POTENTIAL-ENERGY EFFECTS IN HEAVY-ION TRANSFER REACTIONS*

R. M. Diamond, A. M. Poskanzer, F. S. Stephens, W. J. Swiatecki, and D. Ward
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 29 January 1968)

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.

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 36-μ ΔE counter and a 500-μ E counter. Some typical particle spectra 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. Although we could easily integrate the total yield of a given element, it was more difficult to integrate accurately the individual isotopes of that element. We estimate an average uncertainty of around 30% in the ratio due to the integrations, although in one or two cases with poor statistics it could be as large as a factor of 2. 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 at 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-

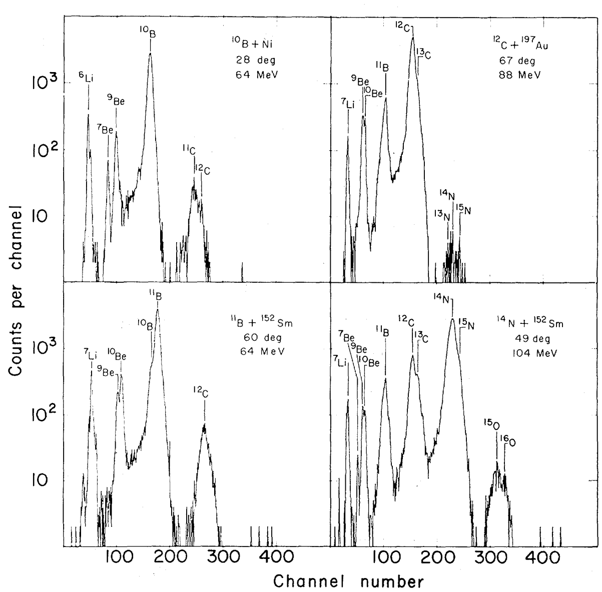

FIG. 1. Some representative particle spectra resulting from bombardment of various thin foils with heavy ions are shown, and the bombarding conditions are indicated. The two spectra in each vertical pair were taken without changes in either the counter telescope or the particle-identifier system.

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 cutoff 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 cutoff 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 cutoff point. Since these cutoff 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 one-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 over-all 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 $1\frac{1}{2}$ or 2.

Table I 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 I 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 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

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

Projectile (E in 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

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 reaction, 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. 2(b) 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. 2(b), 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

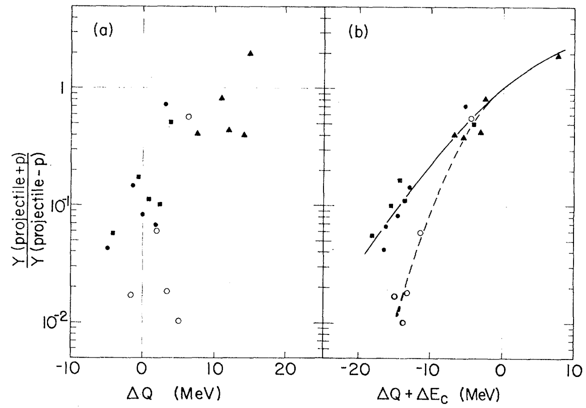

FIG. 2. The ratio of the yield for the projectiles picking up a single proton to that for the projectiles losing a single proton is plotted versus (a) the difference in Q values for the two reactions and (b) the difference in Q values plus the difference in Coulomb interaction energies. The shape of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

in Fig. 2(b) is a great improvement over that in Fig. 2(a) 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, however, such a correlation is not at all unexpected from first principles, it may be well to point out the broader range of consequences following from it. Thus, since the average trends of nuclear masses are known to be reproduced by the liquid-drop model, it should be possible to predict the average trends of transfer-reaction yields from a consideration of the elementary problem of two tangent, polarizable,[7] spherical liquid drops. The results that one finds may be summarized in the following two "average rules":

(A) The charge-to-mass ratio 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 $(Z_1+Z_2)^2/(A_1+A_2)\lesssim30$, the heavy fragment tends to suck up the lighter one, but for heavier systems this is the case only if the disparity in the masses exceeds a certain critical value [an increasing function of the excess of $(Z_1+Z_2)^2/(A_1+A_2)$ over about 30]. Otherwise the fragments tend towards equality. In the above we are only giving a general idea of the results; the details may be deduced from Frankel and Metropolis[8] and Marshall,[8] or may be derived from the energy of tangent charged polarizable spheres.

To illustrate these rules we consider the present transfer reactions. For all of our systems except $^{11}B+Ni$ the projectile has a charge-to-mass ratio appreciably greater than that of the target. Rule (A) then indicates that protons should be transferred preferentially into the target nucleus, or neutrons into the projectile. Rule (B) suggests, for all our cases, that the target should tend to absorb the projectile. For neutrons, these tendencies conflict, producing no systematic effect. But for protons they reinforce each other, giving the rather strong systematic effect observed. Consideration of the charge-to-mass ratios alone gives considerable insight into the data of Table I, although one must remember that shell effects are not included in these general rules and such effects can be important (even to the extent of reversing the predictions of the average rules in particular cases).

In summary, we have shown that there is a strong tendency to transfer protons out of the projectile nuclei when heavy targets are bombarded with moderately heavy projectiles. This tendency can be understood by considering the potential energies of the systems near contact and, furthermore, can be shown to be a consequence of the average trends of nuclear masses as described by the liquid-drop model.

We would like to acknowledge helpful discussions with J. R. Nix and the participation of E. K. Hyde in the early phases of the experiment.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]Proceedings of the Third International Conference on Reactions Between Complex Nuclei, edited by A. Ghiorso, R. M. Diamond, and H. E. Conzett (University of California Press, Berkeley, Calif., 1963), Sessions B and C, pp. 81-198.

[2]W. E. Frahn and R. H. Ventner, Nucl. Phys. 59, 651 (1964), and references therein.

[3]A. G. Artyukh, V. V. Volkov, and T. Kwiecinska, Yadern. Fiz. 4, 1165 (1966) [translation: Soviet J. Nucl. Phys. 4, 839 (1967)].

[4]V. V. Volkov and J. Wilczynski, Nucl. Phys. A92, 495 (1967).

[5]P. M. Strudler, I. L. Priess, and R. Wolfgang, Phys. Rev. 154, 1126 (1967).

[6]J. Cerny, S. W. Cosper, G. W. Butler, H. Brunnader, R. L. McGrath, and F. S. Goulding, Nucl. Instr. Methods 45, 337 (1966).

[7]I.e., the neutron and proton density distributions in the spheres may be different.

[8]For the energy of two uniformly charged spheres, see S. Frankel and N. Metropolis, Phys. Rev. 72, 914 (1947), p. 923. A formula for the optimum charges on two polarizable tangent spheres is given on p. 43 of H. Marshall Blann, thesis, University of California Radiation Laboratory Report No. UCRL-9190, 1960 (unpublished). There is a misprint in the expression for $F(\lambda)$, which should read $F(\lambda)=(1-\lambda)[6/5(1+\lambda)^2-1-\lambda-\lambda^2](1+\lambda)^{-1}(1+\lambda^3)^{-5/3}$.