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Optical model analyses of heavy ion fragmentation in hydrogen targets

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Quantum-mechanical optical-model methods for calculating cross sections for the fragmentation of high-energy heavy ions by hydrogen targets are presented. The cross sections are calculated with a knockout-ablation collision formalism which has no arbitrary fitting parameters. Predictions of elemental production cross sections from the fragmentation of 1.2A GeV ^{139}La nuclei and of isotope production cross sections from the fragmentation of 400A MeV ^{32}S nuclei are in good agreement with recently reported experimental measurements.

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I. INTRODUCTION

The fragmentation of high-energy heavy ions in hydrogen targets is an important physical process in several areas of physics research. In fundamental nuclear physics, it is a significant test of nuclear reaction theories and their models. In astrophysics, it is crucial to understanding galactic cosmic ray (GCR) propagation and source abundances [1] because interstellar hydrogen is the major type of material encountered by GCR nuclei traveling through the Universe. In studies of spacecraft shielding for proposed interplanetary missions [2], hydrogen has been found to be the most effective GCR shield material per unit mass. In addition, hydrogen is a major constituent of human tissue. Therefore, cross sections are needed for properly estimating GCR radiation exposures to critical internal body organs of astronauts [3]. Typically, cross sections used in many of these studies have been obtained from semiempirical parametrizations [4–6] incorporating numerous adjustable parameters.

The production of fragments in relativistic heavy ion collisions has received intense scrutiny by theorists and experimentalists since the early 1970s. From time to time, comprehensive reviews are published which summarize current progress and trends in these investigations (Ref. [7], for example). Among early attempts to explain fragmentation, a two-step abrasion-ablation model [8] was invoked.

In an abrasion-ablation model, the projectile nuclei, moving at relativistic speeds, collide with stationary target nuclei. In the abrasion step (particle knockout), those portions of the nuclear volumes that overlap are sheared away by the collision. The remaining projectile piece, called a prefragment, continues its trajectory with its precollision velocity. Because of the dynamics of the abrasion process, the prefragment is highly excited and subsequently decays by the emission of gamma radiation or nuclear particles. This step is the ablation stage. The resultant isotope is the nuclear fragment whose cross section is measured.

Although abrasion-ablation models have been quite successful in predicting fragment production cross sections, their predictive accuracy is hampered by the need to estimate the (unknown) prefragment excitation energy. Various models have been developed for this purpose [8–12]. The most widely used excitation energy formalism [8] treats the fragmenting nucleus as a misshapen liquid drop whose excitation is given by the excess surface energy resulting from the abrasion step. Although this method worked fairly well for nucleus-nucleus fragmentations, its use in nucleus-hydrogen collisions, among other difficulties, required an artificially large proton radius [8].

When it was recognized that additional excitation energy was required to improve the agreement between theory and experiment for nucleus-nucleus collisions, the concept of frictional spectator interaction (FSI) energy was introduced [10,11]. This concept is based upon the assumption that some abraded nucleons are scattered into rather than away from the prefragment, thereby depositing additional excitation energy. This concept significantly improved the agreement between theory and experiment.

Over the past decade, we have formulated an optical-model abrasion-ablation FSI description of fragmentation in relativistic nucleus-nucleus collisions that has been successfully used to predict fragment production cross sections [13–15] and momentum distributions of the emitted fragments [15–17]. In the present work, this fragmentation model is modified to make it applicable to nucleus-nucleon collisions. As previously mentioned, the main shortcoming associated with the use of early abrasion-ablation models for nuclear fragmentation on hydrogen targets is the unrealistically large proton radius needed for the excess surface area estimate of the prefragment excitation energy. This radius is dictated by the reliance on excess surface energy of the misshaped liquid drop as the only source of prefragment excitation. This shortcoming in the model can be rectified by considering the physics of the fragmentation process. For instance, a picture of overlapping nuclear volumes being sheared off may be reasonable for heavier nuclei colliding with each other, but it is not reasonable for a single nucleon striking another nucleus. Instead, a more reasonable physical picture involves individual collisions between the projectile constituents and the target proton. Some struck projectile nucleons exit the fragmenting nucleus without further interaction, and some interact one or more times with the remaining constituents before departing. The remaining nucleus (prefragment), in an excited state because of the energy deposited during the collision, then deexcites by particle- or gamma-emission processes. This picture is easily described by a knockout-ablation FSI model where the knockout stage is described by a quantum-mechanical optical-model formalism, and the ablation stage is modeled with cascade-evaporation techniques. There is no excess surface area energy. Instead, the prefragment excitation energy is assumed to be provided by FSI contributions from the abraded nucleons. This fragmentation model is described in this work.

II. FRAGMENTATION THEORY

In the nucleus-nucleus optical potential formalism [15], the cross section for producing, by abrasion, a prefragment of change $Z_{\rm PF}$ and mass $A_{\rm PF}$ is given by

$$\sigma_{\rm abr}(Z_{\rm PF}, A_{\rm PF}) = \binom{N}{n}\binom{Z}{z} \times \int d^2b[1 - T(\mathbf{b})]^{n+z}[T(\mathbf{b})]^{A_{\rm PF}}, \tag{1}$$

where

$$T(\mathbf{b}) = \exp[-A_T\sigma(e)I(\mathbf{b})] \tag{2}$$

and

$$I(\mathbf{b}) = [2\pi B(e)]^{-3/2}\int \mathbf{dz}_0 \int d^3\xi_T\rho_T(\boldsymbol{\xi}_T) \times \int d^3y\rho_P(\mathbf{b} + \mathbf{z}_0 + \mathbf{y} + \boldsymbol{\xi}_T)\exp[-y^2/2B(e)]. \tag{3}$$

In Eqs. (1)–(3), $\mathbf{b}$ is the impact parameter vector, e is the two-nucleon kinetic energy in their center-of-mass frame, $\mathbf{z}_0$ is the target center-of-mass position in the projectile rest frame, $\boldsymbol{\xi}_i$ ($i = P, T$) are the internal coordinates of colliding nuclei, A_i ($i = P, T$) are the mass numbers of colliding nuclei, and $\mathbf{y}$ is the projectile-nucleon-target nucleon relative separation vector. The nuclear number densities ρ_i ($i = P, T$) are obtained from the appropriate charge densities by an unfolding procedure [13]. The constituent-averaged nucleon-nucleon cross sections $\sigma(e)$ are given in Ref. [18]. Values for the diffractive nucleon-nucleon scattering slope parameter $B(e)$ are obtained from the parametrization in Ref. [19].

In Eq. (1), a hypergeometrical charge dispersion model is used to describe the distribution of abraded nucleons. It assumes that z out of Z projectile protons and n out of N projectile neutrons are abraded where

$$N + Z = A_P, \tag{4}$$

$$A_{\rm PF} = A_P - n - z, \tag{5}$$

and $\binom{A}{B}$ denotes the usual binomial coefficient expression from probability theory.

For nuclear collisions with hydrogen (proton) targets, the appropriate target number density to use is given by ($A_T = 1$)

$$\rho_T(\boldsymbol{\xi}_T) = \delta(\boldsymbol{\xi}_T). \tag{6}$$

Inserting Eq. (6) into Eq. (3) yields

$$I_H(\mathbf{b}) = [2\pi B(e)]^{-3/2}\int \mathbf{dz}_0 \int d^3y\rho_P(\mathbf{b} + \mathbf{z}_0 + \mathbf{y}) \times \exp[-y^2/2B(e)]. \tag{7}$$

With $A_T = 1$, Eq. (2) becomes

$$T(\mathbf{b}) = \exp[-\sigma(e)I_H(\mathbf{b})]. \tag{8}$$

The nucleus-hydrogen knockout cross sections are calculated using Eqs. (1), (7), and (8).

Because there is no surface energy term, the prefragment excitation energies are estimated from the FSI energy contribution

$$E_{\rm exc} = E_{\rm FSI}, \tag{9}$$

which is calculated using the model of Ref. [11]. With this model the rate of energy transfer to the prefragment is

$$\frac{dE}{dx} = \frac{E}{4\lambda}, \tag{10}$$

where for the relative kinetic energies less than several hundred MeV involved in FSI we use

$$\lambda = \frac{1}{\rho\sigma_{NN}}, \quad \sigma_{NN} \approx \frac{300}{E}, \tag{11}$$

yielding

$$\frac{dE}{dx} = 12.75 \text{ MeV/fm}. \tag{12}$$

If a spherical nucleus of uniform density is assumed, the average energy deposited per interaction is

$$\langle E_{\rm FSI}\rangle \approx 10.2A^{1/3} \text{ MeV}. \tag{13}$$

Therefore the abrasion (knockout) cross section for a prefragment species ($Z_{\rm PF}, A_{\rm PF}$) which has undergone q frictional spectator interactions is

$$\sigma_{\rm abr}(Z_{\rm PF}, A_{\rm PF}, q) = \binom{n+z}{q}(1 - P_{\rm esc})^q \times (P_{\rm esc})^{n+z-q}\sigma_{\rm abr}(Z_{\rm PF}, A_{\rm PF}), \tag{14}$$

where $0 \le q \le n + z$, and $P_{\rm esc}$ is the probability that an abraded nucleon escapes without undergoing any frictional spectator interactions [14]. In this work, we choose $P_{\rm esc} = 0.5$ [11]. Such a value assumes that there is no curvature of the nuclear surface and should be reasonably correct for heavy nuclei.

Depending upon the magnitude of its excitation energy, the prefragment will decay by emitting nucleons, composites, and gamma rays. The probability $\alpha_{ij}(q)$ that a prefragment species j, which has undergone q frictional spectator interactions, deexcites to produce a particular final fragment of type i is obtained using the EVA-3 Monte Carlo cascade-evaporation computer code [20]. Therefore, the final hadronic cross section for production of the type i isotope is obtained from

$$\sigma_{\rm nuc}(Z_i, A_i) = \sum_j \sum_{q=0}^{n+z} \alpha_{ij}(q)\sigma_{\rm abr}(Z_j, A_j, q), \qquad (15)$$

where the summation over j accounts for contributions from different prefragment isotopes j, and the summation over q accounts for the effects of different FSI excitation energies. Finally, the elemental production cross sections are obtained by summing over all isotopes of a given element according to

$$\sigma_{\rm nuc}(Z_i) = \sum_{A_i} \sigma_{\rm nuc}(Z_i, A_i). \qquad (16)$$

Contributions from electromagnetic dissociation are small (≤ 1 mb) and are ignored in the present work.

III. RESULTS

Figure 1 shows element production cross sections obtained with Eq. (16) for ^{139}La nuclei at 1.2A GeV incident kinetic energy fragmenting in hydrogen targets. Also displayed are recently reported experimental results obtained from the HISS facility at the Lawrence Berkeley Laboratory [21]. The ^{139}La nuclear density used in the calculations was a Woods-Saxon form with skin thickness and half-density radius obtained using the methods described in Ref. [18]. From the figure we note that the agreement between theory and experiment is very good, especially considering that there are no arbitrary fitting parameters in the model. Comparing predicted cross sections with measured values indicates that over 60 percent are within quoted experimental uncertainties.

Isotope production cross sections for ^{32}S beams at 400A MeV fragmenting in hydrogen targets are shown in Figs. 2 and 3. The theoretical estimates were obtained using Eq. (15). The experimental results were obtained by the Transport Collaboration using the HISS facility at Lawrence Berkeley Laboratory [22]. For clarity of presentation, the results have been separated into odd charge number fragments (Fig. 2) and even charge number fragments (Fig. 3). Experimental error bars are plotted where they are larger than the cross section symbols used in the figures. The ^{32}S nuclear density used in the calculations was a Woods-Saxon form [18]. Again, the agreement between theory and experiment is very good. Quantitatively, a distribution analysis of cross-section differences between theory and experiment finds that one-third agree within the quoted experimental uncertainties, one-half agree within a 25 percent difference, and approximately three-fourths agree within a 50 percent difference.

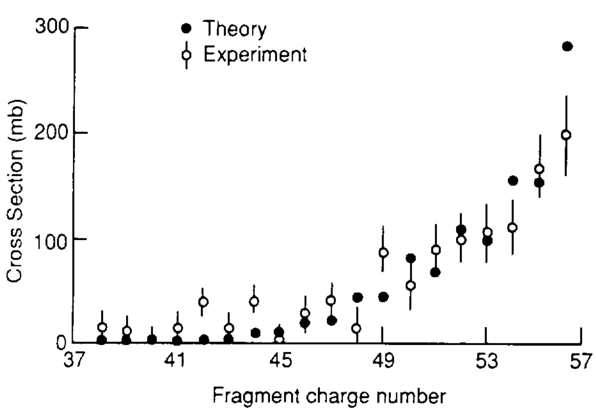

FIG. 1. Element production cross sections for 1.2A GeV ^{139}La fragmentation on hydrogen targets. The experimental data were obtained from Ref. [21].

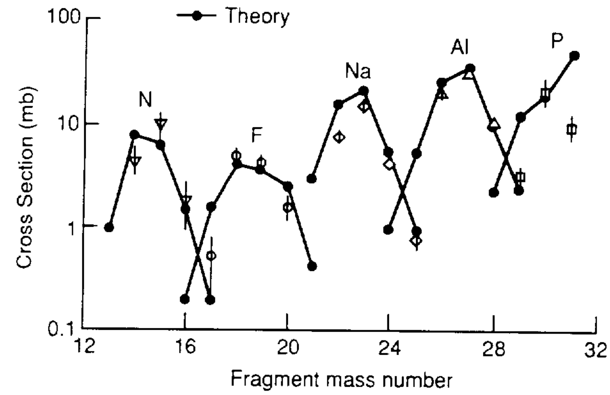

FIG. 2. Isotope production cross sections for 400A MeV ^{32}S fragmentation on hydrogen targets for isotopes of P, Al, Na, F, and N fragments. The experimental data were obtained from Ref. [22].

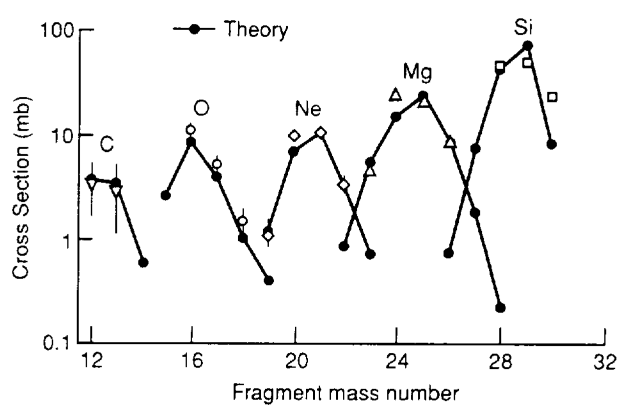

FIG. 3. Isotope production cross sections for 400A MeV ^{32}S fragmentation on hydrogen targets for isotopes of Si, Mg, Ne, O, and C fragments. The experimental data were obtained from Ref. [22].

IV. CONCLUDING REMARKS

A simple, yet accurate, optical potential knockout-ablation fragmentation model has been presented for use in describing fragment yields for high-energy heavy ions breaking up on hydrogen targets. The model has no arbitrary fitting parameters. Model predictions are in very good quantitative agreement with recent laboratory measurements of lanthanum and sulfur beams fragmenting on hydrogen targets.

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