Fragmentation of Exotic Oxygen Isotopes

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Abrasion-ablation models and the empirical EPAX parametrization of projectile fragmentation are described. Their cross section predictions are compared to recent data of the fragmentation of secondary beams of neutron-rich, unstable ^{19,20,21}O isotopes at beam energies near 600 MeV/nucleon as well as data for stable ^{17,18}O beams.

I Introduction

Fragmentation of energetic heavy-ion beams is widely used to produce secondary beams of exotic nuclei far from stability [1]. In order to assess the feasibility of experiments utilizing secondary beams, a precise knowledge of the relevant production cross sections is necessary. Usually, production cross sections are deduced from empirical parameterizations of measured cross sections, e.g., the frequently used EPAX parametrization [2]. Alternatively, fragmentation models with a microscopic background have been applied, such as abrasion-ablation models [3-5] or intranuclear cascade simulations [6].

The validity of both the empirical parameterization and the physical models has been verified mainly for medium- to heavy-mass fragments (see, e.g., Refs. [2,7-10]). In particular, it has been shown that in the few cases in which fragmentation cross sections of projectiles with different neutron-to-proton ratios were studied the observed shift of the centroids of the isotope distributions was rather well reproduced by EPAX (see Fig. 11 in Ref. [2]). The data are much too scarce, however, to investigate in detail how the shapes of the distributions, in addition to their centroids, vary with the neutron- or proton-excess of the projectiles.

Recently, two-step fragmentation processes were discussed in the context of an efficient production of very neutron-rich isotopes. This process involves an unstable neutron-rich fragment as an intermediate product which undergoes fragmentation again, yielding the final nucleus of interest. On the basis of the EPAX parameterization, considerable gain factors for the production of specific very neutron-rich isotopes in two-step fragmentation processes in comparison to one-step fragmentation were deduced. These findings, however, are in contrast to results obtained on the basis of an abrasion-ablation model [11].

Here, we briefly describe various abrasion-ablation models as well as the EPAX parametrization and compare their predictions with experimental data of the fragmentation of the unstable neutron-rich nuclei ^{19,20,21}O, together with those of the stable ^{17,18}O isotopes[12]. The results can serve to illustrate the effect of isospin on the fragmentation process and thus help to clarify the above discrepancies between various predictions.

II Fragmentation Models

The EPAX parameterization follows earlier approaches by Rudstam or Silberberg, Tsao, and coworkers (see references in [2]). It assumes that for each fragment mass A_f the nuclear charges Z_f are distributed according to a skewed Gaussian curve around the central value; the location of the center and the width follow smooth analytical functions of A_f. The total yields at each mass A_f are assumed to decay exponentially with increasing mass difference from the projectile. Correction factors model the more narrow isotope distributions close to the projectile and the influence of the neutron-to-proton ratio of the projectile on the fragment distribution (the "memory effect"). EPAX has been shown to reproduce measured fragmentation cross sections from heavy-ions with masses above ^{40}Ar within a factor of about 2 [2]. For lighter projectiles, the agreement with data can be expected to deteriorate somewhat, since odd-even effects in the isotope distributions (which are not contained in the present version of EPAX) can be shown to become increasingly important.

Abrasion-ablation models describe fragmentation reactions as a two-stage process. In the abrasion stage of the reaction, the nucleons in the overlap region of two energetic heavy ions are scraped off (abraded) as the ions pass each other. In the subsequent ablation stage, the excited projectile and target fragments decay by statistical particle emission. One of the first models of this kind was developed by Bowman, Swiatecki and Tsang [3]. They used the geometrical overlap of two colliding spheres to determine the mass of the primary fragment and estimated its excitation energy as the difference in the surface energy of the abraded fragment and that of a sphere of equal volume. Although the model roughly described the overall characteristics of the data, it systematically placed the fragment mass distribution at larger values of the mass than those observed experimentally.

Later work used the Glauber approximation [13] to improve the description of primary fragment formation but concluded that the principal defect of the model was its low estimate of the primary excitation energy, which inhibited particle emission in the subsequent ablation stage [14]. The underestimate of the excitation energy can be attributed in part to the neglect of interaction of the outgoing participant nucleons with the spectator nucleons in the fragments. When these interactions were taken into account, much better agreement with the experimental data was obtained [15].

More recently, two attempts have been made to improve the estimate of primary energy deposition by using a consistent independent-particle picture of the abrasion process [4,5]. The basic premises of these works are 1) that the collisions between projectile and target nucleons result in a primary fragment in which nucleons have been knocked out of some subset of the initially occupied independent-particle orbitals and 2) that the excitation energy of this configuration can be estimated as the energy of the corresponding particle-hole configuration of this primary fragment.

In Ref. [4], the geometrical formulation of the abrasion model, which distinguishes between a participant and two spectator zones [3], was combined with the independent-particle picture to predict the mass and nuclear-charge distribution [16], the excitation energy, and the angular momentum [17] of the spectators. An additional contribution to the excitation energy from interactions of the spectators with nucleons from the participant zone was deduced from experimental data [18]. The ablation stage was calculated within an evaporation model, where the emission of neutrons, protons and alpha particles is considered. Binding energies from the finite-range liquid drop model including microscopic corrections [19] are used in combination with level densities based on the Fermi-gas model with pairing correlations, shell effects, and collective contributions included [20-22].

The model of Ref. [5] attempts to provide a completely microscopic independent-particle model of the abrasion process. A survival probability $P_j(\vec{b})$ is calculated for each single-particle orbital at each value of the impact parameter $\vec{b}$, as an overlap between the projectile orbital $o_j(\vec{r})$ and its interaction with the target. In the Glauber approximation this is given by

$$P_j(\vec{b}) = \left| \int dz\, d^2s\; |o_j(z,\vec{s})|^2 \times \exp\left[-i\frac{m}{\hbar^2 k} \int_{-\infty}^{\infty} dz\, U_T^{opt}(z,\vec{b}-\vec{s}) \right] \right|^2 ,$$

where U_T^{opt} is the nucleon-target optical potential. The survival probabilities are combined to obtain the probability for the formation of a fragment in which a particular subset of the orbitals remains occupied. The excitation energy of the fragment is taken to be the particle-hole energy of the configuration relative to the ground state of the fragment. When the many combinations of orbitals that can lead to a fragment with the same mass number and charge are summed and then integrated over impact parameter, one obtains the differential cross section for the formation of that fragment as a function of the excitation energy,

$$\frac{d\sigma_0}{d\epsilon}(\epsilon, Z_f, A_f) = \sum_{occ} \omega(\epsilon, occ) \times \int d^2b \prod_{j\in occ} P_j(\vec{b}) \prod_{k\in nocc} (1 - P_k(\vec{b})),$$

where occ denotes each of the possible sets of orbitals consistent with the final proton number Z_f and neutron number $N_f = A_f - Z_f$ while $nocc$ refers to the remaining orbitals. The corresponding density of states is given by $\omega(\epsilon, occ)$.

In the ablation stage of the model, it is assumed that the fragments decay by multiple statistical particle emission from an equilibrated primary fragment. Any pre-equilibrium effects that might be associated with the original particle-hole description are neglected. The ablation calculations are performed using the Weisskopf-Ewing evaporation formalism in which angular momentum conservation is neglected [23].

In the calculations presented here, harmonic oscillator wavefunctions with a characteristic energy of $\hbar\omega = 40/A^{1/3}$ MeV are used for the projectile states. The single-particle energy levels are obtained from a spherical Nilsson scheme with the same characteristic energy but including spin-orbit splitting and an $l(l+1)$ shift. The optical potential used to calculate the survival probabilities, is estimated within the impulse approximation. Differences between neutron and proton target densities are taken into account, although the same geometry is used for the two. The emission of gammas, neutrons, protons, and alpha particles is taken into account in the statistical decay of the ablation stage. The giant dipole resonance is assumed to dominate the γ emission. Cross sections for particle emission are obtained from global fits to reaction cross sections. The calculations use low-energy constant-temperature level densities matched to higher-energy Fermi-gas ones with level density parameters of $a = A/7$ MeV^{-1}, pairing shifts of $12/\sqrt{A}$ MeV, and experimental ground-state masses.

III Discussion

The target dependence of fragmentation cross sections can be approximately factorized. As an example, Fig. 1 compares fragment cross sections obtained from a carbon target with those from a lead target for the case of an ^{20}O beam. Except for the one- and two-neutron removal channnels, the ratios of the fragment cross sections range between values of 1.8 and 2.9 with a mean value of 2.1 ± 0.1. For a lead target, the few-neutron removal cross sections are influenced by the electromagnetic excitation process, which has been discussed in detail elsewhere [24]. The ratio of 2.1 for the other isotopes is indicative of a more pheripheral nature of the nuclear fragmentation process. A scaling with the sum of projectile and target radii would yield a ratio of 1.7, a scaling with the target radius alone a ratio of 2.6. The latter value is the one used in EPAX.

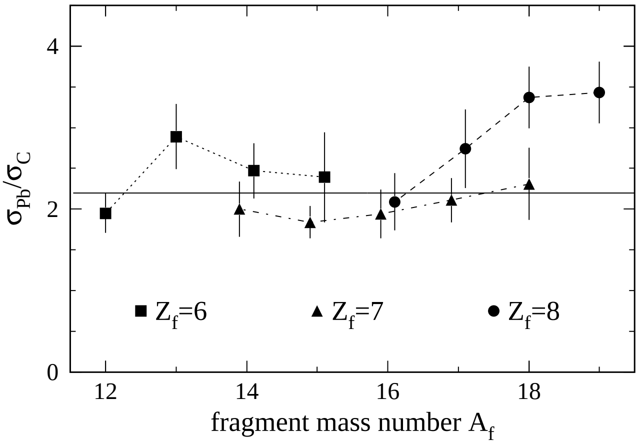

Figure 1. Ratio of cross sections measured with a lead target to those measured with a carbon target yielding oxygen, nitrogen, and carbon fragments, from Ref. [12].

For the stable beam ^{17}O fragmentation cross sections have been measured at 1700 MeV/nucleon beam energy for beryllium and aluminum targets, see Ref. [25]. We include the experimental results for the beryllium target of Ref. [25] in Fig. 2 for comparison. The results of Ref. [25] agree with those of Ref. [12] within maximum deviations of about 40 %. A certain trend towards larger cross sections for oxygen fragments and lower cross sections for carbon fragments in Ref. [25] with a beryllium target in comparison to the results of Ref. [12] with a carbon target can be observed, while both measurements deliver almost identical cross sections for nitrogen fragments.

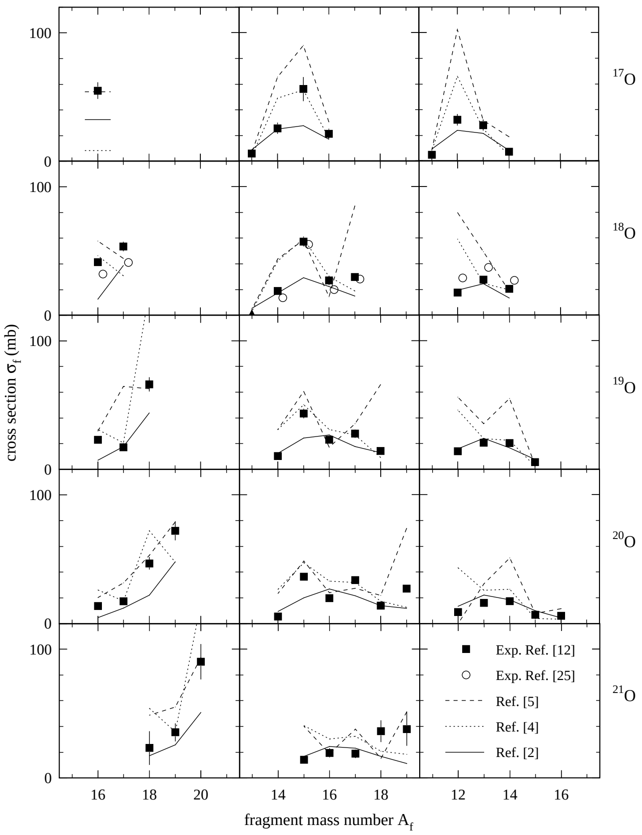

Figure 2. Cross sections of projectile fragments with nuclear charges Z_f and masses A_f produced from $^{17-21}$O beams in a carbon target, from Ref. [12]. In the case of the ^{18}O beam, experimental results obtained in [25] for ^{18}O beams of 1700 MeV/nucleon on a Be target are included. The experimental cross sections (symbols) are compared to those calculated using various models: Two abrasion-ablasion models (dashed line from [5], dotted line from [4]). The solid line shows the results of the empirical EPAX parameterization [2].

As can be seen from the full lines in Fig. 2, the EPAX parameterization seems to reproduce the general trend of the data rather well. While the few-nucleon removal channels are less accurately predicted, as is known, the comparison for, e.g., carbon fragments is almost perfect. Though the EPAX formula was obtained by adjusting to fragmentation data of stable beams only, the overall very good description indicates that the parameterization of the 'memory effect' is valid also for unstable projectiles as neutron-rich as ^{21}O (A/Z = 2.625). This confirms the previous observation by Sümmerer and Blank [2] that the fragment distributions for somewhat less neutron-rich secondary beams like ^{28}Mg (A/Z = 2.333) and ^{43}Ar (A/Z = 2.389) are well reproduced over more than one order of magnitude in cross section.

An obvious deficiency of the EPAX parameterization is the fact that the odd-even effects observed in the data cannot be reproduced. This is expected since the EPAX parameterization does not contain a description of the physical process and no attempt has been made to parameterize the odd-even effects. The experimental data show that isotopes with even neutron numbers, especially ^{15}N with a closed $N = 8$ shell, are more abundantly produced than their neighbors with odd neutron numbers. The large difference in neutron separation energy between unpaired and paired neutrons is most likely responsible for the even-odd staggering in the production cross sections. This is illustrated by quoting the one-neutron separation energies of the ^{15,16,17,18}N isotopes which are 10.8, 2.5, 5.9, and 2.8 MeV, respectively. The unpaired neutron in ^{16}N or in ^{18}N is thus easily removed at the end of the evaporation chain, explaining their lower production cross sections in comparison to ^{15}N or ^{17}N, respectively. Even-odd effects in the production cross sections are predicted by both formulations of the abrasion-ablation model as seen from Fig. 2. Both calculations, however, overestimate the effects. Nevertheless, in general the results agree with the experimental data within roughly a factor of two.

When comparing the general behavior of the data with the different model calcuations, all models reproduce the tendency of the measured cross sections as a function of neutron number of the reaction products reasonably well. In the range which is accessible to the available data, systematic discrepancies between the empirical parametrization and the results of the abration-ablation models, which are reported in Ref. [8] for heavier extremely neutron-rich fragmentation products, are not observed.

IV Conclusion

Several models of projectile fragmentation were compared with the experimental data of unstable, neutron-rich oxygen beams, up to ^{21}O, of Ref. [12]. The experimental data could be reproduced by an empirical parameterization based on fragmentation data from stable nuclei. The trend towards more neutron-rich fragments with increasing neutron excess of the unstable beam seems to be well reproduced. Nuclear structure effects, however, influence the cross sections leading to odd-even effects which can qualitatively be accounted for in descriptions using abrasion-ablation models.

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