COSY EXTENSIONS FOR BEAM-MATERIAL INTERACTIONS*

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Abstract

While COSY INFINITY provides powerful DA methods for the simulation of fragment separator beam dynamics, the master version of COSY does not currently take into account beam-material interactions. These interactions are key for accurately simulating the dynamics from heavy ion fragmentation and fission. In order to model the interaction with materials such as the target or absorber, much code development was needed. There were four auxiliary codes implemented in COSY for the simulation of beam-material interactions. These include EPAX for returning the cross sections of isotopes produced by fragmentation and MCNPX for the cross sections of isotopes produced by the fission and fragmentation of a ^{238}U beam. ATIMA is implemented to calculate energy loss and energy and angular straggling. GLOBAL returns the charge state. The extended version can be run in map mode or hybrid map-Monte Carlo mode, providing an integrated beam dynamics-nuclear processes design optimization and simulation framework that is efficient and accurate. The code, its applications, and plans for large-scale computational runs for optimization of separation purity of rare isotopes at FRIB will be presented.

INTRODUCTION

The next generation of nuclear physics research will require advanced exotic beam facilities based on heavy ion driver accelerators. There are many next-generation facilities that are currently under commissioning, construction, or envisioned [1-5]. Included amongst these is the future Facility for Rare Isotope Beams (FRIB) at the National Superconducting Cyclotron Lab at Michigan State University. These facilities are capable of producing exotic beams composed of rare nuclei in large quantities. The exotic isotopes are produced via projectile fragmentation and fission in targets. High-performance fragment separators, a key component of all rare isotope facilities, consist of superconducting magnets that are used for the capture, selection, and transport of rare isotopes. Large aperture magnets are necessary in order to accept rare isotope beams with large emittances resulting from their production mechanism.

The beam optics code COSY INFINITY uses powerful differential algebraic (DA) techniques for computing the dynamics of the beam in the fragment separator through high order transfer maps [6]. However, until now it has lacked the ability to calculate the beam-material interactions occurring in the target and energy absorbers. Here, a hybrid map-Monte Carlo code has been developed and integrated into COSY in order to calculate these interactions. The code tracks the fragmentation and fission of the beam in target and absorber material while computing energy loss and energy and angular straggling as well as charge state evolution. This is accomplished by implementing auxiliary codes such as ATIMA [7] and GLOBAL [8]. EPAX [9] is utilized to return cross sections of fragmentation products. The special case of fission has been treated by using the code MCNPX [10] to accurately predict the cross sections and dynamics of exotic beams produced by a ^{238}U beam incident on a Li or C target. The extensions to the code have made it possible to simultaneously compute high order optics and beam-material interactions in one cohesive framework.

The hybrid map-Monte Carlo code can be used to calculate important quantities that describe the performance of the fragment separator. These include the transmission and the separation purity. In a map-only approach, calculations such as these are not possible. Experimental planning and optimization is possible with the map-Monte Carlo code, as various fragment separator settings can be readily adjusted. Here we present a description of the code and how it is implemented in COSY.

DESCRIPTION OF HYBRID MAP-MONTE CARLO CODE

While COSY INFINITY possesses a powerful DA framework for accurate simulation of beam dynamics in electromagnetic fields, the master version does not allow for the simulation of beam-material interactions. This ability is necessary, however, in order to model the dynamics of fission and fragmentation products. In order to track heavy ions through target and absorber material, much code development to COSY was needed.

New additions made to the code include the implementation of auxiliary codes to determine how many of each type of isotope are produced from the fragmentation and fission of an energetic heavy ion beam.of a given nuclear mass A and nuclear charge Z incident on a specified target of a given thickness. Also, the dynamics of these new particles need to be determined. It is necessary to model the cross sections and dynamics of fragmentation and fission separately due to the auxiliary codes available.

Fragmentation Cross Sections

In the case of any primary beam that has nuclear charge $Z<92$, the secondary particles of interest are fragmentation products. The cross sections of these

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particles are found via the code EPAX, which has been integrated into the code. The parameters that must be input to the code are the nuclear mass A and nuclear charge Z of the primary beam and the nuclear mass and charge of the product. Also, it is necessary that the target's nuclear mass and charge and thickness are input. EPAX will then return the cross section of the product in millibarns.

Fragmentation Dynamics

The secondary particles that emerge from the target have different kinematics depending on the production mechanism by which they were formed. For nuclear fragmentation, the angular divergence and momentum deviation of the secondary particle will solely be based on its mass and on the initial mass of the nucleus that fragments. This is called the "fireball" method, where thee momentum is given by a Gaussian distribution with the standard deviation given by.

$$\sigma = \frac{85}{c_{light}} \sqrt{\frac{A_c (A_p - A_c)}{A_p - 1}} \, ,$$

where A_c is the child particle and A_p is the parent particle from which the child particle fragments. The momentum of the new fragment is modified by adding a random number chosen by Gaussian distribution with standard deviation σ. The parallel component of the momentum is used to calculate energy loss and straggling, and the perpendicular component is used to calculate the angular divergence of the particle and angular straggling.

Fission Cross Sections

In contrast to the fragmentation process, the cross sections of fission products are energy-dependent. The map-Monte Carlo code utilizes MCNPX in order find the cross sections of all the isotopes produced by a ^{238}U beam incident on a Li or C target. These are two targets under development for the FRIB (Figure 1). MCNPX was run for four different beam energy and target combinations, namely 200, 400, 800, and 1500 MeV/u incident on both Li and C targets of thickness 0.1068 g/cm^2. The ^{238}U beam was assumed to be point-like and have no angular divergence or energy spread. The output from MCNPX is the number of particles of each isotope produced N_{prod}. This number includes all the isotopes produced from all nuclear processes. With this number, the cross section of any isotope may be computed by the formula:

$$\sigma_{cs} = \frac{N_{prod} A}{N_0 x \rho N_A} \, ,$$

where A is the nuclear mass of the target, N_0 is the number of source ^{238}U particles, x is the target thickness, ρ is the target density, and N_A is Avogadro's number. The number of source particles in each run was between 6x10^8 and 1x10^9.

The cross section data provided by MCNPX were used to interpolate the cross section of the fission products as a second order polynomial in energy given by

$$\sigma_{cs} = c_0 + c_1 E + c_2 E^2 \, ,$$

where E is the energy of the ^{238}U beam and the c_n's are the coefficients of the interpolation for a given isotope with nuclear mass A and nuclear charge Z. The coefficients of this polynomial are listed in a file that is read once by COSY and stored in an array each time the code is run. This method is fast and uses very little memory. Another benefit to this method is the in which a more up-to-date fission model may be included in the future as developments in the field occur.

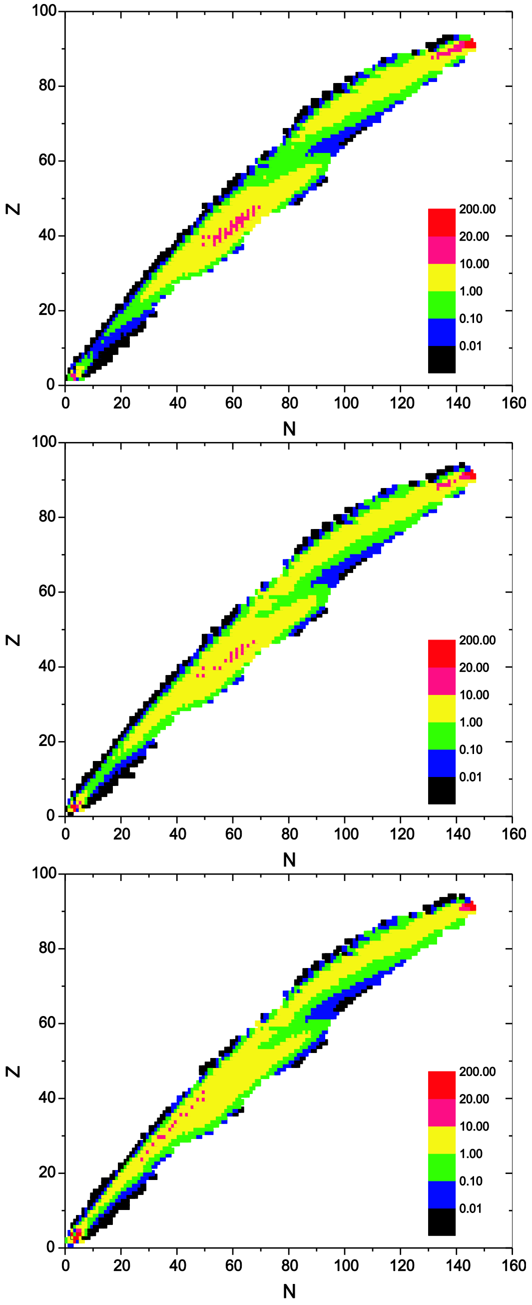

Figure 1: Cross sections of all isotopes produced by 200, 400, and 1500 MeV/u ^{238}U beam incident on a 0.1068 g/cm^2 Li target.

Fission Dynamics

For fission, the coordinates are not only based on the masses of the nuclei as is the case for fragmentation. There is an extra energy release that results from the fissioning nucleus. This extra energy release means that the products will have large δ, or energy spread, and also large angular divergences. If δ and the angular coordinates are plotted, then the result is a "fuzzy" spherical shell that represents the phase space that is occupied by fission products (Figure 2).

The fact that all fission products are emitted from the target in a sphere can be used to model the dynamics of the emitted beam. More precisely, the coordinates of these fission products are best represented by a spherical shell with some thickness. In order to determine the initial coordinates of each isotope that will pass through the fragment separator, we must have a method to obtain the "sphere" of each isotope in a random manner. At low energies, the thickness of the spherical shell is large, with the most particle density at larger radii. As the energy increases, the thickness of the spherical shell becomes thinner and more dense and, hence, represents a lower beam emittance.

CONCLUSION

A hybrid map Monte Carlo code has been developed to accurately model beam-material interactions for the purpose of fragment separator beam dynamics simulation. A comprehensive fission model was developed to accurately model cross sections and kinematics of isotopes produced from a ^{238}U primary beam. Using the code, one may simulate a variety of exotic beam experiments and compute important quantities such as the separation purity and transmission of various rare isotopes.

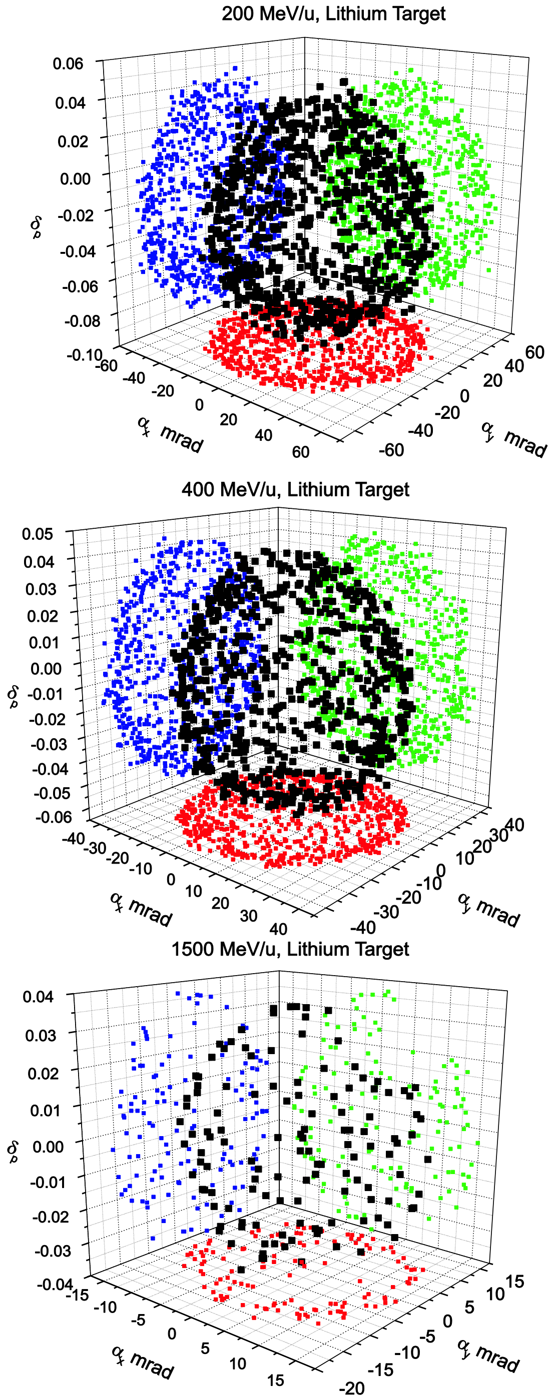

Figure 2: Kinematics of a ^{132}Sn beam resulting from the fission of 200, 400, and 1500 MeV/u ^{238}U primary beam upon interaction with a 0.1068 g/cm^2 Li target. The ^{132}Sn coordinates are shown in black with the colored circles representing the projection of these coordinates on the various coordinate planes. The coordinates shown are the momentum deviation (δ_p) and scaled horizontal and vertical momenta (α_x,α_y).

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