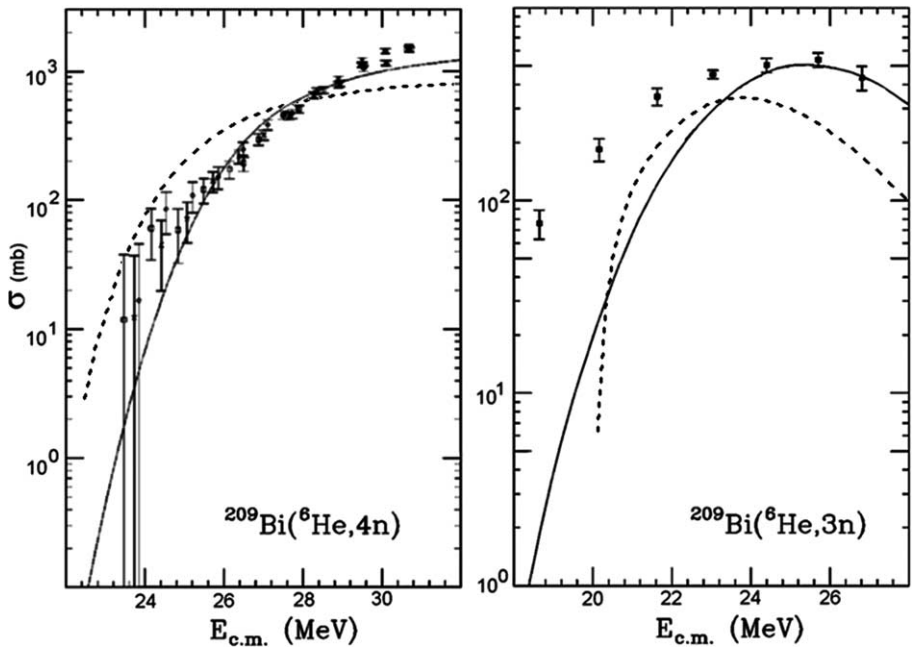

Fig. 2. The measured four-neutron evaporation cross-section from [10] (left picture) and three-neutron evaporation cross-section from [11] (right picture) as a function of the center-of-mass energy. The solid line is the prediction of the statistical model code PACE and the dashed line is the prediction of the LisFus code.

does not take into account the contribution of the angular momentum, as well as the deexitation channels by gamma emission and fission. Despite these approximations the calculations obtained with this model are in reasonable agreement with other programs using more complicated algorithms shown for example in the case of an excited ^{215}At nucleus evaporation process (see Fig. 1). Comparison of LisFus and PACE calculations with experimental data [10,11] are shown in Fig. 2.

3. Fusion residue transmission through a fragment separator

In order to calculate fusion residue transmission through a fragment separator it is necessary to also calculate their kinematics: velocity distribution (mean velocity and widths of longitudinal and transverse momentum distributions), and angular distribution. The residue velocity after the reaction (fusion and evaporation of light particles) is assumed to be equal to the compound nucleus recoil velocity. A Maxwell distribution of velocities is used to calculate the root-mean-square velocity after evaporation of light particles. In order to simplify the calculations and obtain the result in analytical form it was assumed that:

- Each step represents only one-nucleon evaporation;
- The excitation energy of the daughter nucleus after each step is a delta function;
- The one-nucleon separation energy is averaged out between the compound and the residue.

Under these assumptions it is possible to consider the final distribution as a convolution of N Gaussian distributions with $\sigma_i = \sqrt{\tau_i/amu/A_i}$, where N is the number evaporated nucleons, A_i is the mass number of the intermediate nucleus, and τ_i its temperature. Angular distributions in the center-of-mass system are assumed to be isotropic. The calculated widths of longitudinal and transverse momentum distributions are used to obtain the angular distributions.

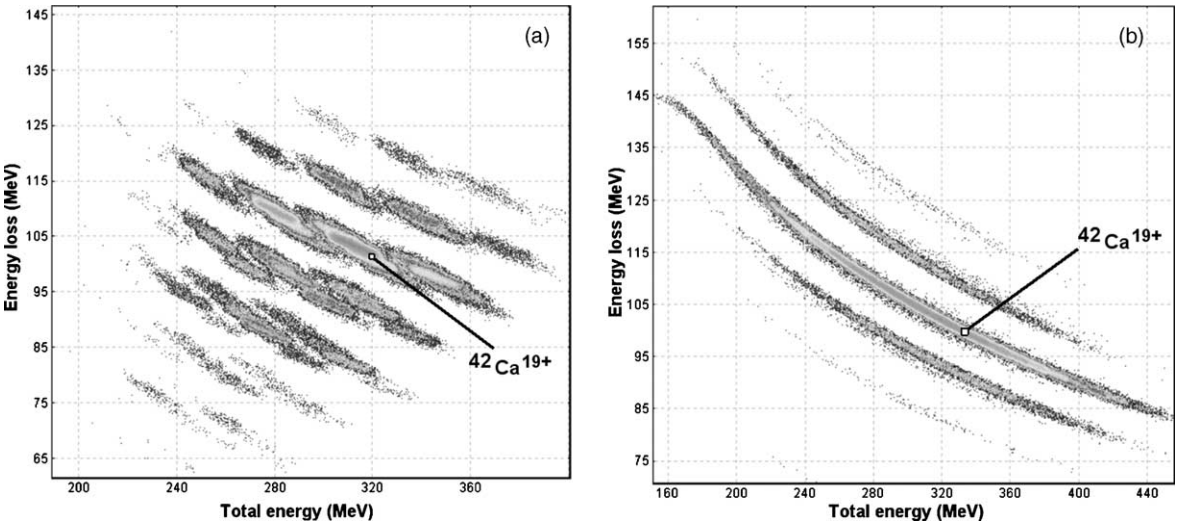

Fig. 3. $\Delta E - E$ plots for two different selection methods. The left plot shows the selection by a magnetic dipole, the right plot by a combination of Wien velocity filter and a dipole which compensates the filter's dispersion. Both devices are tuned on $^{42}Ca^{19+}$.

Table 1
Comparison of the performance between different kinds of low-energy fusion residue selection

Selection	Yield of $^{42}Ca^{19+}$(1/s)	Transmission (%)	Yields of all ions (1/s)	Purification (%)
Dipole ($dp/p = 3\%$)	1.4e+6	2.34	4.9e+6	28
Dipole and Wien velocity filter	6.8e+5	1.14	8.9e+5	76
Wien velocity filter	7.0e+5	1.17	2.8e+6	25
Wien velocity filter $\otimes$ Dipole	6.0e+6	10.0	6.5e+6	93

In the case of fusion reactions attention should be paid to the ionic charge of the residue, as fusion reactions take place at lower energies than fragmentation. For this purpose a Fusion-Residue calculator has been developed and incorporated in the LISE package.

The last step is selection of a chosen fusion residue by the separation devices to maximize transmission and purity. In today's version, four methods of separation are available in the program LISE: magnetic rigidity, energy loss in a wedge located at the dispersive focal plane, Wien velocity filter, and combination of a Wien filter and a dipole. The most popular method of separation for low energies is velocity separation (velocity filter). At small energies using energy loss in a wedge is ruled out. Electrostatic and gas-filled separators will be available as well in the program LISE in the future. Comparisons between different selection methods of fusion residues in the reaction $^{40}Ar(15\ MeV/u) + Be(64.4\ \mu m)$ are shown in Fig. 3 and Table 1, where it is apparent that the combination of a Wien velocity filter and a dipole (like in the spectrometer VAMOS [12]) gives the best results: best purification and largest transmission of the chosen fusion residue.

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