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DYNAMICS OF HEAVY ION TRANSFER REACTIONS*

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Abstract

An exact calculation has been made of the kinematics for the transfer of one or more nucleons from projectile to target at bombarding energies above the Coulomb barrier. The calculation presumes that the transfer occurs in an overlapping region of the projectile and target. A comparison of calculated results with measurements of angular momentum transfer shows much better agreement than obtained from purely peripheral transfer calculations. The calculation also reproduces in detail the dependence of ejectile velocities on the ejectile mass and charge.

The dynamics of the quasi-elastic transfer of large numbers of nucleons from a heavy ion projectile to a target nucleus at energies above the Coulomb barrier are still poorly understood. Various observable features of these reactions have been separately modelled, but a consistent, unified picture has not yet emerged. For instance, Wilczynski et al. [1] and Abul-Magd [2] have analyzed cross sections and angular momentum transfers, using models in which there is strong spatial overlap between the colliding nuclei. Udagawa et al. [3] made exact finite range DWBA calculations for the reaction $^{181}Ta(^{14}N,^{4}He)^{191}Pt$ and concluded that the collisions responsible for the ^{4}He production were centered around a radius that was about 2 fm smaller than the sum of the ^{14}N and ^{181}Ta radii.

Friedman [4] used approximate wavefunctions and spectroscopic factors to calculate the probability that a projectile breaks into an observed fragment and a residue that might be captured or that might escape. The projectile breakup probability is highest when the observed fragment is formed in contact with the target nucleus. In this model, the spatial overlap between projectile and target nucleus increases as the ejectile mass decreases.

On the other hand, Siemens et al. [5] deduced from a calculation of Q-values for transfer reactions near the Coulomb barrier that the reactions were purely peripheral. Brink [6] similarly assumed that the transfer of a small number of nucleons takes place in peripheral collisions. His linear and angular momentum-matching hypotheses are thought to explain why ejectiles resulting from small mass transfers retain nearly the projectile velocity, as observed in many experiments. However, approximations in the Brink model restrict its application to systems in which the projectile mass and the mass of the transferred nucleons are much smaller than the target mass. Moreover, the incident energy must be high enough that the ejectiles emerge near 0° in the lab.

We present here a semiclassical nonrelativistic calculation of ejectile energies and the angular momentum transferred to the target in heavy-ion stripping reactions. It is based on the momentum-matching conditions of Brink [6] but assumes a geometry of overlapping nuclei similar to that of Abul-Magd [2]. The calculation treats all of the reaction kinematics exactly and can be applied to all projectile-stripping reactions at energies above the Coulomb barrier.

Figure 1 illustrates the geometry of the model for the reaction $A_2(A_1,A_3)A_4$, which is assumed to proceed in three steps. First, the projectile with initial velocity $\vec{v}_0$ approaches the target along a Coulomb trajectory: at the point where the transfer begins, the projectile has Coulomb-scattered through angle Θ_1 and has decelerated to a velocity $\vec{v}_1$, while the target has recoiled with velocity $\vec{v}_2$. The initial trajectory is such that at closest approach the projectile overlaps the target by an amount h, as shown in fig. 1. The spherical cap of height h (shown shaded in fig. 1) forms the cluster that will be transferred to the target. Thus the impact

parameter determines the mass of the transferred cluster. (The geometry is approximate, in that the cap's bottom has a flat surface, rather than the curvature of the target.) In the second stage, the projectile scatters into an angle $\Theta_3 = \Theta_1 + \Theta_S$, and the cluster A_c is transferred to the target. According to Brink's hypotheses [6], the total linear momentum of the cluster is conserved, and its angular momentum λ_2 around the target balances the dinuclear system's orbital angular momentum, so the total angular momentum normal to the reaction plane is also conserved. In the third stage, the ejectile A_3 is accelerated away from the target along a new Coulomb trajectory, and is observed at an angle Θ_3^∞ in the lab. The angle Θ_S is adjusted for each transfer channel so that Θ_3^∞ coincides with the lab angle of observation in the relevant experiments.

To be as precise as possible, the exact centers of mass (CM) for the final state constituents at the moment of transfer are used to calculate the Coulomb energies and angular momenta. (The mass and charge distributions are assumed to be the same.) Referring again to fig. 1, the distance h' locates the CM of the cap A_c, h" locates the CM for A_3, which consists of a sphere minus a cap, and h" locates the CM for the sphere-plus-cap, which comprises A_4.

For nuclei of finite radius, the point at which the final state is formed could occur anywhere from the point of initial contact ($R = R_1 + R_2$) to the point of closest approach ($R = R_1 + R_2 - h$). It is therefore a parameter that must be adjusted. Fixing it at a point approximately midway between the two limits gave results that are in good agreement with experimental data. The Coulomb and nuclear radius parameter r_0 was fixed at 1.4 fm.

A few details of the calculation are summarized below to illustrate the procedure for solution. Let $\vec{b}_i$ be the vector between the centers of mass for A_1 and A_2 at the moment of transfer ($R_1 + R_2 - h < |\vec{b}_i| < R_1 + R_2$). The initial Coulomb energy V_i is calculated using $|\vec{b}_i|$. In the final state the corresponding quantities are $\vec{b}_f$ and V_f. At the moment of transfer the initial velocities are

$$\frac{v_1}{v_0} = \frac{1}{1+A_2/A_1}\left[\cos\theta_1 + \sqrt{\cos^2\theta_1 - 1 + \frac{A_2^2}{A_1^2} + \frac{A_2}{A_1}\left(1 + \frac{A_2}{A_1}\right)\frac{V_i}{E_0}}\right]$$

$$\frac{v_2}{v_0} = \sqrt{\frac{1 - V_i/E_0 - v_1^2/v_0^2}{A_2/A_1}}$$

If the cluster has zero angular momentum in the projectile A_1, then the first Brink condition requires that it have angular momentum

$$\lambda_2\hbar\hat{z} = A_c(\vec{v}_1 - \vec{v}_4) \times \vec{R}_t$$

in the final nucleus A_4. (The x-y plane is the reaction plane, and $\vec{R}_t$ is the vector connecting the center of A_2 with the center of mass of the transferred cluster.) If the orbital angular momenta of the initial and final dinuclear systems are designated $\mathcal{L}_i^{CM}$ and $\mathcal{L}_f^{CM}$, then the second Brink condition requires

$$\lambda_2\hbar = \mathcal{L}_i^{CM} - \mathcal{L}_f^{CM} \quad .$$

Here $\vec{\mathcal{L}}_i = \mu_i(\vec{v}_1 - \vec{v}_2) \times \vec{b}_i$, and similarly for $\vec{\mathcal{L}}_f$. These two matching conditions, when combined with conservation of energy and linear momentum, allow the calculation of $\vec{v}_3$ and $\vec{v}_4$ as a function of Θ_3^∞. The results are termed the optimum conditions for transfer. The corresponding Q-value may be defined either at the Coulomb barrier (Q_e) or with the Coulomb energy difference assimilated:

$$Q = Q_e + V_i - V_f \quad .$$

A comparison of experimental ejectile energies [7] for the reaction of 338 MeV ^{20}Ne with ^{197}Au with calculated values is shown in fig. 2. The ejectile spectra were measured in Si(Li) telescopes while any coincident charged particles were detected with plastic scintillators subtending nearly 4π around the target. The experimental values shown in fig. 2 are for those fragments that were not in coincidence with additional charged particles. By this technique the contribution of projectile breakup reactions is eliminated from the ejectile spectra. The agreement is good and in particular two features of the experimental results are reproduced by the calculation. At a fixed Z, the energy per nucleon of the ejectile decreases with increasing ejectile mass. This comes about because the ejectile radius increases with mass, making the value of V_f become less negative and Q more negative. Second, at fixed A, the energy per nucleon of the ejectile decreases as Z decreases. Again, this effect is due to the variation of V_f with ejectile charge.

If the overlap is set equal to zero, to correspond to a strictly peripheral collision, the results shown as dashed lines in fig. 2 are obtained. The divergence between the peripheral and overlap calculations increases with the mass transferred. For the large mass transfers, the peripheral calculations are in poor agreement with the experimental values.

This calculation also predicts the angular momentum λ_2 transferred to the target, both for the optimum conditions and as a function of Q in the absence of the Brink matching conditions. Hsu et al. [8] have measured the angular momentum transferred to the target nucleus in reactions induced by ^{20}Ne ions of various energies on ^{181}Ta. Only a single ejectile fragment

was detected, so a two-body final state was certainly not observed in all cases. However, at the two lowest ^{20}Ne energies (150 and 200 MeV) it is likely that transfer reactions to two-body final states dominate, especially for the smaller mass transfers and for Q-values not too far from the optimum Q-value, Q^{opt}.

Figure 3 shows a comparison between the model calculations and the experiment of Hsu et al. [8] for the angular momentum transfer as a function of Q-value. The solid line marks the calculated angular momenta for the case of overlapping nuclei. Agreement is good for Q-values near or greater than Q^{opt} (marked with an arrow). For more negative Q-values the calculated angular momenta are always greater than the experimental values. A streamer chamber experiment [9] has shown that fragments with kinetic energies below the quasi-elastic peak are more likely to be produced by the breakup of the projectile, a process in which the angular momentum transferred to the target nucleus is probably small or even zero. Agreement of the inclusive experimental results with calculations based on a two-body final state model is therefore not to be expected at the more negative Q-values.

The dashed lines in fig. 3 show the calculated angular momentum transfer when the overlap is eliminated. These values correspond to peripheral transfers. In this case the transferred angular momenta are systematically too high, especially for the larger mass transfers. This reinforces our hypothesis that the more massive transfers occur at smaller impact parameters. We note that the Z = 8 channel shows a singularly poor agreement. This is probably due to a significant contribution from the $^{20}Ne \rightarrow {}^{16}O + \alpha$ breakup reaction in which little or no transfer of angular momentum is to be expected.

In this model, the geometrical overlap associated with a given mass transfer is assumed to be independent of projectile velocity. It follows that the angular momentum transferred in a given mass transfer will increase indefinitely with projectile velocity. If, however, the angular momentum transfer is limited by some critical value [1], the reaction to a two-body final state will either disappear at some projectile velocity or continue to higher velocities, perhaps with reduced probability, by exploiting partial waves smaller than those required by the overlap. In this latter case, there would presumably be an increased probability that the ejectile would be broken up during its passage through the edge of the target nucleus [4]. Experiments in which transfer events are distinguished from other mechanisms leading to the same ejectile have not yet been done over a large enough energy range to test the energy dependence of the overlap.

This calculation has introduced a number of refinements to the simple transfer model of Brink [6] in order to enlarge its applicability and also to see if a picture of overlapping nuclei better explains transfer data. We find that the new model, which relates the transferred mass to the impact parameter by a geometrical overlap of projectile and target, accurately predicts transfer Q-values for a broad range of reaction channels. If a purely peripheral (zero-overlap) reaction is calculated instead, the results are good for transfers involving small mass transfers but become increasingly inaccurate for very massive transfers. (The earlier models of Siemens [5] and Brink [6] correspond to the calculation for zero overlap.) The angular momentum transferred to the target in such reactions also depends on whether the nuclei overlap; we again find the data to be better explained by the overlap picture. We conclude that the momentum-matching hypothesis of Brink [6] is indeed a good explanation of the reaction dynamics, but that transfer reactions are not strictly peripheral.

Rather, the mass transfer appears to vary with impact parameter in the manner of Fig. 1. This accounts in a natual way for both the early deduction that few-nucleon transfer is a peripheral process, and the later evidence that massive transfer resembles incomplete fusion. It also makes a smooth connection with the abrasion and fireball models [10] that are used to describe noncentral nucleus-nucleus collisions at relativistic velocities. At some projectile velocity, the overlapping nucleons of both the projectile and the target emerge as a fireball rather than remaining bound in an excited nucleus. The questions of why and at what energy this process begins remain to be answered.

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FIGURE CAPTIONS

Fig. 1. The transfer reaction geometry. The shaded cap of height h contains the A_c nucleons to be transferred to the target. The distances h', h", and h"' in the final state locate the centers of mass of A_C, A_3, and A_4.

Fig. 2. The data points (ref. 7) are lab. energies of ejectiles resulting from transfer reactions in the system $^{20}Ne + ^{197}Au$ at 338 MeV. The errors are statistical only. Dash-dot lines are the result of calculations with overlap. The dashed lines show the calculation without the overlap. They correspond to peripheral collisions.

Fig. 3. The data points (ref. 8) are the angular momenta transferred to the target in the reaction $^{20}Ne + ^{181}Ta \rightarrow (Z,A) + X$, as a function of reaction Q-value. The charge Z refers to the ejectile. The solid lines are the calculated results for $\mathcal{L}_i^{CM} - \mathcal{L}_f^{CM}$ vs Q-value, for the case of geometric overlap. The dashed lines are calculated results for no overlap. The arrows locate the calculated optimum Q-values.

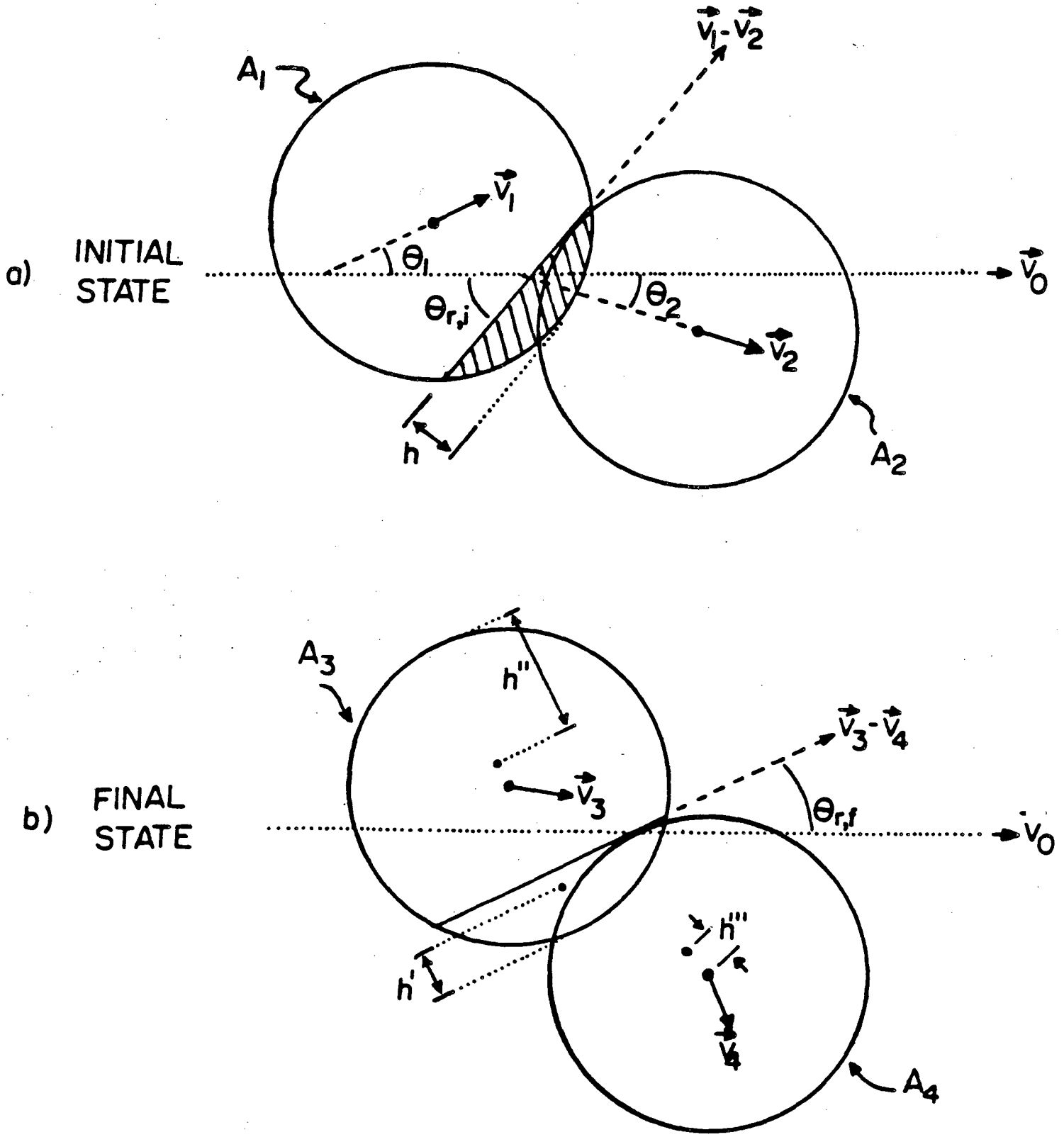

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Fig. 1

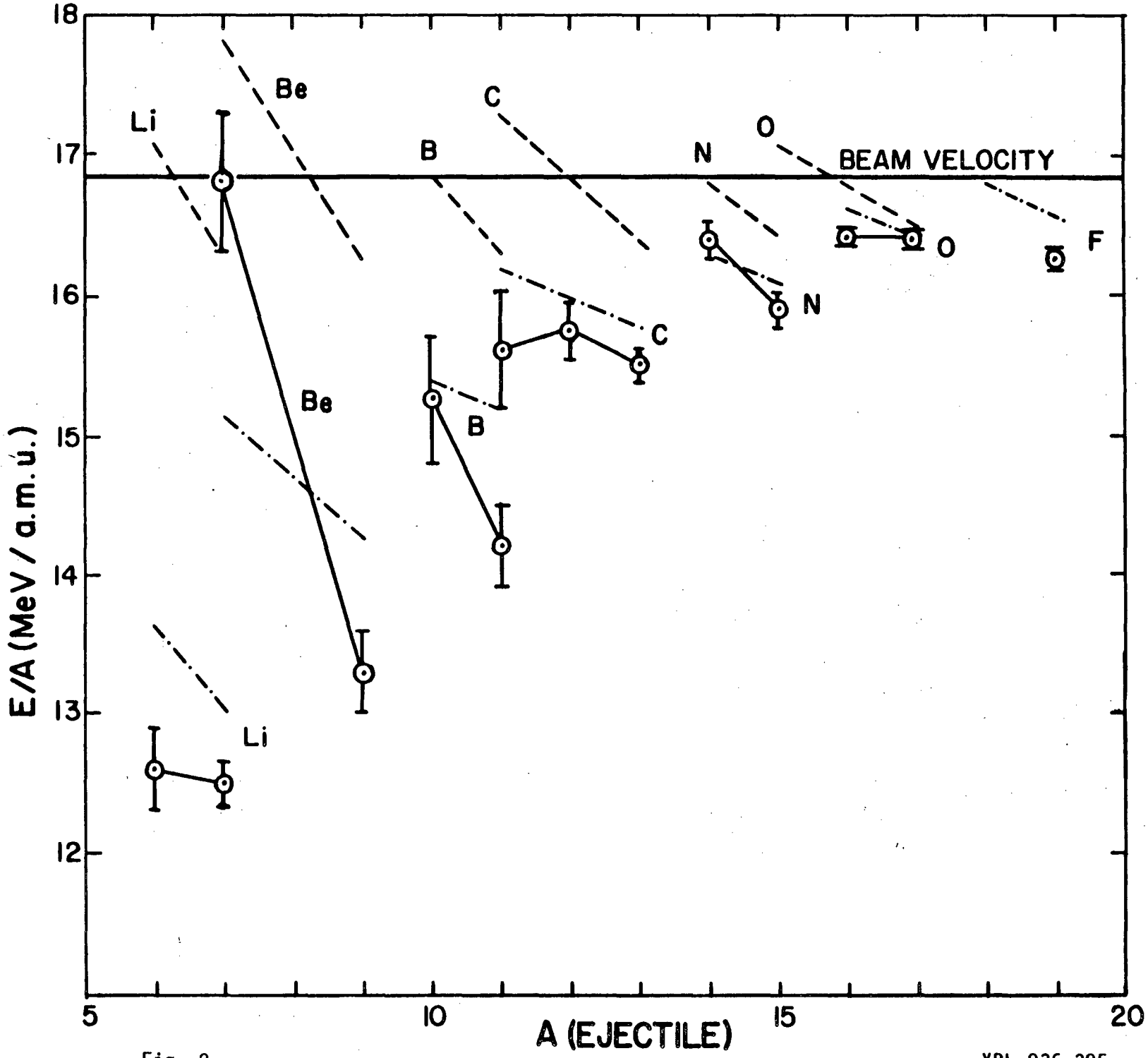

Fig. 2

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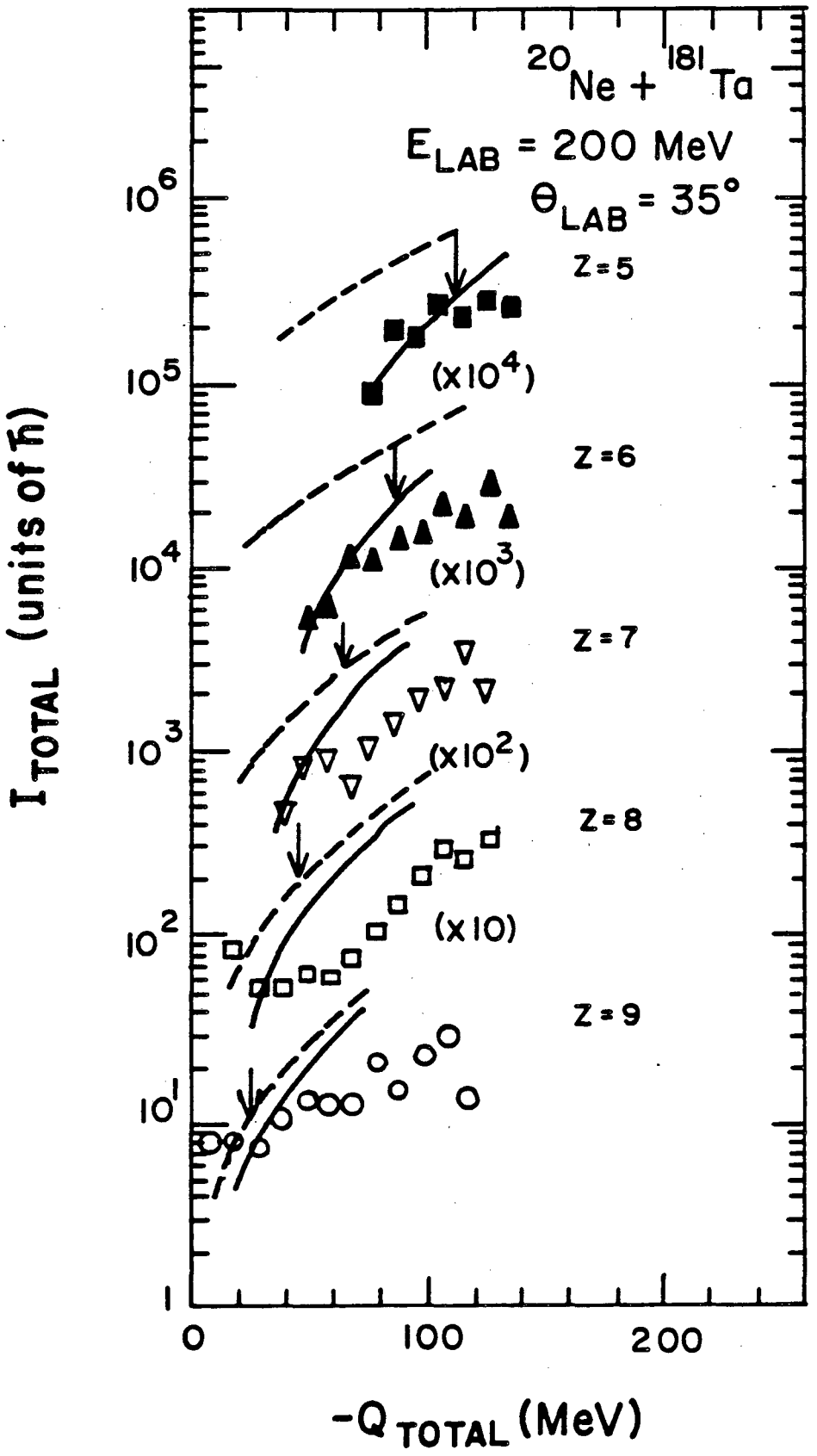

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Fig. 3

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