Effects of Collectivity on Target-Fragmentation Reactions

J. B. Cumming
Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 21 September 1979)

A new approach based on the collective tube model is developed for understanding momentum transfer to target fragments in high-energy hadron-nucleus collisions. Collectivity manifests itself in an enhanced dependence of momentum transfer on projectile energy, consistent with experimental results for deep-spallation reactions. The effective target for ^{149}Tb production from ^{197}Au by high-energy protons is deduced to consist of 3.1 ± 0.4 nucleons. Extensions of this model to nucleus-nucleus collisions are discussed.

Investigations of hadron-nucleus collisions at high energies offer possibilities for probing the space-time character of strong interaction processes at small distances. Experimental data have been interpreted as showing that asymptotic final states of the fastest secondary particles are reached only in distances $\gtrsim 10$ fm,[1] and that the immediate product of a hadron-nucleon collision is a state similar to the incident hadron.[2] Such conclusions follow from the observed weak dependence of the number of secondary particles, i.e., the multiplicity, on nuclear size and projectile energy.[3] Cascade development in nuclear matter appears to be suppressed relative to the predictions of a multiple, independent collision model (MICM) which treats the interaction as a series of quasifree particle-particle scattering events.[4]

The collective tube model (CTM)[5] represents another approach to understanding such phenomena. A salient point in the CTM is that the incident particle sees a nucleus that is Lorentz contracted to a thin disk. Consequently, nucleons in the path of the incident hadron can be viewed as acting collectively and in a first-order approximation can be considered as a single object, an effective target which may have a mass greater than that of an individual nucleon. Evidence of collectivity has been reported by Vary, Lassila, and Sandel,[6] who found that subthreshold $\bar{p}$ production data were more consistent with the predictions of the CTM than with those of an MICM which included effects of Fermi motion. While the CTM has been applied primarily to particle production, it has been speculated recently[7,8] that it might account for low momentum transfers and sideward-peaked angular distributions of target-fragmentation products. In this Letter, the CTM is used to analyze quantitatively longitudinal momentum transfers to target fragments from hadron-nucleus collisions. It is shown that experimental data for a proton-induced deep-spallation reaction are consistent with an initial interaction involving several nucleons.

Consider the single-particle inclusive reaction in which a projectile of mass m_p, momentum P, and total energy E interacts with a target m_T. A mass Δm is abraded from the target giving a prefragment (i.e., the precursor of the observed product) which recoils at an angle θ to the beam direction with a momentum q. The remainder of the system is treated kinematically as a single object having mass w. This "missing mass" includes fragments of the projectile, the Δm abraded nucleons, any particles which may be produced during the collision, and the relative kinetic energies of all these in their center-of-mass system. It follows from the conservation laws that the longitudinal momentum transfer $q_{\parallel}$ $(=q \cos\theta)$ is given by[9]

$$2Pq_{\parallel} = 2E\Delta E - \Delta E^2 + q^2 + w^2 - m_p^2 - \Delta m^2 - 2(E - \Delta E)\Delta m. \quad (1)$$

In this equation, $\Delta E = E^* + E_S + T_R$, where E^* is the excitation energy of the prefragment, T_R is its kinetic energy, and E_S is the separation energy of Δm from m_T. E^* will be expended subsequently to form the observed product. For the special case $\Delta m = 0$, Eq. (1) reduces to the Ericson equation,[10]

$$2Pq_{\parallel} = 2E\Delta E - \Delta E^2 + q^2 + w^2 - m_p^2, \quad (2)$$

which has been applied successfully to $(p, p\pi^+)$ reactions in complex nuclei.[11]

The original contribution of the present work is the introduction into Eq. (1) of the value of w^2 for the coherent interaction of the projectile with the effective target Δm;

$$w^2 = (E + \Delta m)^2 - P^2 = m_p^2 + \Delta m^2 + 2E\Delta m. \quad (3)$$

Here, the term $2E\Delta m$ is the square of the center-of-mass energy available for particle production. It is immaterial for our development whether these particles are actually produced or whether this remains as relative kinetic energy of the constituents of the w system. However, collectivity has important effects on the production of massive particles such as $\bar{p}$, ψ/J, and W.[6] Combining Eqs. (1) and (3) we obtain

$$2Pq_{\parallel} = 2\Delta E(E + \Delta m) + q^2 - \Delta E^2. \quad (4)$$

The last two terms are generally small and may be ignored at high energies, so that

$$q_{\parallel} \approx \Delta E(E/P + \Delta m/P). \quad (5)$$

Within the framework of the CTM, mean momentum transfer at high energies depends on two parameters: ΔE, the high-energy limit for $q_{\parallel}$, and the mass of the effective target, Δm, which governs the dependence of q on the projectile momentum. Equations indentical in form to Eq. (5) have been derived by Turkevich[12] on the basis of a single-collision model and by Abul-Magd, Hufner, and Schurmann[13] from an MICM approach. However, in both those cases, Δm was uniquely identified as the mass of a single nucleon, m_n. This need not be so for the CTM.

In order to obtain values of Δm from experimental data, it is convenient to define from Eq. (5) a reduced momentum

$$\beta q_{\parallel} = \Delta E + \Delta E \Delta m/E, \quad (6)$$

which is linear in E^{-1} with intercept ΔE and slope $\Delta E \Delta m$. Data for two different proton-induced target-fragmentation reactions, ^{24}Na production from ^{27}Al (Ref. 14) and ^{149}Tb formation from ^{197}Au,[15] are presented in this form in Figs. 1(a) and 1(b), respectively. Solid lines in both figures are least-squares fits of Eq. (5) to the points for which $E \geq 2.5$ GeV. The parameters derived for ^{24}Na are $\Delta E = 54 \pm 2$ MeV and $\Delta m = (0.9 \pm 0.2)m_n$. Since $\Delta m = m_n$ within errors we cannot distinguish between the different models for this simple reaction in a low-mass target. As a consequence, a linear relationship (the solid line and its dashed extension) fits the data to much lower energies than would be expected on the basis of the CTM. It has been suggested that this model might only be valid above ≈ 8 GeV.[7]

Results for ^{149}Tb production [Fig. 1(b)] are also consistent with a linear relationship at high energies for which $\Delta E = (269 \pm 12)$ MeV and $\Delta m = (3.1 \pm 0.4)m_n$. They are inconsistent with the $\Delta m = m_n$ dependence predicted by the MICM or Turkevich model which is shown as the dashed line. Note, however, that there is evidence for a failure of the CTM for this deep-spallation reaction at proton kinetic energies below 1.7 GeV. The values

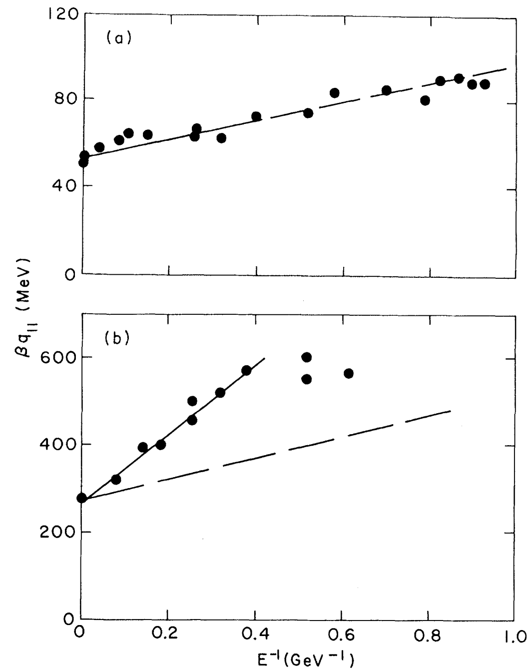

FIG. 1. Dependence of reduced longitudinal momentum ($\beta q_{\parallel}$) on reciprocal of the proton's total energy. (a) Data for ^{24}Na production from Al from Ref. 14; (b) points for ^{149}Tb production from Au from Ref. 15. Solid lines in (a) and (b) are least-squares fits to the data for $E > 2.5$ GeV. The dashed line in (a) is an extension of the solid one to lower energies. The dashed line in (b) shows the dependence predicted by the MICM or the Turkevich model (see text).

of ΔE derived for both reactions agree with those reported previously.[14,15] The substantially higher value for ^{149}Tb production reflects the greater energy required to remove 48 nucleons from ^{197}Au compared with only 3 from ^{27}Al. (E^* is the dominant contributor to ΔE.) Values of Δm for average proton-nucleus collisions have been estimated[1] from cross-section measurements to be given by $0.7A^{0.31}$, i.e., 1.9 for Al and 3.6 for Au. This implies that processes leading to ^{24}Na are more peripheral than an "average" event in Al while ^{149}Tb formation is more nearly representative of average behavior in Au.

A note of caution is appropriate at this point. What is determined experimentally is the momentum or velocity of some final product while the model applies to an excited prefragment. If the deexcitation step is not isotropic or symmetric about 90° in the moving system, analysis of experimental data in terms of a two-step model will give an incorrect value of $q_{\parallel}$. For the two cases discussed above, detailed experiments[16] are consistent with the assumption of symmetry. However, deviations have been observed for light fragments ejected from heavy-element targets by gigaelectronvolt protons.[17]

Many features of target fragmentation reactions induced by relativistic heavy ions appear similar to those of incident hadrons. For a wide range of products, single-particle inclusive cross sections depend on projectile type only via a total-cross-section term, consistent with the hypotheses of factorization and limiting fragmentation.[18] Momentum transfer in heavy-ion–induced reactions has been described as a frictional effect[13] occurring as the abraded nucleons climb out of the nuclear potential well one at a time, an MICM approach. To the extent that collective effects are important in nucleus-nucleus collisions, kinematics of the more general type with $\Delta m \neq m_n$ may be expected to apply.

Momentum transfer in projectile fragmentation is known to depend only weakly on target mass[19] (<10% variation) and the reverse is expected for target fragmentation. Equation (6) may be modified to show the projectile mass dependence explicitly;

$$\beta q_{\parallel} = \Delta E[1 + (\Delta m/m_p)(1-\beta^2)^{1/2}]. \quad (7)$$

If ΔE and Δm are the same for a given product, then momentum transfer in a heavy-ion–induced reaction will be lower than in one induced by a proton of the same β. Values of $q_{\parallel}$ for 2.1-GeV/nucleon ^{12}C ions are predicted to be close to those of 28-GeV protons, consistent with experimental data for Au targets.[20] On the other hand, limited data for reactions of ^1H, ^4He, and ^{12}C with Cu suggest[21] that it is the ratio $\Delta m/m_p$ which is projectile invariant, rather than Δm by itself. More data are needed to resolve this apparent contradiction. It would be particularly interesting to study the reactions of energetic π mesons to explore further the dependence of momentum transfer on projectile mass.

In summary, it has been shown that the CTM can account for several aspects of target fragmentation reactions, most notably the rapidly decreasing momenta of deep-spallation residues at energies above several GeV. It is thought that the model and the equations developed above will serve as a new and useful framework for systematizing and interpreting a wide variety of experimental data.

The author is indebted to L. P. Remsberg for numerous helpful discussions. This work was performed under the auspices of the U. S. Department of Energy.

[1]C. Halliwell, J. E. Elias, W. Busza, D. Luckey, L. Votta, and C. Young, Phys. Rev. Lett. 39, 1499 (1977).

[2]J. E. Elias, W. Busza, C. Halliwell, D. Luckey, L. Votta, and C. Young, Phys. Rev. Lett. 41, 285 (1978).

[3]For a summary of experimental data, see C. Halliwell, in *Proceedings of the Eighth International Conference on Multiparticle Dynamics, Kaysersberg, France, 1977,* edited by R. Arnold, J. B. Gerber, and P. Schübelin (Centre National de la Recherche Scientifique, Strasburg, France, 1977).

[4]H. W. Bertini, A. H. Culkowski, O. W. Hermann, N. B. Gove, and M. P. Guthrie, Phys. Rev. C 17, 1382 (1978).

[5]G. Berlad, A. Dar, and G. Eilam, Phys. Rev. D 13, 161 (1976); Meng Ta-chung, Phys. Rev. D 15, 197 (1977).

[6]J. P. Vary, K. E. Lassila, and M. S. Sandel, Phys. Rev. C 20, 715 (1979).

[7]S. Biswas and N. T. Porile, Phys. Rev. C 20, 1467 (1979).

[8]B. D. Wilkins, S. B. Kaufman, E. P. Steinberg, J. A. Urbon, and D. J. Henderson, Phys. Rev. Lett. 43, 1080 (1979).

[9]We adopt the convention $c = 1$.

[10]T. Ericson (private communication); see also L. P. Remsberg, Phys. Rev. 138, B572 (1965), and A. M. Poskanzer, J. B. Cumming, and L. P. Remsberg, Phys. Rev. 168, 1331 (1968).

[11]Remsberg, Ref. 10; Poskanzer, Cumming, and Remsberg, Ref. 10.

[12]A. Turkevich, as quoted by N. T. Porile and N. Sugarman, Phys. Rev. 107, 1410 (1957). Although the forms are the same, the implied mechanisms are different. The Turkevich equation arises from the assumption of a single elastic collision is which the low-energy partner is captured by the target nucleus. It may be derived from Eq. (2) by setting $w = m_p = m_n$ and $q^2 = \Delta E(\Delta E + 2m_n)$. In the CTM, $\Delta m = m_n$ also corresponds to a single collision (not necessarily elastic), but all particles are presumed to escape.

[13]A. Abul-Magd, J. Hufner, and B. Schurmann, Phys. Lett. 60B, 327 (1976).

[14]L. Winsberg, E. P. Steinberg, D. Henderson, and A. Chrapkowski, unpublished, and earlier work cited therein.

[15]L. Winsberg, M. W. Weisfield, and D. Henderson, Phys. Rev. C 13, 279 (1976), and earlier work cited therein.

[16]A. M. Poskanzer, J. B. Cumming, and R. Wolfgang, Phys. Rev. 129, 374 (1963); V. P. Crespo, J. B. Cumming, and J. M. Alexander, Phys. Rev. C 2, 1777 (1970).

[17]J. B. Cumming, R. J. Cross, Jr., J. Hudis, and A. M. Poskanzer, Phys. Rev. 134, B167 (1964); A. M. Poskanzer, G. W. Butler, and E. K. Hyde, Phys. Rev.

C 3, 882 (1971); G. D. Westfall, R. G. Sextro, A. M. Poskanzer, A. M. Zebelman, G. W. Butler, and E. K. Hyde, Phys. Rev. C 17, 1368 (1978).

[18]See the review by A. S. Goldhaber and H. H. Heckman, Annu. Rev. Nucl. Part. Sci. 28, 161–205 (1978).

[19]D. E. Greiner, P. J. Lindstrom, H. H. Heckman, B. Cark, and F. S. Bieser, Phys. Rev. Lett. 35, 152 (1975).

[20]S. B. Kaufman, E. P. Steinberg, and B. D. Wilkins, Phys. Rev. Lett. 41, 1359 (1978).

[21]J. B. Cumming, P. E. Haustein, and H.-C. Hseuh, Phys. Rev. C 18, 1372 (1978).

Comparison of the Reaction ^{4}He$(p, 2p)$ ^{3}H at Intermediate Energies with the Distorted-Wave Impulse Approximation

M. B. Epstein, D. J. Margaziotis, and J. Simone
California State University, Los Angeles, California 90032

and

D. K. Hasell, B. K. S. Koene, B. T. Murdoch, and W. T. H. van Oers
University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

and

J. M. Cameron, L. G. Greeniaus, and G. A. Moss
University of Alberta, Edmonton, Alberta T6G 2J1, Canada

and

J. G. Rogers
TRIUMF, Vancouver, British Columbia V6T 1W5, Canada

and

A. W. Stetz
Oregon State University, Corvallis, Oregon 97331

(Received 16 October 1979)

The ^{4}He$(p, 2p)^3$H reaction has been measured at 250, 350, and 500 MeV using symmetric geometries. The energy dependence of the cross section at zero recoil momentum and angular distributions are presented. The data are compared to distorted-wave impulse-approximation (DWIA) calculations. Unlike at lower energies, the zero-recoil-momentum data are well described by the DWIA at these energies. For the angular distributions, the DWIA increasingly underestimates the data as the recoil momentum is increased.

The reaction ^{4}He$(p, 2p)^3$H has previously been measured at 65, 85, 100,[1] 156,[2] 460,[3] and 590[4] MeV with the primary objective of studying quasielastic p-p scattering in the p-^{4}He system. These data were taken in kinematically complete experiments using coplanar symmetric geometries and were compared to distorted-wave impulse-approximation (DWIA) predictions. The data taken under conditions of zero recoil momentum for the ^{3}H spectator could only be fitted by the DWIA if the calculations were normalized by a factor of ~ 0.5, except at 590 MeV where the calculations agreed fairly well with the data.[5] Since the 460- and 590-MeV data differed by a factor of 1.6 (see Fig. 1) and since there were no data between 156 and 460 MeV, the reaction ^{4}He$(p, 2p)^3$H was measured at 250, 350, and 500 MeV in an attempt to resolve the existing experimental ambiguity and to understand better the applicability of the DWIA to this reaction. In addition, the measured region of the ^{3}H recoil momentum (P_R) was extended to 500 MeV/c, 200 MeV/c beyond the previous limit.

The data were obtained using the variable-energy proton beam of the TRIUMF cyclotron and were collected at symmetric geometries using four range telescopes interfaced to a minicomputer. Each range telescope consisted of a plastic scintillator, a set of vertical and horizontal multiwire-proportional–counter planes, appro-

