Tests of models for inclusive production of energetic light fragments at intermediate energies

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Several models of light fragment emission are confronted with data from electron and proton induced reactions. The data appear to favor a mechanism, called the snowball model here, in which there is a single collision of the projectile and a few collisions of the secondary nucleons which then form the observed fragment. The parameter of the model is determined by fitting new isotopically separated inclusive differential cross section data.

NUCLEAR REACTIONS Statistical, knockout, and coalescence models, light fragment emission, electron and proton induced reactions.

There have been several models, each with very different assumptions, proposed over the last decade or so to explain light fragment inclusive production data at intermediate energies.[1] There are now sufficient data available to show that one class of models seems to be preferred, although the data are not yet detailed enough to make a unique selection. We will briefly review the current theoretical and experimental situation, and advance a mechanism, called the snowball model, which is consistent with the extant data.

Our attention will be concentrated entirely on proton and electron induced emission of light fragments. The differential cross sections for these reactions, as exemplified by the (p,α) and (e,α) reactions[2,3] at bombarding energies of about 100 MeV, are very similar, showing an evaporative peak at low energy and a long "tail" at higher energy. The evaporation region being well understood, we will concentrate on the explanation of the high energy tails. Because of the very strong similarity of the (e,α) and (p,α) data, any model of fragmentation should be tested against both data sets.

One of the earliest models proposed to explain inclusive data was a two step model[4] in which an equilibrated excited source nucleus with a mass near the target nucleus is produced in the first step, and a fragment is evaporated from this source in the second step. It has already been pointed out[5] in a rapidity analysis of the (p,α) data at 200–500 MeV incident proton kinetic energy that the momenta of such sources are significantly larger than the projectile momenta. This implies that a large amount of momentum be carried off at 180° to the beam. The (e,α) reaction is a good test of this model since the electromagnetic vertex strongly favors forward scattering of the electron.[6] We have performed the standard rapidity analysis of the (e,α) data[2] for α's emitted with 30 to 50 MeV kinetic energy. We find that the ratio of source momentum to projectile momentum is about 5, similar to ratios found in the (p,α) analysis. Because the electron is very likely scattered into the forward direction, conservation of momentum implies that the target nucleus must lose at least two high energy nucleons at 180° to the beam (for a 40 MeV α) just to produce a source all of whose excitation energy goes into the kinetic energy of one fragment. A more realistic source with more excitation energy requires even more backward emitted nucleons. Still larger numbers of backward emitted nucleons were found to be required in the (p,α) analysis. It is very difficult to imagine a model in which this is the most likely source velocity. In fact, the nickel (e,α) data require a source with the same momentum as the electron to have only about ten nucleons. Hence, we feel that models which involve a thermally equilibrated target nucleus are argued against by both the (e,α) and (p,α) data.

At the other extreme are direct knockout models[7] in which the projectile strikes a cluster of nucleons moving with high momentum, a model analogous to one[8] which successfully describes inclusive proton emission in (p,p') and (γ,p) reactions. Using this approach there are three parameters: $n_{\rm eff}$, the effective number of clusters in the nucleus, E^*, the average excitation energy of the residual nucleus, and lastly k_0, appearing in the cluster momentum distribution, which goes like $\exp(-k/k_0)$ for large cluster momentum, k. The p-cluster scattering amplitude is assumed to be the on-mass-shell elastic amplitude. This can be extracted from $d\sigma/dt$. We fitted the intermediate energy data in the literature by

$$\frac{d\sigma}{dt} = 106A^{1.65}\exp(5.5A^{1.06}t)\ \ \text{mb/GeV}^2\ , \qquad (1)$$

where the four-momentum transfer t has units of

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GeV^2. With these assumptions and using the integration approximation described in Ref. 6, we found that k_0 in MeV/c (and E^* in MeV) had values of 80 (20), 90 (35), and 100 (40) for ^{4}He, ^{12}C, and ^{16}O, respectively, emitted from Ag. Shown in Fig. 1 is a comparison of the direct knockout predictions with the data[9] for these fragments observed at 90°. The fit was made to data at 20°, 90°, and 160° simultaneously, which is why the curves do not go straight through the data.

The fit is reasonably good, and the average excitation energies are not grossly different from what one might expect. Although one might expect n_{eff} to be small, we found for a silver target that the values were about $\frac{1}{2}(A_T/A_f)$ for ^{4}He and $\frac{1}{10}(A_T/A_f)$ for ^{12}C and ^{16}O, where A_T and A_f are the target and fragment mass numbers, respectively. Further, it was found[7] for α emission that n_{eff}/A_T actually decreased for light targets whose ground states might be expected to have a larger fraction of α clusters (e.g., ^{12}C, ^{9}Be) compared to heavy targets. The absence of a quasifree peak [and any significant analyzing power[10]], in contrast to the characteristics of the (p,p') reaction, also argue against the preformed cluster model. Hence, although the model gives acceptable fits to the inclusive data, it has the above mentioned interpretational problems. An attempt to fit the (e,α) data with the direct knockout model was inconclusive.[6]

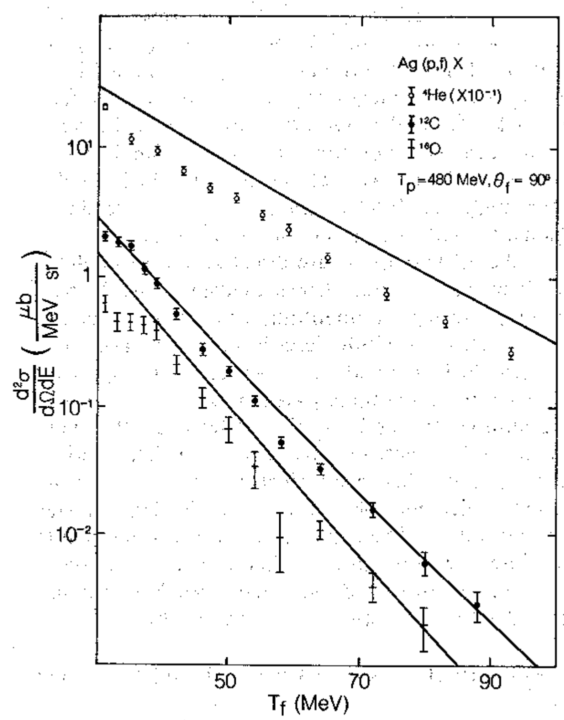

FIG. 1. Comparison of direct knockout model with experiment (Ref. 9) for ^{4}He, ^{12}C, and ^{16}O fragments emitted at 90° from 480 MeV protons on a silver target.

The lack of any significant analyzing power for (p,α) may argue for multiple scattering, probably in the pickup or coalescence of nucleons near the nuclear surface to form the fragment. This approach was first investigated some years ago,[11] although the steps which led up to the final coalescence state were not treated in detail and no explicit or implicit mechanism for the production of the coalescing nucleons was given. What is often called the coalescence model in heavy ion physics[12] is a model in which there are multiple scatterings of the incident projectile to produce a cascade of nucleons, some of which coalesce. We feel that cannot be the case for noncomposite projectiles, since multiple scatterings of the electron would reduce the $(e,\alpha)/(p,\alpha)$ ratio to many powers of $e^2/4\pi\hbar c$ ($\equiv\alpha_{\text{em}}$) lower than the observed value[6] of roughly $\alpha_{\text{em}}{}^2$. Further, fragment formation would be difficult because of the much smaller e-n coupling compared to e-p: Energetic neutrons would have to be produced through secondary p-n scatterings.

We propose that a more appropriate mechanism, which we will call the snowball model to avoid confusion with the models discussed above, uses coalescence as a final step but assumes that there is one primary scattering of the projectile [so that $(e,\alpha)/(p,\alpha)\sim\alpha_{\text{em}}{}^2$] and it is the nucleons involved in the A_f-1 multiple scatterings of the first struck nucleon that form the observed fragment. The cross section is then of the approximate form

$$\frac{1}{C_{Tf}}\frac{d^2\sigma(p,\text{frag})}{d\Omega_f\,dE_f}=\frac{d^2\sigma(p,N')}{d\Omega\,dE}\times\left[\frac{1}{\sigma_R}\frac{d^3\sigma(p,N')}{d^3p}V_s\right]^{A_f-1}, \qquad (2)$$

where the first cross section on the right hand side (rhs) is the inclusive (p,N') cross section at θ_f and $E=E_f+E^*$ [we assume $(p,n)\simeq(p,p')\equiv\frac{1}{2}(p,N')$]. The combinatoric factor C_{Tf} is given by

$$C_{Tf}=\frac{Z_T!N_T!A_f!(A_T-A_f)!}{N_f!(N_T-N_f)!Z_f!(Z_T-Z_f)!A_T!}. \qquad (3)$$

Fortunately, $(1/A_T)\,d^2\sigma/d\Omega\,dE$ for (p,p') at $T_p=50-100$ MeV (the energies appropriate for the secondary scatterings) and at forward angles is roughly constant with an average about 40–60 μb/MeV sr nucleon. As well, $(1/A_T)\sigma_R$ has a value[3] of about 25 mb/nucleon, similar to the value of the free N-N total cross section. The phase space volume V_s into which the struck nucleons must scatter to form the cluster, we parametrize at these low velocities as $\frac{4}{3}\pi p_s^3$. A plot of $\log_{10}\{C_{Tf}^{-1}[d^2\sigma(p,\text{frag})/d\Omega\,dE]\}$ vs A_f-1 allows extraction of p_s. For electron induced reactions, the only change is that the first cross section on the rhs is replaced by that for the (e,p) reaction.

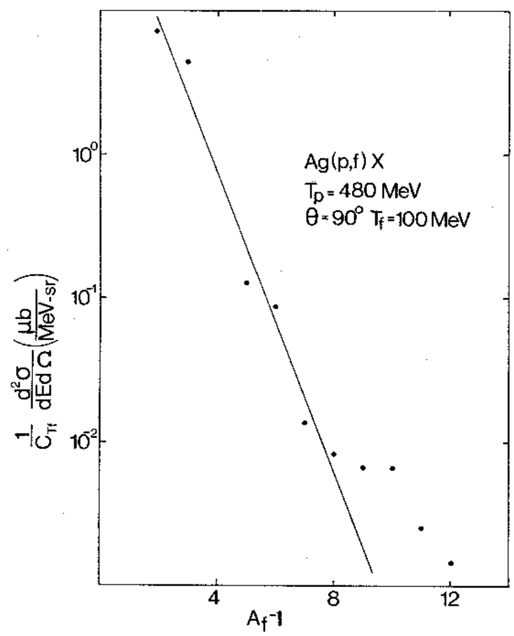

FIG. 2. $\mathrm{Log}_{10}(C_{Tf}^{-1}\, d^2\sigma/d\Omega\, dE)$ vs A_f-1 for fragments emitted at 100 MeV and other conditions as in Fig. 1. The points are from smooth fits to the data of Ref. 9.

We performed this fit for several angles and energies of the observed fragments and found that the fits consistently gave $p_s \simeq 140$ MeV/c. A sample is shown in Fig. 2, the data points[9] being the average of all major isobaric contributors to a given value of A_f. These new data from TRIUMF allow a better test of the model than would be obtained by analysis of data for an individual fragment: extraction of p_s from an individual fragment involves taking p_s to a large power and hence, large changes in the data will be hidden in small changes in p_s. The fit was to A_f in the range 3 to 9.

Since we have neglected Pauli blocking, we would intuitively expect that p_s should have a value less than the Fermi momentum, and so the 140 MeV/c result obtained here is quite acceptable. Although we have not shown the detailed angle and energy dependence the agreement is generally good to about 50% up to $A_f \simeq 9$. Above this, the momenta per fragment nucleon are below 150 MeV/c, and the approximations in (2) are no longer valid. Treatment of isotopically separated fragments and predictions for (e, fragment) reactions will be given in more detail later.

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