LBL-15539
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

RECEIVED
BERKELEY LABORATORY
MAY 16 1983
LIBRARY AND
DOCUMENTS SECTION

Submitted to Physics Letters

DYNAMICS OF HEAVY ION TRANSFER REACTIONS

B.G. Harvey and M.J. Murphy

February 1983

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-15539

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-15539

DYNAMICS OF HEAVY ION TRANSFER REACTIONS*

B.G. HARVEY[+]

Institut des Sciences Nucléaires
Grenoble 38026 France

and

M.J. MURPHY

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720
and
Nuclear Physics Laboratory
University of Washington, Seattle, WA 98195

[+]Permanent address: Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

*Work supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

This manuscript was printed from originals provided by the authors.

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 studied 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.

On the other hand, Siemens et al. [4] deduced from a calculation of Q-values for transfer reactions near the Coulomb barrier that the reactions were purely peripheral. Brink [5] 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 retain nearly the projectile velocity, as observed in many experiments [6].

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 [5] but assumes a geometry of overlapping nuclei similar to that of Abul-Magd [2]. The calculation uses no adjustable parameters and treats all the reaction kinematics exactly. It can be applied to all projectile-stripping reactions at energies above the Coulomb barrier.

Figure 1 illustrates our scenario 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 moment of transfer the projectile has 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 [5], the cluster's total linear momentum 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.

While formulating the reaction scenario, it became clear to us that 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 ($R = R_1 + R_2 - h$). We have arbitrarily chosen it to be the point midway between these two extremes: the results show this to be a reasonable choice. The Coulomb and nuclear radius parameter r_0 was fixed at 1.4 fm.

A few particulars 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

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

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 cluster's center of mass.) 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

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

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:

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

The mean energies for quasi-elastic ejectiles from three different reactions [6-8] are shown in fig. 2. The solid lines are the results of this calculation. Only the ^{16}O + CsI data [7] are known for certain to be for transfer reactions, but the other reactions were at sufficiently low energies that three-body final states are unlikely. The ^{20}Ne + ^{197}Au measurement [8] obtained isotope resolution for the ejectiles and thus provides the most complete comparison with the calculation. The agreement is good and in particular two features of the ^{20}Ne + ^{197}Au 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.

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. [9] 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. [9] 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 [7] 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 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 λ_2 when the overlap is eliminated. These values correspond to peripheral transfers. In this case

the transferred angular momenta are systematically too high: the discrepancy increases with transferred mass directly in proportion to the (missing) overlap. This reinforces our hypothesis that the more massive transfers occur at smaller impact parameters. We also note that the $Z = 8$ channel shows a singularly poor agreement. This is undoubtedly due to the significant $^{20}Ne \rightarrow {}^{16}O + \alpha$ breakup probability.

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. 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 model of the geometry and dynamics of transfer reactions 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 projectile and target emerge as a fireball rather than remaining bound in an excited nucleus. The questions of why and where this process begins remain to be answered.

This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

REFERENCES

[1] J. Wilczynski et al., Phys. Rev. Lett. 45 (1980) 606.

[2] A.Y. Abul-Magd, Z. Physik A298 (1980) 143.

[3] T. Udagawa, D. Price and T. Tamura, Phys. Lett. 118B (1982) 45.

[4] P.J. Siemens et al., Phys. Lett. 36B (1971) 24.

[5] D.M. Brink, Phys. Lett. 40B (1972) 37.

[6] C.K. Gelbke et al., Phys. Rep. 42 (1977) 312.

[7] M.J. Murphy et al., Phys. Lett. 120B (1983) 75.

[8] Ch. Egelhaaf and H. Homeyer, private communication (1982).

[9] C.C. Hsu et al., LBL Report 12512 (1981).

[10] G.D. Westfall et al., Phys. Rev. Lett. 37 (1976) 1202.

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 are lab energies of ejectiles observed in three measurements of heavy ion transfer reaction products. The lines are the calculated energies. The masses (A_c) and charges (Z_c) refer to the (presumed) transferred cluster. For ^{16}O + CsI and ^{16}O + ^{208}Pb, ejectile masses were not identified. The two points for each Z_c represent the expected most probable mass transfers.

Fig. 3. The data points 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.

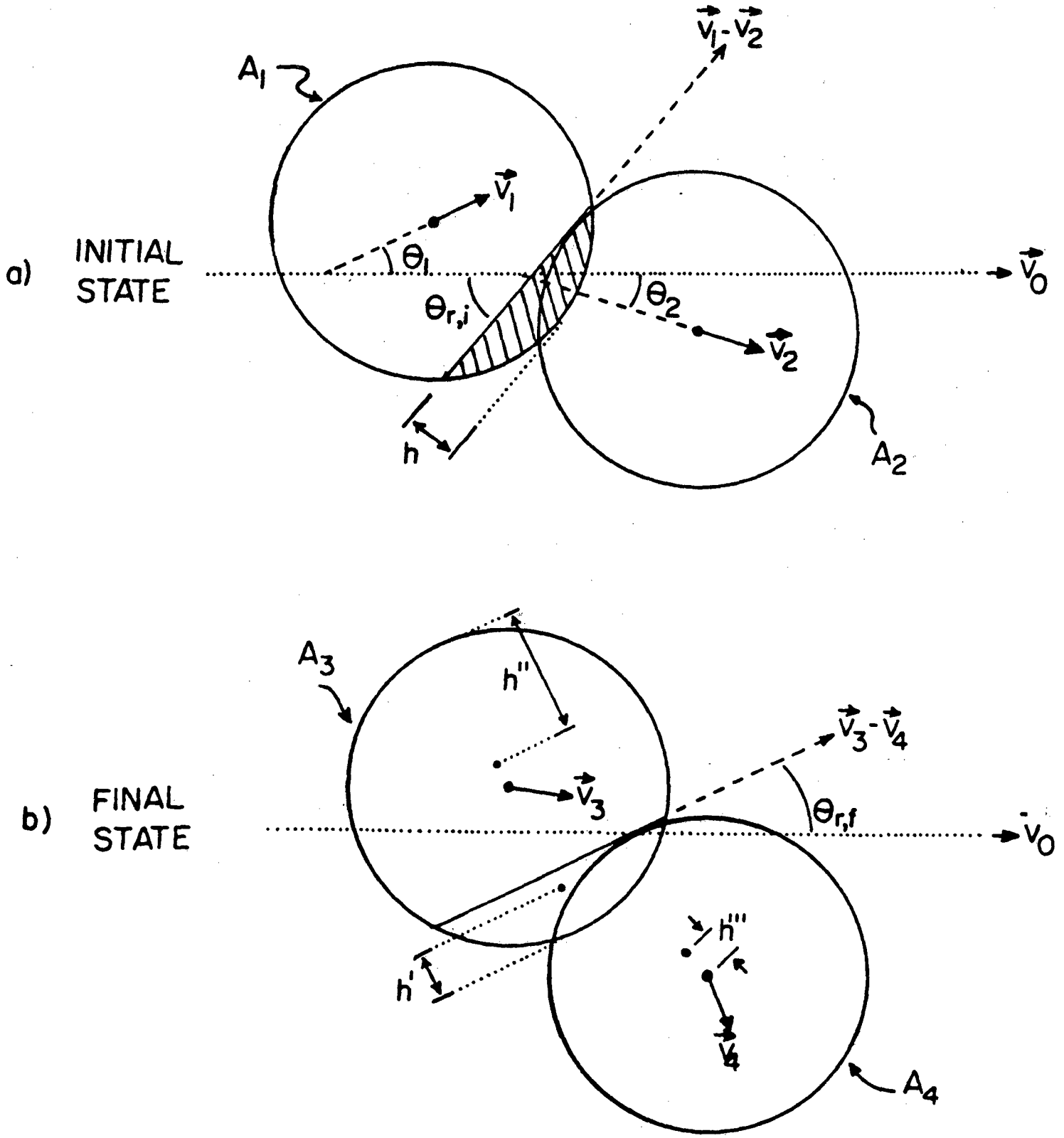
a)
INITIAL STATE
A_1
A_2
$\vec{v}_1 - \vec{v}_2$
$\vec{v}_1$
$\vec{v}_2$
$\vec{v}_0$
θ_1
θ_2
$\theta_{r,i}$
h
b)
FINAL STATE
A_3
A_4
h''
h'
h'''
$\vec{v}_3 - \vec{v}_4$
$\vec{v}_3$
$\vec{v}_4$
$\vec{v}_0$
$\theta_{r,f}$

Fig. 1

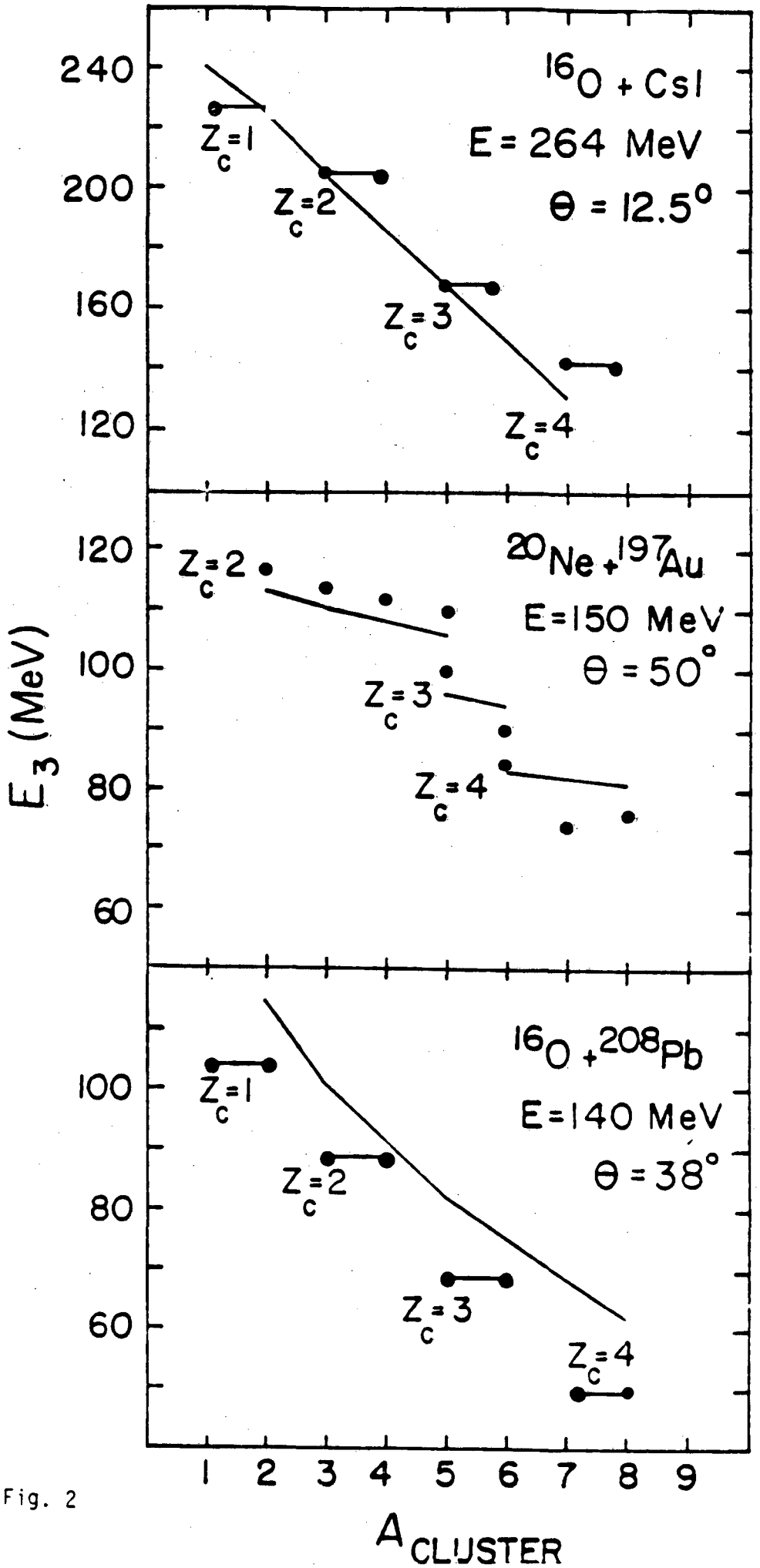
$^{16}O + CsI$
E = 264 MeV
$\Theta = 12.5^{o}$
$Z_c=1$
$Z_c=2$
$Z_c=3$
$Z_c=4$
$^{20}Ne + ^{197}Au$
E=150 MeV
$\Theta = 50^{o}$
$Z_c=2$
$Z_c=3$
$Z_c=4$
$^{16}O + ^{208}Pb$
E=140 MeV
$\Theta = 38^{o}$
$Z_c=1$
$Z_c=2$
$Z_c=3$
$Z_c=4$
E_3 (MeV)
$A_{CLUSTER}$

Fig. 2

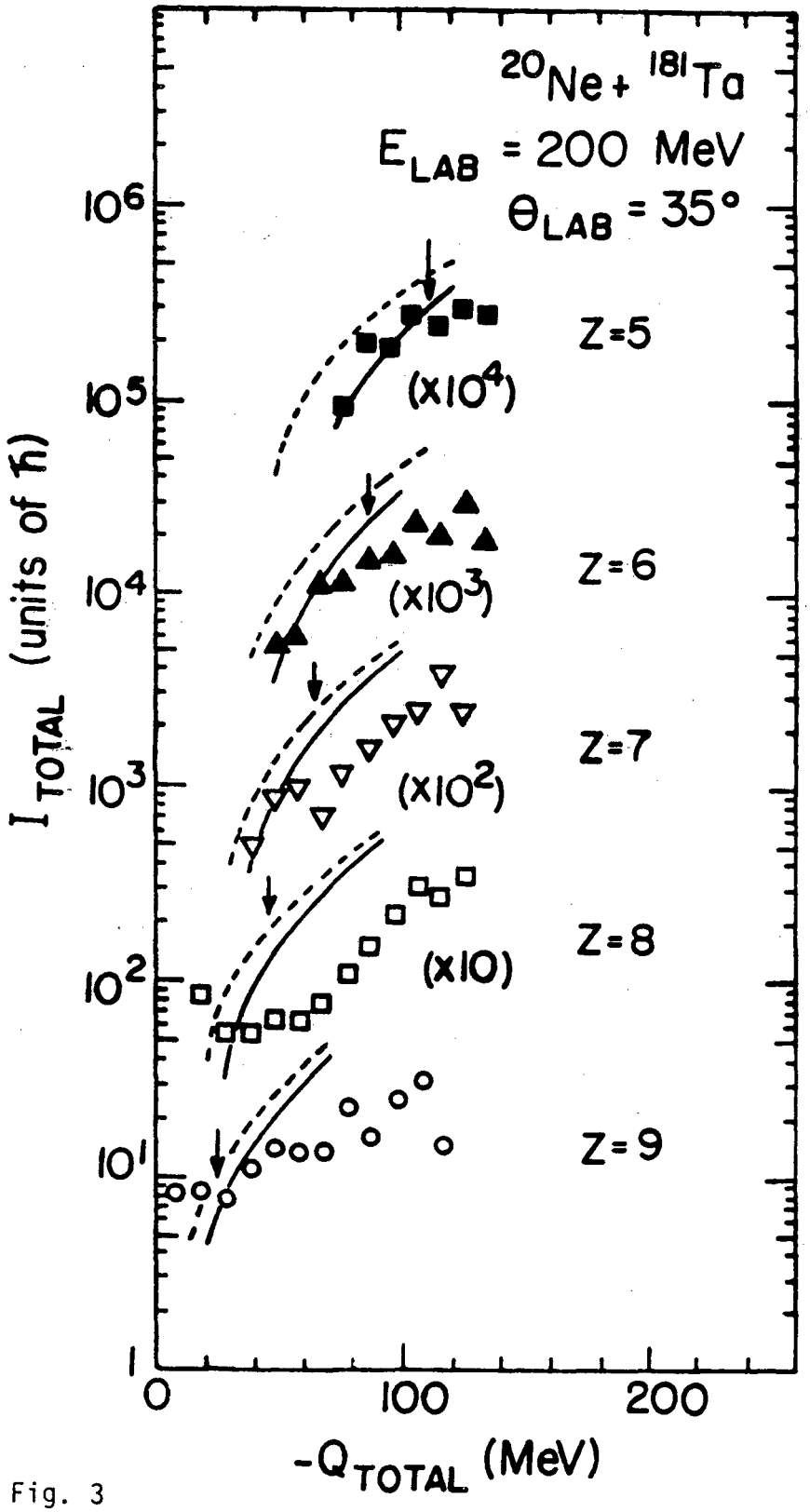
$^{20}Ne + ^{181}Ta$
E_{LAB} = 200 MeV
Θ_{LAB} = 35°
Z=5
(x10^4)
Z=6
(x10^3)
Z=7
(x10^2)
Z=8
(x10)
Z=9
I_{TOTAL} (units of ħ)
$-Q_{TOTAL}$ (MeV)
1
10^1
10^2
10^3
10^4
10^5
10^6
0
100
200

Fig. 3

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720