# COMPLEX NUCLEON TRANSFER REACTIONS OF HEAVY IONS*

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The transfer of a single nucleon in heavy ion reactions involving $N^{14}$ has been studied quite intensively.[1-5] The results are consistent with a mechanism involving tunneling through the Coulomb barrier of nucleons Coulomb-excited to virtual levels.[6] This Letter concerns some studies of high-energy reactions in which several nucleons are transferred. Such reactions were found to be quite prominent and imply the existence of an important new mechanism for transfer reactions.

In initial experiments, stacks of target foils backed with gold catcher foils were irradiated with 160-Mev $O^{16}$ and 140-Mev $N^{14}$. The thickness of these stacks was adjusted so that when the beam reached the gold its energy had been degraded below the energy necessary to give reaction. Thus, after irradiation, the only radioactivity in the gold was due to products which had recoiled into it from the target. This method provides a simple criterion for transfer reaction, since only those products which are formed by pickup and stripping from the projectile (and therefore have sufficient range to reach the catcher) are observed. The distribution of activities in the catcher in a typical experiment (160-Mev $O^{16}$ on tin) is given in Fig. 1. The average ranges of the $F^{18}$, $O^{15}$, $N^{13}$, and $C^{11}$ products correspond to a velocity at the time of their formation which approximates that of the incident $O^{16}$. However, the range straggling increases with the number of nucleons transferred, reflecting a wider range of momentum exchange in the more complex transfer interactions.

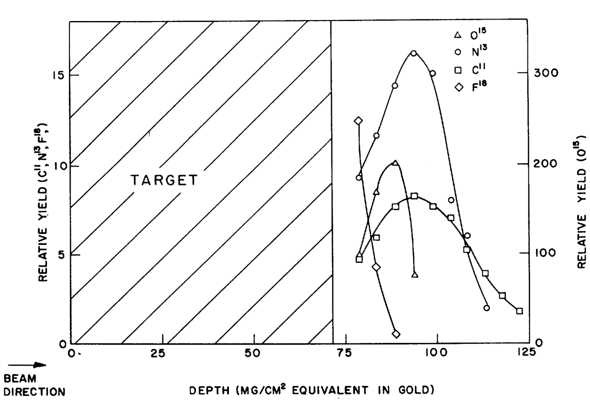


FIG. 1. Distribution of products with depth from the $O^{16}$ bombardment of a tin target.

The average cross sections for these reactions are given in Table I. Two generalizations emerge: (1) The cross section for ($p2n$) and ($2p3n$) transfers are appreciable compared to single nucleon transfers. [This holds also for ($pn$) transfers.] This result is somewhat surprising in view of the result of Alkhazov et al.[7] who find that two-neutron transfer to give $N^{16}$ from $N^{14}$ is reduced by several orders of magnitude compared to single-neutron transfer. (2) The ratio of cross sections for ($p2n$) to ($n$) transfers appears constant at about 0.2 and that for ($2p3n$) to ($n$) at 0.1 over a wide range of interacting systems.

The high cross sections for the ($p2n$) and ($2p3n$) transfers are not consistent with tunneling through the Coulomb barrier. Further, the relatively minor dependence on both the binding energy of the transferred group of nucleons and the $Q$ value of the reaction would not be predicted by barrier penetration considerations. These conclusions hold regardless of the entities that are actually transferred. [It seems plausible that the ($p2n$) stripping actually involves double exchange of a proton and alpha particle, while the ($2p3n$) events

Table I. Thick target cross sections (mb).

| Reaction[a] | ($-n$) | | ($-p2n$) | | ($-2p3n$) |
|---|---|---|---|---|---|
| Error | ± 30 % | | ± 50 % | | ± 50 % |
| Beam / Target | $N^{14}$ | $O^{16}$ | $N^{14}$ | $O^{16}$ | $O^{16}$ |
| Al | | 20 | | 4.0 | 2.3 |
| Cu | 28 | 29 | ≤ 8 | 4.7 | 2.9 |
| Sn | (20) | 7.9 | (4.2) | 1.4 | 0.78 |

Ratios of thick target cross sections.

| Reaction[a] | ($-p2n$)/($-n$) | | ($-2p3n$)/($-n$) |
|---|---|---|---|
| Error | ± 20 % | | ± 20 % |
| Beam / Target | $N^{14}$ | $O^{16}$ | $O^{16}$ |
| Al | | 0.20 | 0.12 |
| Cu | ≤0.29 | 0.16 | 0.10 |
| Sn | 0.21 | 0.18 | 0.10 |

[a]To remove indicated number of nucleons from projectile.

represent transfer of an alpha and a neutron.]

It is postulated that in most of the complex stripping reactions, the projectile approaches with an impact parameter comparable to its radius and breaks through the Coulomb barrier to form a dumbbell-shaped system. Normally this might lead to formation of a compound nucleus. However, it can easily be shown that if the incident energy and the impact parameter exceed certain values, the combined centripetal and Coulomb forces are sufficient to break the nuclear bond before the system has made half a rotation. Yet the time of such contact is certainly sufficient to permit the transfer of particles. We have calculated that the threshold for such "contact transfer" reactions is about 40 Mev for the system $O^{16}$ + Cu and rises rapidly to approximately one barn at 120 Mev. (This estimate includes events in which there is no net transfer.) However, such calculations are quite sensitively dependent on the somewhat arbitrary assumptions that must be made regarding the nuclear binding in the neck of the dumbbell.

It appears likely that such "contact transfer" is the mechanism of the buckshot effect invoked by Chackett et al.[8] to account for product distributions observed in heavy-ion bombardment of aluminum.

Since contact stripping involves penetration of the attractive core, the angular distribution of products from it will be more forward than that from nucleon transfer across the Coulomb barrier. This forward displacement should increase with increasing energy and decreasing impact parameter until finally the deflection becomes attractive rather than repulsive. So many assumptions are involved in our calculation of such deflections that we confine ourselves to the qualitative prediction that the distribution should be peaked near or at zero degrees.

The results of a typical experiment on the angular distribution of radioactive products from bombardment of rhodium with 160-Mev $O^{16}$ is shown in Fig. 2. Evidently the results on $C^{11}$, $N^{13}$, and $F^{18}$ are qualitatively in accordance with the contact transfer model. The distribution of the single-nucleon transfer product $O^{15}$ was somewhat unexpected. A distinct peak, similar to that observed for $N^{14}(Ag^{107,109}, Ag^{108,110})N^{13}$ reactions,[5] should appear at about 24° according to the tunneling mechanism. However, only a small peak or flat spot is found there. We interpret this fact to mean that the tunneling mechanism is no longer dominant for $O^{16}$ because of the higher binding

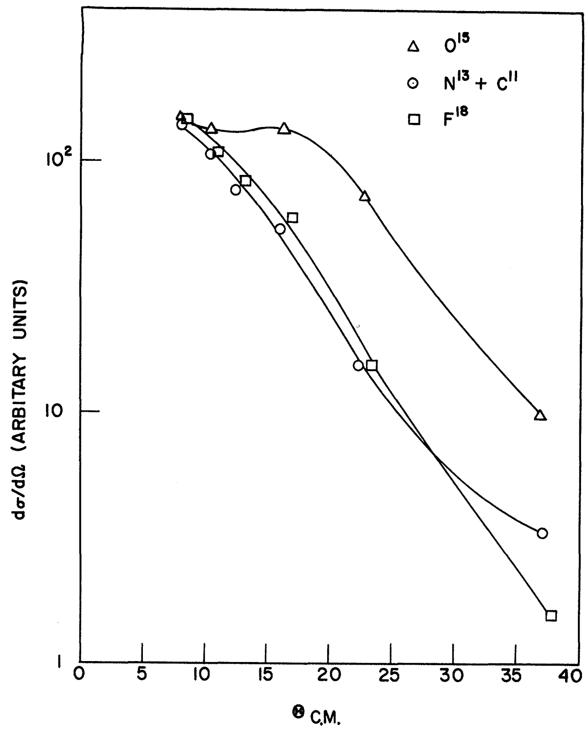


FIG. 2. Angular distribution of several products from the $O^{16}$ bombardment of a 7-mg/cm² rhodium foil.

energy of the last neutron. Instead, the contact transfer mechanism in which this binding energy is not critical becomes important for the single-nucleon transfer also. Preliminary work on angular distributions of single-neutron stripping products from $C^{12}$, $N^{14}$, and $F^{19}$ bombardments appears to support this view.

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## FISSION OF $U^{238}$ INDUCED BY $\mu^-$ CAPTURE*

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It has been pointed out by Wheeler[1] that there are two ways in which a $\mu^-$ meson stopped in uranium may induce nuclear fission. The energy released in the nonradiative transition of the mesonic atom to its $1s$ state as well as that liberated in the nuclear-capture process, $\mu^- + U^{238} \rightarrow Pa^{238} + \nu$, should be sufficient sometimes to induce fission. These two possible fission-inducing mechanisms can be distinguished experimentally, since the fissions induced by atomic transition would be observed to occur promptly ($\tau \ll 10^{-9}$ sec), whereas those due to nuclear capture would occur with the characteristic mean lifetime of a $\mu^-$ meson stopped in uranium.[2]

Galbraith and Whitehouse failed to observe fission by cosmic-ray mesons in an ionization chamber and set an upper limit of 0.25 on the fission-to-stopping ratio.[3] John and Fry, using uranium-loaded nuclear emulsions, observed 7 $\mu^-$ fissions, from which they estimated that fission occurs about 15% of the time when a meson stops in uranium.[4] Considering only the nonradiative atomic transitions, Zaretsky[5] has recently calculated a fission probability that is consistent with the results of John and Fry.

The preliminary results of an experiment performed to obtain the relative probabilities of the two meson-induced fission mechanisms are presented in this Letter. A gas scintillation counter containing nine stainless steel disks $3\frac{1}{4}$ in. in diam by 0.015 in. thick, coated on both sides with 0.85 mg/cm$^2$ $UF_4$ (natural isotopic mixture), was filled to 45 psi above atmospheric pressure with a mixture of 80% A and 20% $N_2$. The $\mu^-$ beam, obtained at the 184-inch cyclotron for studies of the neutron multiplicities from $\mu^-$ capture in various elements,[6] was estimated to contain not more than one $\pi^-$ per 1000 $\mu^-$ mesons.

An oscilloscope was triggered by a threefold coincidence between the two photomultiplier tubes looking at the gas scintillator, and a $3.7\times10^{-7}$-second gate triggered by the coincidence-anticoincidence pulse. This pulse was formed by simultaneous pulses in the plastic scintillators $S_2$, $S_3$, and $S_4$, together with the absence of a pulse in the water Čerenkov counter $C$ (Fig. 1). The absence of a prompt pulse in the last plastic scintillator, $A$, was not required for triggering the oscilloscope because of our concern about accidental pulses in $A$ induced by mesonic x-rays or products of a prompt fission. Pulses from $S_3$, $S_4$, and $A$, as well as a sum pulse from the two gas-scintillator phototubes were displayed on the oscilloscope and photographed. A precision, 50-Mc/sec oscillator was used to calibrate the sweep speed of the oscilloscope, and a weak $Cf^{252}$ spontaneous-fission source was included in the chamber to permit frequent calibrations of the fission-fragment detection efficiency.

The zero-time calibration was obtained by photographing the pulses when a piece of plastic scintillator was placed in the fission chamber and also by photographing $\pi^-$-induced fissions. In both cases the uncertainty in the zero time was about $3\times10^{-9}$ sec. The background counting rate when

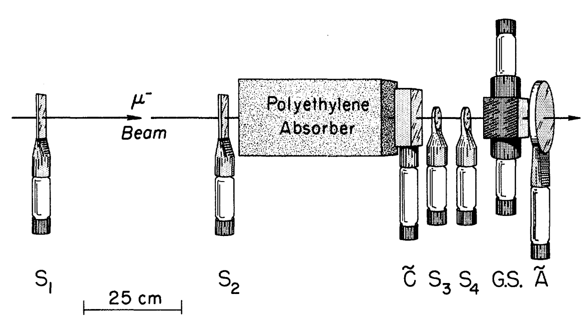


FIG. 1. Counter-telescope arrangement. Here $S_1$, $S_2$, $S_3$, $S_4$, and $A$ are plastic phosphors, $C$ is a water Čerenkov counter in anticoincidence to eliminate the small electron contamination in the beam, and $G.S.$ is the gas scintillator containing the uranium-covered plates.