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IN HEAVY-ION TRANSFER REACTIONS

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ABSTRACT

We have measured the ratio of yields for a single proton transferred into versus out of a projectile in reactions involving four different heavy projectiles on each of five heavy targets. There is a strong preference to transfer the proton out of the projectile, which can be understood in terms of the potential energy of the two nuclei near contact.

*This work was performed under the auspices of the U. S. Atomic Energy Commission.

Nucleon transfer reactions have been rather extensively studied with light projectiles ($Z \leq 2$) on a wide variety of targets. With heavy projectiles ($Z > 2$), however, these studies have been carried out mostly using light targets[1]. The few studies made using both heavy projectiles and medium or heavy targets have been done radiochemically and have been mainly concerned with neutron transfers[1-3]. Recently, however, the reaction (^{12}C, ^{13}N) which transfers a proton from the target to the projectile, has been studied radiochemically using heavy targets[4] and the results yielded much lower cross sections than expected from the neutron transfer cases. Also in a recent radiochemical study of ^{12}C and ^{14}N on ^{115}In, it has been found[5] that the loss of two protons by the target appeared to be much less probable than the corresponding gain of two protons by the target. In the present work, using a counter telescope, we have studied the proton transfers in both directions using five targets between Ni and Au, and four projectiles between ^{10}B and ^{14}N. Although it is clear that these transfers are complex, we found a general trend that the transfer of a proton from a heavy target to the projectile is less favored than the transfer in the other direction. We propose that this can be understood as a simple effect of the potential energy when the target and projectile are near contact.

In these experiments we used a power-law type particle-identifier system with semiconductor detectors, whose operation has been described elsewhere[6]. In most of the measurements we used a two-counter telescope, consisting of a 36μ ΔE counter and a 500μ E counter; however, a few particle spectra were taken with a three-counter telescope (two ΔE counters) which had considerably better particle resolution, largely because the total ΔE thickness was greater, but it required particles of higher energies to penetrate to the E counter. Some typical particle spectra using the two-counter telescope are shown in fig. 1. The targets used were about 1 mg/cm^2 thick which, for any of our beams, corresponded to 1 MeV or less of energy deposition.

We confined our interest mainly to the one proton transfers and thus, for example, when we used ^{11}B projectiles we attempted to measure the ratio of ^{12}C to ^{10}Be produced. From spectra such as those in fig. 1 we could easily integrate the total yield of a given element, as the separations between different elements were quite good. However, it was more difficult to integrate accurately the isotopes of a given element, and we estimate an average uncertainty of around 30% in the ratio due to this effect, although in one or two cases with poor statistics it could be as large as a factor of two. An additional problem with the data analysis had to do with the energy region covered. The particles had to penetrate the ΔE detector and deposit at least 5 MeV in the E detector. This means that we did not look at the entire yield of a product, but only the yield corresponding to particles having a kinetic energy greater than a certain value. Our procedure was to calculate for each light product (^{12}C and ^{10}Be in the above example) the maximum possible energy, based on the ground state masses, and then to integrate the yield over the same energy region below that maximum for each light product. This corresponds to leaving the same total amount of

excitation energy in the products for each transfer. In most cases the kinetic energy of the light product was well peaked within 15 MeV of the maximum energy. Since our energy range was usually two or three times this value, the error introduced by the low-energy cut-off was very small. However, for the lower Z targets at the higher bombarding energies, there were long tails on these peaks, and our procedure could have introduced a significant error. It does not seem likely to us that this error exceeded 30% in the worst cases. In resolving the yield of an individual isotope it was necessary to make the assumption that the same fraction of its energy spectrum was above the cut-off as for the sum of all the isotopes of this element. In many cases this was tested and found not to contribute a significant error. However, taking into account all these effects, the data have to be considered somewhat qualitative, especially in the case of the Ni targets.

The bombarding energy was kept as low as possible, consistent with having about 30 MeV above the low-energy cut-off point. Since these cut-off points ranged from ~30 MeV for Be to ~60 MeV for O, our minimum bombarding energies ranged from ~60 MeV for B to ~100 MeV for N. The angle at which we observed the transfer products was determined by requiring the ratio of the elastic peak to the main transfer peak to be about 10. This normally occurs when the elastic cross section has dropped to about one-quarter of the Rutherford cross section. This is a slightly more backward angle than θ_{crit}, where the elastic cross section has dropped to half the Rutherford value. The more backward angles were picked for two reasons: 1) the smaller elastic peak helped the performance of the particle identifier by reducing the overall rate, and 2) the ratio of proton transfer into the projectile to proton transfer out

of the projectile was not very sensitive to angle at the more backward angles, whereas it decreased rather sharply at angles smaller than θ_{crit}. The latter observation is based on an angular distribution measurement for the system ^{197}Au + 64 MeV ^{11}B. This showed ^{12}C and ^{10}Be to be well peaked around θ_{crit}, but the peaks had somewhat different shapes and the ^{10}Be peaked at slightly more forward angles. Thus, under our experimental conditions, the ratio we obtain is not very sensitive to small variations in the angle; however, if one wants to consider the above ratio integrated over angle so that total cross sections are compared, our values will be high by a factor of about 1-1/2 or 2.

Table 1 summarizes some of the values we obtained with various targets and projectile ions for the ratio of the yield of one proton transferred into the projectile to that of one proton transferred out of the projectile, (projectile + p)/(projectile - p). For three of the projectiles, ^{10}B, ^{11}B, and ^{14}N, these ratios are not very dependent on the bombarding energy. This is demonstrated in table 1 by the ^{11}B results listed for three bombarding energies; however, we did not make measurements on the lighter targets at the higher energies ($\theta_{crit} \lesssim 30°$) where the kinetic energy of the light products was not well peaked. The results are different for ^{12}C, the only even-even projectile we studied, where the ratio dropped with decreasing bombarding energy. The ^{12}C projectile differs from the rest in another respect. We have not measured carefully the cross sections for these transfer reactions, but it is clear that they are comparable for ^{10}B, ^{11}B, and ^{14}N projectiles. The ^{12}C cross sections, while comparable to the others at the highest energies (125 MeV), dropped significantly below the others at lower bombarding energies.

All the proton-transfer cross sections (summed over the two directions) dropped by a factor of 2 or 3 as the Z of the target increased from Ni to Au.

The quantitative interpretation of these transfer reactions would undoubtedly be difficult. As with any dynamical process it would involve several steps, of which the first would be an analysis of the potential energies of the relevant nuclear configurations, in particular the energies of the target and projectile in close proximity before and after transfer. This first step, although it cannot be expected to yield a theory of transfer reactions, is very simple, and we shall examine how well our experimental results can be understood in terms of elementary potential-energy considerations.

It has been recognized for some time that the masses—or more precisely the Q-values—affect the yields of the products of transfer reactions. The Q-values refer, however, to the masses of infinitely separated nuclei, and the relevant energy in transfer reactions must also include the Coulomb interaction energy. For example, in the reaction $^{11}B + {}^{197}Au$, the Q values favor ^{12}C over ^{10}Be by 14 MeV. If one considers the target and projectile as two spheres in close proximity, one can easily write down the expression for their electrostatic interaction energy and, using the same separation distance, also for the interaction energy following the transfer of particles. It is apparent that systems where the projectile loses protons are favored by the Coulomb interaction energy, since $(Z_t + 1)(Z_p - 1) < (Z_t - 1)(Z_p + 1)$. Here Z_t and Z_p are the atomic numbers of target and projectile. For the above example one finds that the interaction energy favors ^{10}Be over ^{12}C by about 17 MeV. If one combines the difference in Q values ($\Delta Q = +14$ MeV) with the difference in Coulomb interaction energies ($\Delta E_c = -17$ MeV), one finds that ^{12}C is less

favorable energetically than ^{10}Be ($\Delta Q + \Delta E_c \approx -3$ MeV). Experimentally the yield of ^{10}Be is, indeed, larger (by a factor of 2 or 3).

To test these energy considerations further we have plotted in fig. 2 the ratio of yields (projectile + p)/(projectile - p) against: a) the difference in Q-values for the reactions, ΔQ, and b) that difference plus the difference in Coulomb interaction energy, $\Delta Q + \Delta E_c$. We calculated interaction energies using projectile-target distances deduced from the experimental conditions themselves (bombarding energy and θ). The results do not differ significantly from what would be obtained assuming tangent spheres whose sizes were given by a radius parameter equal to about 1.4 fm.

The correlation in fig. 2b is rather good, in that the ^{10}B, ^{11}B and ^{14}N results fall approximately on a single curve which goes through the point of equal yields for $\Delta Q + \Delta E_c = 0$. The points for ^{12}C, although lying on a different curve (for a reason that is not obvious to us) also confirm the existence of a correlation between yield ratios and potential energy differences. Moreover this curve also passes approximately through the neighborhood of the equal yield point when $\Delta Q + \Delta E_c = 0$. There is considerable scatter of the points in fig. 2b, part of which may be due to experimental error, but which may also reflect real effects not included in this simple treatment. It is apparent, however, that the correlation in fig. 2b is a great improvement over that in fig. 2a where the Coulomb interaction energy is not included.

More extensive experiments will be necessary to determine the extent of the correlation between yields of transfer reactions and the relevant potential energy changes of two nuclei in close proximity. Since such a correlation is, however, not at all unexpected from first principles, we believe it may not

be premature to point out some of the consequences of the existence of this correlation.

For any given pair of nuclei the most direct method of estimating the potential energy or mass is to add to the experimental masses of the nuclei the electrostatic interaction energy. Insofar as the average trends of nuclear masses are known to be reproduced by the liquid drop model, it should be possible to predict what the gross average trends of transfer reaction yields should be, from a consideration of the elementary problem of two tangent charged polarizable† spheres. The results may be summarized in the following two "average" rules:

A) The charge-to-mass ratios of two touching fragments will tend to become nearly equal, but the lighter fragment would prefer a charge-to-mass ratio up to a few percent higher than the heavy one.

B) For light systems where $(Z_1 + Z_2)^2/(A_1 + A_2) \lesssim 30$ the heavy fragment tends to suck up the lighter one, but for heavier systems this is only the case if the disparity in masses exceeds a certain critical value. Otherwise the fragments tend toward equality. In the above we are only giving a general idea of the results; the details may be deduced from ref. 7, or may be derived elementarily from the energy expression of tangent charged (polarizable) spheres. It should be stressed that the rules only predict the average trends (in the same sense that the liquid drop model predicts the average trends of nuclear masses), and in any given case the masses may be seriously affected by shell effects, even to the extent of reversing the predictions of the "average rules."

One can extract much more information from particle spectra such as those shown in fig. 1. We have confined our attention to single-proton

† i.e., the neutron and proton density distributions in the spheres may be different

transfers because 1) the asymmetry in the direction of proton transfer is very striking, and 2) the case of a single particle transferred each way should be the easiest to interpret. Thus, although we expect the potential energy differences that we have discussed above to provide the driving force also in transfer reactions involving more than one particle, other factors may also be involved in such cases. For example, the yields for the transfer of many nucleons would be expected to decrease with the number of particles involved because of the greater inertia of the nuclear matter being transferred. What we have proposed here is that the asymmetry in the direction of proton transfers, as well as the apparent gross differences in proton and neutron transfers, can be understood by considering the relevant potential energies of the systems. These energies have been approximated by the masses at infinite separation (Q values) plus a Coulomb interaction energy term. The latter term is important when heavy projectiles and targets are involved, and its inclusion brings the proton data into reasonable accord with expectations. A useful way to estimate the preferred direction of a proton transfer (which is equivalent to considering the energetics, though it avoids explicit calculations) is based on the realization that in most cases a projectile and a heavy target nucleus in contact constitute a system in which the region of the projectile is proton rich compared to the region of the target. This (in most cases) provides a driving force for the transfer of protons into the target nucleus rather than out of it (rule A, above), and the effect is the larger, the greater the difference in the charge densities (i.e., neutron/proton ratios) of the target and projectile.

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7) For the energy of two uniformally charged spheres see S. Frankel and N. Metropolis, Phys. Rev. 72 (1947) 914, p. 923. A formula for the optimum charges on two polarizable tangent spheres is given on p. 43 of H. Marshall Blann's Thesis (unpublished), University of California Radiation Laboratory document UCRL-9190, May 1960. There is a misprint in the expression for $F(\lambda)$, which should read

$$F(\lambda) = (1-\lambda)[\tfrac{6}{5}(1+\lambda)^2-1-\lambda-\lambda^2](1+\lambda)^{-1}(1+\lambda^3)^{-5/3}$$

Table 1. Measured ratios of Y(projectile + p)/Y(projectile - p).

Projectile (E, MeV)	Target				
	Ni (natural)	^{115}In	^{124}Sn	^{152}Sm	^{197}Au
^{10}B (64)	0.50	0.17	0.056	0.11	0.10
^{11}B (64)	1.9	0.90	0.47	0.45	0.38
^{11}B (77)		0.82	0.41	0.41	0.38
^{11}B (114)				0.53	0.57
^{12}C (88)	0.55	0.059	0.017	0.018	0.010
^{14}N (104)	0.71	0.15	0.042	0.082	0.067

Figure Captions

Fig. 1. Some representative particle spectra resulting from bombardment of various thin foils with heavy ions are shown, and the bombarding conditions are indicated. The two spectra in each vertical pair were taken without changes in either the counter telescope or the particle-identifier system.

Fig. 2. The ratio of the yield for the projectiles picking up a single proton to that for the projectiles losing a single proton is plotted versus a) the difference in Q values for the two reactions and b) the difference in Q values plus the difference in Coulomb interaction energies. The shape of the symbol indicates the projectile, the code being: solid squares, ^{10}B; solid triangles, ^{11}B; solid circles, ^{14}N; and open circles, ^{12}C.

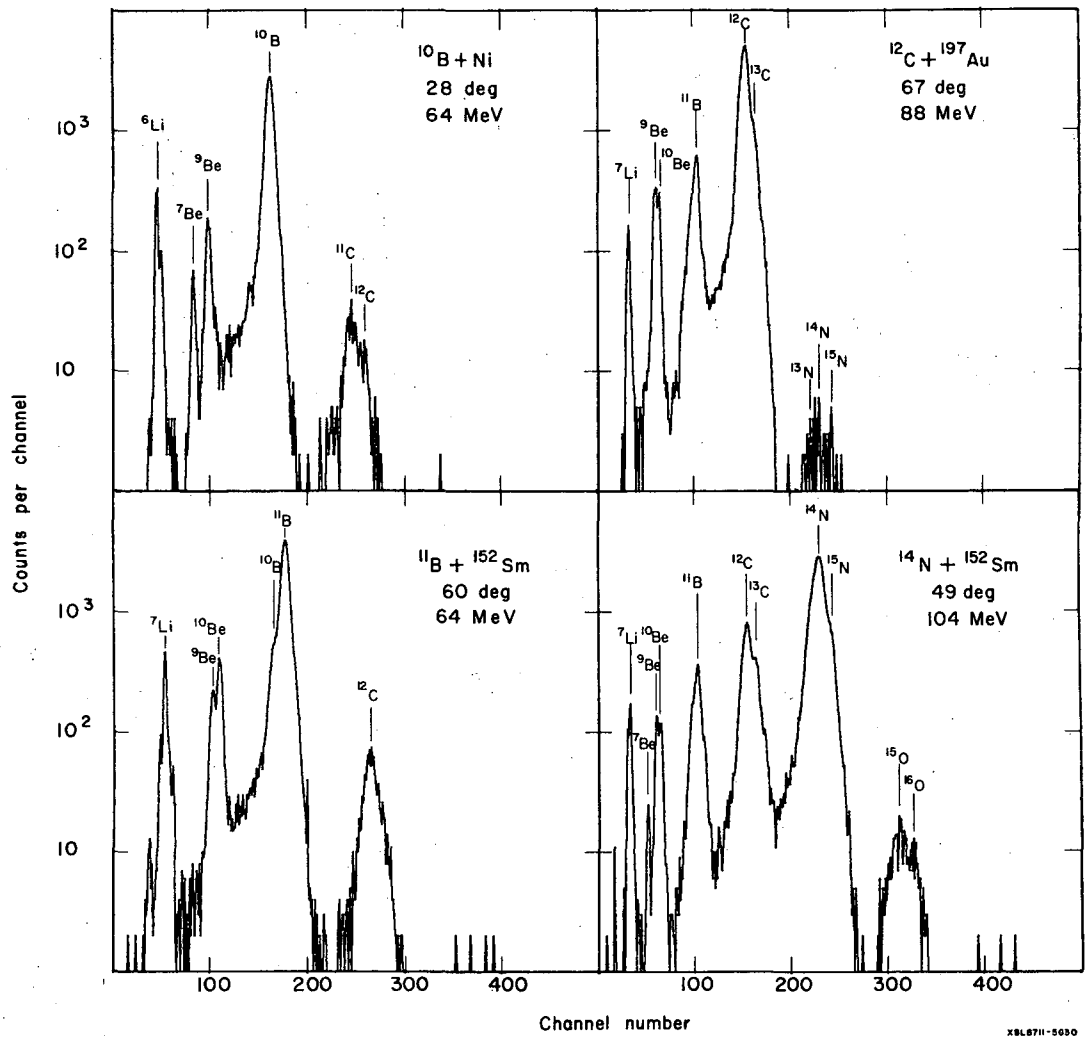
^{10}B + Ni
28 deg
64 MeV
^{12}C + ^{197}Au
67 deg
88 MeV
^{11}B + ^{152}Sm
60 deg
64 MeV
^{14}N + ^{152}Sm
49 deg
104 MeV
Counts per channel
Channel number
10^3
10^2
10
100
200
300
400
^{6}Li
^{7}Li
^{7}Be
^{9}Be
^{10}Be
^{10}B
^{11}B
^{11}C
^{12}C
^{13}C
^{13}N
^{14}N
^{15}N
^{15}O
^{16}O
XBL6711-5030

Fig. 1

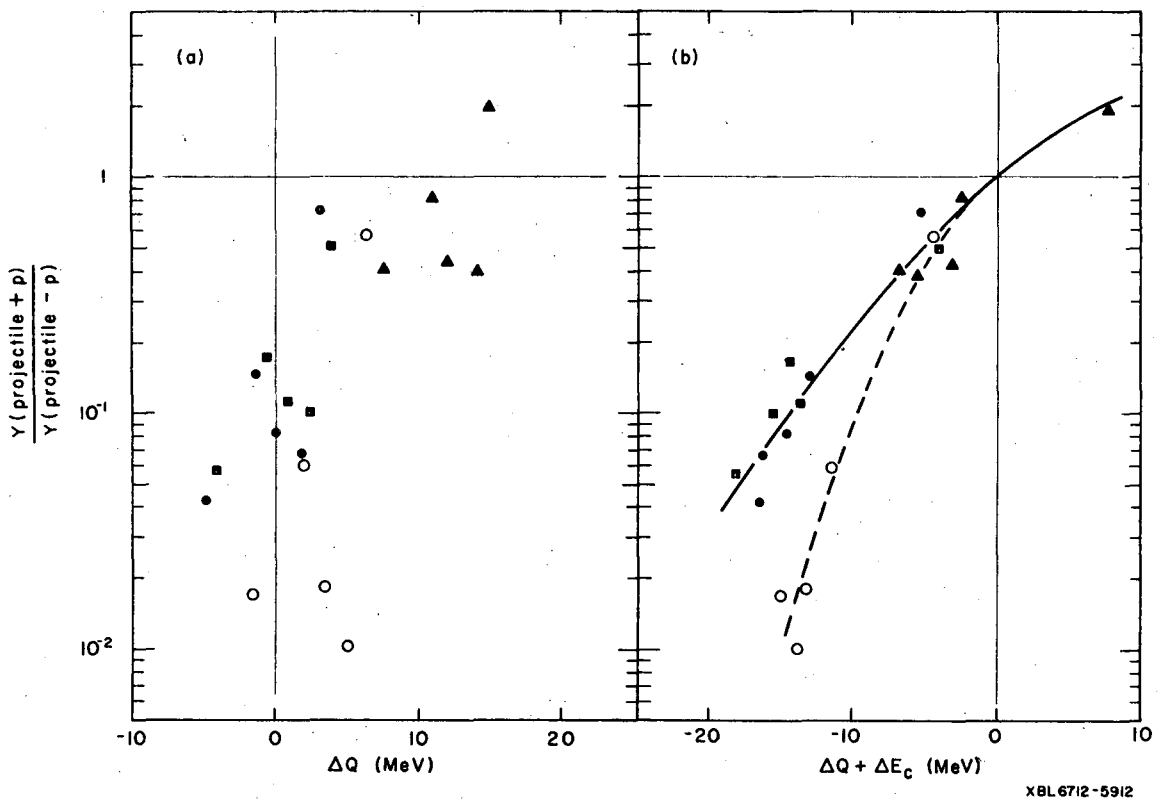
(a)
(b)
1
10^{-1}
10^{-2}
$\frac{Y(\text{projectile} + p)}{Y(\text{projectile} - p)}$
-10
0
10
20
ΔQ (MeV)
-20
-10
0
10
ΔQ + ΔE$_c$ (MeV)
XBL6712-5912

Fig. 2

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