Experimental Studies of (p,t) Reactions

B. L. COHEN AND T. H. HANDLEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received July 20, 1953; revised manuscript received October 28, 1953)

Several (p,t) reactions in heavy nuclei are studied by measuring excitation functions and angular distributions. While the data are not sufficiently extensive to justify general conclusions, they seem to indicate that: (1) a "pick-up" process is important only when the target nucleus contains two loosely bound neutrons; and (2) the inherent probability for the emission of tritons in the breakup of a compound nucleus is not much (if any) less than for the emission of neutrons or protons.

INTRODUCTION

OF the several new types of nuclear reactions that first became accessible to study with the entrance of proton accelerators into the 20-Mev energy region, one of the most interesting is the (p,t) reaction on various nuclei. In the first place, there is the question of whether the reaction can proceed by a "pick-up" process such as operates in (p,d) reactions. In accordance with the reciprocity theorem, such a process must be important in at least some cases if we are to accept the evidence of Kundu and Pool[1] that (t,p) reactions proceed by double neutron stripping. In the second place, if the reaction goes only by a compound nucleus interaction, there is the question of how well the statistical theory of nuclear reactions[2] can predict its cross section. An implicit assumption of that theory is that, aside from energy and Coulomb barrier considerations, all particles are emitted with equal probability; however, it would seem that there should be a greater inherent probability for emission of a simple particle like a neutron or proton than of a complex, loosely bound structure such as a triton (cf. the "many-body" theory of alpha decay[3,4]).

In this paper, we present the results of experimental studies of (p,t) reactions carried out with the internal, circulating beam of the Oak Ridge National Laboratory 86-in. cyclotron. While the results are not as complete and clear-cut as one would prefer, they give indications of the answers to the foregoing questions.

The data obtained, shown in Figs. 1–5, consist of excitation functions for (p,t) reactions on beryllium-9 and iron-54 and angular distributions of tritons from (p,t) reactions on beryllium, niobium, and palladium. Due to the extreme experimental difficulties, it is not considered feasible to carry the work further at this time.

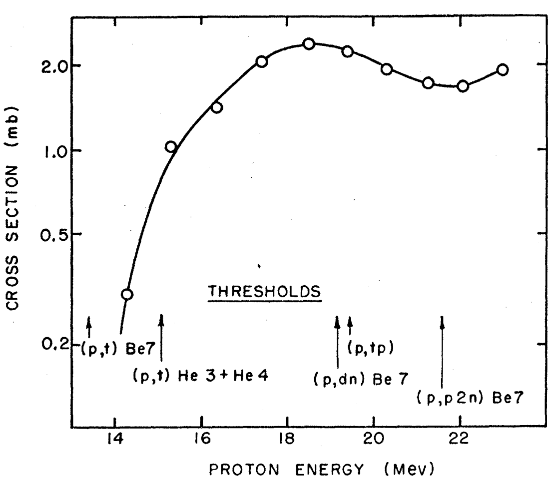

FIG. 1. Excitation function for $Be^9(p,t)Be^7$. Two other runs are in substantial agreement with these data; they are not shown because, in one case, the incident proton energy was not sufficiently homogeneous and, in the other, counting statistics were considerably poorer than in this run. Due to a calibration error, the ordinates should be multiplied by five. For example, the absolute cross section at 22 Mev is 9.0 mb.

EXPERIMENTAL METHODS

Excitation Functions

The excitation functions were measured by the stacked-foil method, modified for use with an internal cyclotron beam as described in detail elsewhere.[5] The beryllium foil was counted with a scintillation spectrometer set on the 480-kv peak. In one run, chemical purification was used. The iron was processed radiochemically after the bombardment and counted under an end-window Geiger counter with a 5-mg/cm^2 silver foil interposed to remove the Fe^{55} x-rays. Absolute decay rates were determined for beryllium with a Geiger counter which has been calibrated for gamma sensitivity[5a] and for iron by absolute beta-counting techniques. Absolute cross sections were determined by comparing with the known cross section for the (p,n) reaction in copper; the probable errors in the absolute cross sections shown in Figs. 1 and 2 are about 30 percent.

Angular Distributions

The general method of measuring angular distributions of nuclear reactions products with the internal,

[1] D. N. Kundu and M. L. Pool, Phys. Rev. **73**, 22 (1948).
[2] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[3] H. A. Bethe, Revs. Modern Phys. **9**, 161 (1937).
[4] B. L. Cohen, Phys. Rev. **80**, 105 (1950).
[5] Cohen, Newman, Charpie, and Handley, (to be published).
[5a] *Note added in proof.*—New measurements have recently been made by counting with a scintillation spectrometer set on the 480-kv gamma peak and comparing with a well-assayed Be^7 source.

circulating cyclotron beam has been described in detail elsewhere;[6] only the most pertinent details will be discussed here. The target assembly consists essentially of a thin target of the element being studied at the center of a $3\frac{1}{2}$-in. radius semicircular detector holder. The tritons are detected by the 1.6-hr activity of Co^{61} which they induce in cobalt metal foil by the (t,p) reaction. The cobalt foil is prepared[7] by electroplating from a $CoCl_2$-boric acid solution onto a stainless steel plate; the cobalt is then easily peeled off.

In the case of beryllium, the variation of triton energy with angle due to center-of-mass motion is corrected

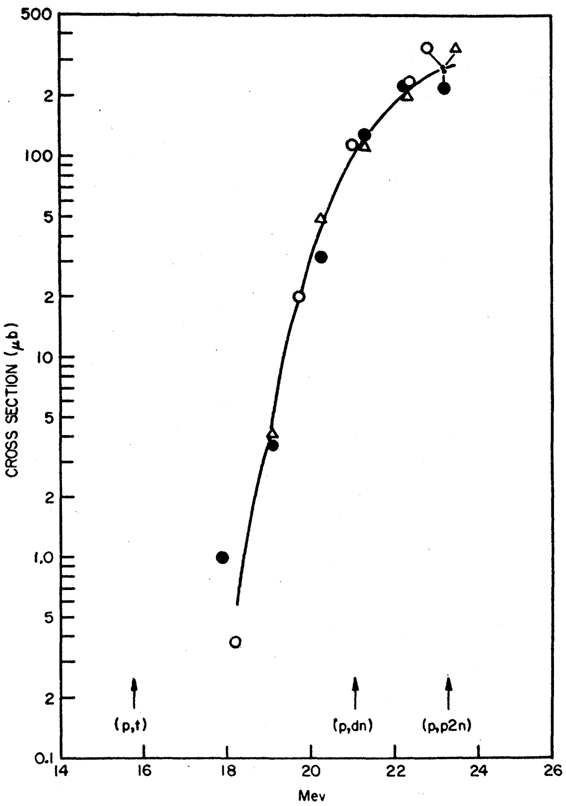

FIG. 2. Excitation function for $Fe^{54}(p,t)Fe^{52}$. The arrows show the thresholds for production of Fe^{52} by various reactions.

for by covering the detectors with a stepped absorber to reduce the long-range groups (those coming from reactions which leave Be^7 in its ground state or 470-kev excited state) to the same energy at each angle, and completely to absorb all lower-energy triton groups. For niobium and palladium, no effort was made to distinguish between the various triton groups.

All parts of the target assembly which are exposed to the cyclotron beam are covered with carbon; this minimizes or eliminates backgrounds of tritons,

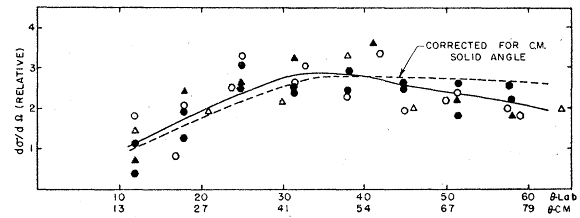

FIG. 3. Angular distribution of tritons from $Be^9(p,t)Be^7$. Only tritons from reactions in which Be^7 is left in its ground or first excited states are counted.

neutrons, deuterons, and alpha particles, since (p,t), (p,n), (p,d), and (p,α) reactions have very high thresholds in carbon-12. The target is bombarded for $1\frac{1}{2}$ hr with about 10 μa of 22-Mev protons, after which the cobalt foils are removed, processed chemically to remove all elements except cobalt, and then counted under end-window Geiger counters with 70-mg/cm^2 aluminum absorbers interposed. The chemical processing eliminates the products of (n,α) and $(\alpha,2n)$ reactions on cobalt which have half-lives comparable with that of Co^{61} and at the same time eliminates activities from impurities. Counting under an absorber removes the 9-hr internal conversion activity of Co^{58}, which is produced in great abundance by elastically scattered protons, and strongly absorbs the 70-day Co^{58} activity which is the principle source of background. The most serious background difficulty is at the 20° position for the palladium target where the counting rates for the 70-day, the 9-hr grow-in of the 70-day, and the cosmic-ray background are initially greater than the 1.6-hr Co^{61} activity by ratios of 10, 2, and 3, respectively. At larger angles, only cosmic-ray background interferes, but even this presents a problem because it is at all times considerably larger than the 1.6-hr counting rate. It is therefore necessary to place each cobalt sample under a separate counter and use automatic recording over at least a 24-hr period. In almost every case, the activity remaining after background has been subtracted indicates a half-life between 1.3 and 2.0 hr. with 1.6 hr representing a fair average. However, due to the errors introduced by subtracting the large background, the uncertainties in individual points in Figs. 3–5 are about 40 percent.

To check whether the 1.6-hr activity could be due to proton or neutron induced activities on impurities (in spite of the original purity of the foils and the rather exhaustive chemical processing), one of the detecting foils was covered with a 100 mg/cm^2 absorber during the bombardment. In every case, the 1.6-hr activity was removed. Since the angular distributions of both elastically and inelastically scattered protons and of deuterons from (p,d) reactions exhibit strong maxima in the forward direction, the possibility that the 1.6-hr activities are induced by either deuterons or protons would seem to be excluded by the fact that the results for beryllium and palladium, Figs. 3 and 5, showed no

[6] B. L. Cohen and R. V. Neidigh, Rev. Sci. Instr. (to be published).
[7] O. Sissman and C. D. Bopp, Oak Ridge National Laboratory Report ORNL-299 (unpublished).

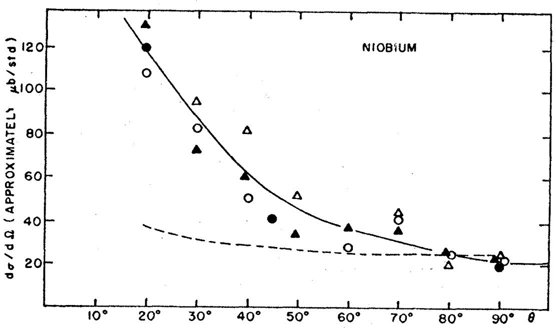

FIG. 4. Angular distribution of tritons from $Nb^{93}(p,t)Nb^{91}$. All triton groups are included. The dashed line is the line through the palladium data of Fig. 5.

forward peak; and even the forward rise for niobium, Fig. 4, was much too slow. Alpha particles could cause difficulty, however, expecially since the $(\alpha,2p)$ reaction on cobalt also produces Co^{61}. Three types of tests were made which indicate that, for beryllium at least, this reaction is a negligible contributor:

(a) Determinations were made of the 3.4-hr Cu^{61} activity in some of the foils. This activity is produced by $(\alpha,2n)$ on cobalt, which should have a cross section much larger than $(\alpha,2p)$. The corrected activity of Cu^{61} was found to be only twice that of Co^{61}.

(b) A rough excitation function for the detecting reaction was obtained by covering several cobalt foils at the same angle with different thicknesses of absorber. Three thick-target relative yields of 6.5, 2.5, and $\lesssim 0.5$ must be due either to tritons of 8.0 to 4.5, 6.6 to 2.5, and 5.0 to 0 Mev, or to alpha particles of 18 to 10, 13 to 0, and 4 to 0 Mev.[8] Since the $(\alpha,2p)$ energetic threshold is 11.6 Mev and proton emission is through a Coulomb barrier of 6 Mev, it hardly seems possible that thick target yields of this reaction should decrease by only a factor of 2.6 from 18 to 13 Mev. On the other hand, these yields agree roughly with what might be expected for the (t,p) reaction.

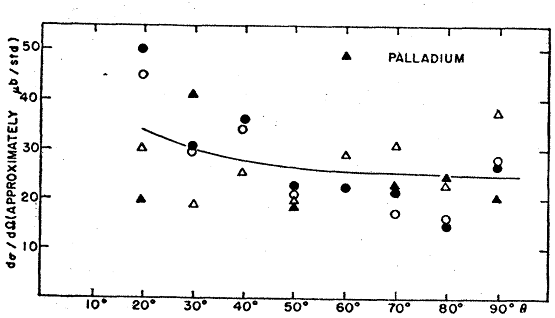

FIG. 5. Angular distribution of tritons from (p,t) reactions on palladium. All triton groups from all palladium isotopes are included.

[8] The spread in energies is due to the finite thickness of the beryllium target.

(c) By estimating the (t,p) absolute cross section from Kundu's work,[9] the cross section for the (p,t) reaction can be calculated from angular distribution data. The results agree roughly with the measured $Be(p,t)$ cross section, Fig. 1.

For niobium and palladium, test (a) indicated the relative yields of Cu^{61} and Co^{61} to be in the ratio of about 8 to 1 at large angles (there was difficulty at small angles because Cu^{61} is produced by elastically scattered protons on the nickel impurity). Test (b) could not be performed because the tritons are not monoenergetic. With regard to test (c), the total (p,t) cross section for palladium is estimated to be about 300 microbarns, which is in reasonable agreement with the theoretically expected value (see below). In view of the inconclusiveness of these tests, it must be admitted that there is little direct evidence against the possibility that alphas contribute appreciably to the observed activity. However from test (a) [and even this may be due to effects of scattered protons], the ratio of alphas to tritons from niobium and palladium targets is only about four times larger than that ratio from a beryllium target, where alphas were found to be negligible. Moreover, the $Co(\alpha,2p)$ reaction has an 11.6-Mev energetic threshold, and each outgoing proton must overcome a Coulomb barrier of more than 6 Mev, so that the cross section for that reaction would not be appreciable below about 24 Mev, which is more than the maximum alpha energy emitted from these targets. Therefore, theoretical estimates of the various cross sections indicate that contributions to the 1.6-hr activities from $Co(\alpha,2p)$ reactions are negligible.

RESULTS AND DISCUSSION

In the comparison of the angular distributions of Figs. 3, 4, and 5, the most striking feature is that the niobium data show a strong forward maximum, whereas the beryllium and palladium data do not. In a "pick-up" reaction, the momentum of the outgoing particle is essentially the vector sum of the momentum of the incoming particle, which is large and in the forward direction, and the momentum of the particles that are picked up, which have no strongly preferred direction. The angular distribution of the outgoing particles is therefore characterized by a strong maximum in the forward direction or at a relatively small angle. A compound nucleus interaction could, of course, also give a strong forward maximum in special cases of resonance reactions. However, the tritons that are detected in the experiments on niobium or palladium come from reactions in which the final nucleus is left in all states of excitation up to several Mev. Furthermore, the incident proton energies are inhomogeneous by about 1 Mev, and the compound nucleus excitation is about 30 Mev, so that a very large number of compound states are

[9] D. N. Kundu and M. L. Pool, Phys. Rev. 82, 772 (1951).

involved. The observed angular distributions are therefore averages over a tremendous number of resonant reactions, which fact precludes the possibility that strongly nonisotropic angular distributions can be observed unless there is some strongly systematic reason for it. Goldhaber[10] has suggested that there may be some such reason connected with the rather large spin of niobium (9/2). However, incident orbital angular momentum waves up to $l=7$ are important in formation of the compound nucleus so that the range of compound-nucleus spins that can be formed in the bombardment of niobium is not much larger than in the bombardment of palladium. Moreover, there is no obvious way in which an unpolarized spin of a target nucleus, no matter how large, can introduce complexity into angular distributions averaged over large numbers of resonances.

It thus seems likely that a "pick-up" process is important in the niobium (p,t) reaction but not in the (p,t) reactions on palladium and beryllium. This is especially interesting from the standpoint of nuclear-shell theory since the niobium nucleus contains two neutrons outside of closed shells whereas the palladium isotopes have from eight to fourteen. For beryllium, the alpha-particle model, which predicts only one loosely bound neutron is probably most pertinent. The minimum in the forward direction for beryllium[11] is somewhat difficult, though certainly not impossible, to understand on the basis of compound-nucleus theory. The indication of a slight forward maximum for palladium could be interpreted as due to a "pick-up" process with low probability. The absolute differential cross section for palladium indicates a total (p,t) cross section of about 3×10^{-4} barn which is in good agreement with the predictions for a compound-nucleus reaction as calculated from statistical theory[2] [the (p,t) thresholds for the palladium isotopes average about 7 Mev].

[10] M. Goldhaber (private communication).

[11] There was a possibility that the minimum was the result of a miscalculation of absorber thicknesses resulting from an overestimation of the incident proton energy; however, separate runs with the absorbers calculated for an incident energy $1\frac{1}{2}$ Mev lower (open points in Fig. 3) caused only a small change. (Runs without the stepped absorber showed a forward maximum.)

If our conclusion that a "pick-up" process is only important in cases where two loosely bound neutrons are available is correct, the (p,t) reaction on Fe^{54} should proceed by a pure compound-nucleus interaction since the Fe^{54} nucleus contains 28 neutrons. A comparison of the data from Fig. 2 with the predictions of the statistical theory of nuclear reactions indicates that the theoretical values are too small by about a factor of two. Since most predictions from statistical theory in this mass region are too small by factors of from 2 to 10,[12] this result indicates that the inherent probability of triton emission is not a great deal lower than for neutron or proton emission. This conclusion is consistent with the absolute cross-section determination from the palladium angular distribution.

In summary, although the data are not sufficiently extensive to justify definite conclusions, they seem to indicate the following answers to the two questions posed in the introduction:

(1) The "pick-up" process is significant in (p,t) reactions only in cases where the target nucleus contains two loosely bound neutrons (outside of closed shells).

(2) The inherent probability for triton emission in compound-nucleus decay is not much, if any, lower (i.e., less than an order magnitude) than for neutrons or protons.

The authors would like to acknowledge the assistance of A. Timnick (Michigan State College) in some of the chemical separations and the many helpful suggestions, discussions, and comments of K. Boyer (Los Alamos), J. L. Fowler, and R. A. Charpie.

[12] E. B. Paul and R. L. Clark, Can. J. Phys. **31**, 267 (1953).