Letters to the Editor

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Stripping and Pick-Up Differential Cross Sections

S. T. BUTLER AND E. E. SALPETER
Cornell University, Ithaca, New York
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THE fact that, at small angles, the angular distributions of nuclear reactions such as (d, t) and (t, d) contain large contributions from pick-up or stripping, respectively, is evidenced by the pronounced forward structure observed[1] in the distribution for the reaction $Be^9(d, t)Be.$[8] For this reason we have calculated the differential cross sections to be expected from such reactions as a result of stripping and pick-up, the method employed being identical with that used previously for (d, p) and (p, d) reactions,[2] Coulomb effects again being neglected. For simplicity we will present the results here which are derived assuming S states only in the deuteron and triton wave functions. Possible admixtures of other angular momentum states have also been considered, but for admixtures of the order to be expected negligible changes in the cross sections result.

The formula for the (d, t) and (t, d) angular distributions is very similar to that for the (d, p) and (p, d) distributions given by Eq. (34) of reference 2 (and we use the notation of reference 2). The term under the summation over l_n is identical with the corresponding term in the $(d, p)(p, d)$ case, except that now we have $Z=|\mathbf{k}_T-(M_1/M_2)\mathbf{k}_D|$ instead[3] of $|\mathbf{k}_D-(M_1/M_2)\mathbf{k}_P|$. ($\mathbf{k}_T$, $\mathbf{k}_D$, and $\mathbf{k}_P$ are the wave numbers for the triton, deuteron, and proton, respectively, in the appropriate center-of-mass systems, and M_1 and M_2 are the masses of the lighter and heavier of the initial and final nuclei, respectively.) For the other angle dependent factor in the cross section we now have a function $\varphi_T^2(|\frac{2}{3}\mathbf{k}_T-\mathbf{k}_D|)$ depending on the triton momentum distribution which replaces the deuteron momentum distribution $\varphi_D^2(|\frac{1}{2}\mathbf{k}_D-\mathbf{k}_P|)$.

The form factor φ_T^2 may be described as follows: Expand the (unsymmetrized) triton wave function in terms of states t of the deuteron, thus

$$\psi_T(\mathbf{r}, \mathbf{R})=\Sigma_{ti}A_{ti}\chi_{ti}(\mathbf{r})f_{ti}(\mathbf{R}). \quad (1)$$

Here $\mathbf{r}$ is the difference between the coordinates of the proton and a neutron, and $\mathbf{R}$ is the position of the second neutron with respect to the midpoint of $\mathbf{r}$. The χ_{ti} are wave functions of states t of the deuteron with spin orientations i, and both χ_{ti} and f_{ti} are assumed to include spin functions and to be normalized to unity. Then the function φ_T is merely the Fourier transform of $f_{0i}(\mathbf{R})$ ($t=0$ corresponding to the deuteron ground state) which is independent of i. Thus φ_T^2 is the momentum distribution (of the third particle) in a triton when it has the configuration of a deuteron ground state plus third particle.

Also, apart from known factors, the nuclear parameter $Nl_n s_n j^J$ which enters under the summation over l_n is the same for (d, t), (t, d), (p, d), and (d, p) reactions between the same nuclear levels. With the same nuclear (N) factor in these cases, and with φ_T and φ_D normalized to the same number, the multiplying angle independent factors for the above four reactions are in the ratios $(4/9)m_D{}^*m_T{}^*(k_T/k_D)A_0{}^2$, $\frac{2}{3}m_D{}^*m_T{}^*(k_D/k_T)A_0{}^2$, $m_P{}^*m_D{}^*(k_D/k_P)$, and $\frac{2}{3}m_P{}^*m_D{}^*(k_P/k_D)$, respectively, where $m_T{}^*$, $m_D{}^*$, $m_P{}^*$ are the appropriate reduced masses of the triton, deuteron, and proton. Here $A_0{}^2=\Sigma_i|A_{0i}|^2$ is the probability of finding the triton in the configuration of a deuteron and third particle.[4]

The same selection rules on l_n apply in the (d, t) and (t, d) cases as in the (d, p) and (p, d). However, rather than to try to use (d, t) and (t, d) reactions for obtaining information about the spins and parities of nuclear energy levels, as is done with (d, p) and (p, d) reactions,[2] it seems more desirable in this case that information be sought concerning the triton wave function. If the angular distribution for a (d, t) reaction (say) be obtained in a case where one known value of l_n is allowed, then by dividing this distribution by the oscillatory (Bessel) factor in the formula, a plot of the function $\varphi_T^2(k)$ is obtained, for k ranging over the values of $|\frac{2}{3}\mathbf{k}_T-\mathbf{k}_D|$ which enter into the forward part of the distribution. The range of values of this argument can easily be varied by judicious choice of different experiments employing, for example, different incident energies or different reactions.

Once the form of φ_T^2 has been obtained, the factor $A_0{}^2$ can be found directly by measuring the ratio of (d, t) or (t, d) to (p, d) or (d, p) cross sections between the same two nuclear states. Thus the probability of the triton being in the configuration of a deuteron and third particle can be obtained. Although φ_T^2 is the momentum distribution for this configuration alone, it should give a good approximation to that of the triton as a whole *if* $A_0{}^2$ is found to be reasonably large.

Performing both a (d, t) or (t, d) and a (p, d) or (d, p) reaction between the same two nuclear states would also be advantageous in obtaining φ_T^2 in the first place, since the value used for the nuclear radius r_0 in the formula could be checked from the (d, p) or (p, d) case and adjusted if necessary.

By way of indicating how the (d, t) and (t, d) angular distributions depend on the form factor φ_T^2 we show in Fig. 1 some distributions for the reaction $C^{13}(d, t)C^{12}$ with 8-Mev (lab) deuterons. The dotted curves are the distributions resulting (a) if φ_T^2 had the same form as the deuteron momentum distribution φ_D^2 and (b) if it were constant. The actual curve should lie between these, and the solid curve is that obtained from a reasonable but approximate triton wave function. In this example $l_n=1$ and r_0 was taken to be 4.5×10^{-13} cm.

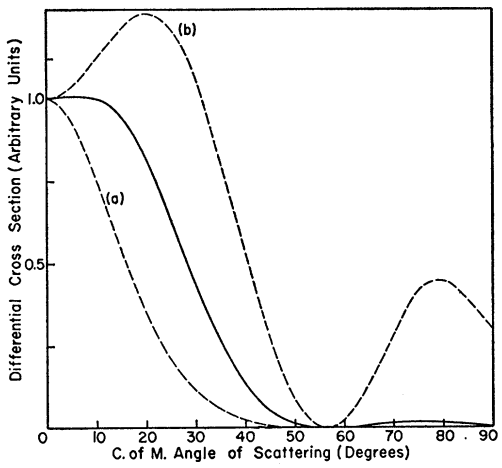

FIG. 1. Angular distributions for the reaction $C^{13}(d, t)C^{12}$ with 8-Mev (lab) deuterons. Curve (a) pertains to the case that φ_T^2 is the same as the deuteron momentum distribution, and curve (b) to the case that it is constant. The solid curve is the distribution more nearly to be expected. The three curves have been normalized to be equal at zero angle.

Finally, if it were possible to perform a (t, d^*) reaction in which deuterons in the singlet state are observed, the momentum distribution and the magnitude of the term $t=1$ in (1) could also be obtained. The discussion presented here applies equally well, of course, to the reactions (He^3, d), (d, He^3), (d, n), and (n, d). Full details of these calculations will be published later.

We are indebted to Dr. N. Austern for valuable discussions, and to Mrs. E. Baranger and Mrs. P. Greifinger for some numerical calculations.

[1] Tai, Middleton, and El Bedervi, Proceedings of the Chicago Nuclear Physics Conference (1951), p. 43 (reported by J. M. Cassels).
[2] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[3] The ratio M_1/M_2 appearing in Z is a refinement neglected in reference 2.
[4] The maximum possible value of A_0^2 is $\frac{3}{4}$, since this is the probability of obtaining a triplet neutron-proton spin factor from the triton spin function.

X-Rays from Mesic Atoms*

M. Camac, A. D. McGuire, J. B. Platt, and H. J. Schulte
University of Rochester, Rochester, New York
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SEVERAL authors[1-3] have discussed the possible formation of a mesic atom composed of a positively charged nucleus to which a negative pion or muon is bound in a Bohr-like orbit. There have been at least two experiments performed which gave indirect evidence for such phenomena.[4,5] We have found direct evidence for π-mesic atom formation with the nuclei of carbon, oxygen, and beryllium. For $Z<10$ the nuclear radius is small compared to the radii of even the lowest mesic orbits, and hence a simple Coulomb potential should suffice for calculating the expected energy levels. Such a calculation for the $2p-1s$ transition (assuming a pion mass$=276\ m_e$) gives quantum energies of 100 kev in carbon, 178 kev in oxygen, and 44.3 kev in beryllium.

We have searched for such x-rays in coincidence with the stopping of negative pions in the above elements. The fringing field of the 130-inch Rochester cyclotron was used to select and focus an external beam of 40±3 Mev negative pions produced by protons striking an internal copper target. The pions passed through three liquid scintillators and were stopped in a target of the desired element. Identification of the pions was by means of magnetic deflection and range. Beyond the stopper we placed an x-ray detector consisting of a 0.145-in. thick, 1.5-in. diameter disk of NaI(Tl) and a 5819 photomultiplier. The amplitude distribution of those NaI(Tl) pulses which were in coincidence with the three liquid scintillators was analyzed with a 24-channel discriminator. In order to reduce the background counting rate in the x-ray detector approximately five feet of brass was used between it and all parts of the cyclotron tank except for a channel in the brass to pass the pions.

0.55 g/cm^2 of lead or aluminum could be inserted between the stopper and the x-ray detector without disturbing the geometry. These absorbers are roughly equivalent in stopping power for charged particles but differ greatly in their x-ray absorption.

The energy calibration of the x-ray detector was a two-step process. 74-kev lead $K\alpha$ fluorescence radiation was used as a primary standard. A light pulser was constructed using a 5823 gas triode through which a condenser was discharged. Some of the resulting light was directed onto the 5819 photocathode, and the amplitude of the resulting pulses was adjusted to match the output of the 5819 when the NaI(Tl) was irradiated by the primary standard. The light pulser then remained permanently attached to the x-ray detector. It was possible to synchronize the light pulser with the arrival of the protons at the cyclotron target so that the energy calibration and resolution could be checked at the time of maximum background counting rate in the crystal. By this means an energy calibration of about 10 percent accuracy was established. Somewhat less accurate calibrations were also made at 44, 100, and 140 kev. The energy spread indicated in the spectrum in Fig. 1 is consistent with that observed during light pulser calibration.

Representative pulse-height spectra obtained during our most recent runs are shown in Fig. 1. Each curve represents 65,600 pions stopped in carbon. The data were taken in a total of 26 runs by alternating the lead and aluminum absorbers. The aluminum-lead differences with standard deviations due to counting statistics are also plotted. The calculated transmission in our geometry at 100 kev was 0.018 for the lead and 0.79 for the aluminum. Similar

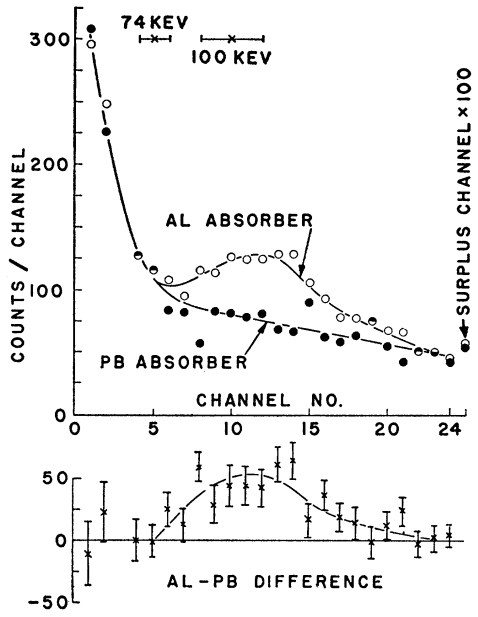

FIG. 1. Pulse-height spectrum from carbon.

spectra have been taken with the pions stopping in a water cell. A third series of runs was made with the pions stopping either in beryllium or carbon.

In all three elements x-rays were observed at the expected energies within the limits of our energy calibration. In carbon and water quantitative yield measurements were possible. The yield from beryllium is uncertain in amount at this time because of the large background counting rate at 44 kev. In carbon the number of x-rays emitted per stopped pion is 0.13±0.03. The corresponding yield for water is 0.21±0.07.

The largest uncertainty in our measurements is in determining the number of stopped pions which can contribute to the x-ray yield. Less than 2 percent of the particles stopping are muons. The yield from carbon agrees well with the predictions of Marshak and Messiah.[6] If the nuclear absorption from the $2p$ state were comparable in carbon and oxygen, the oxygen yield should be roughly 0.6 of the carbon yield, contrary to our measurement. This may indicate the operation of a special selection rule for negative pion absorption in the "magic number" oxygen nucleus. Work is continuing in attempts to improve the energy resolution, decrease the yield uncertainties, and extend the investigations to other low Z materials.

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[1] E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1947).
[2] J. A. Wheeler, Revs. Modern Phys. **21**, 133 (1949).
[3] R. E. Marshak, *Meson Physics* (McGraw-Hill Book Company, Inc., New York, to be published).
[4] W. Y. Chang, Revs. Modern Phys. **21**, 166 (1949).
[5] Panofsky, Aamodt, and York, Phys. Rev. **78**, 825 (1950).
[6] R. E. Marshak and A. M. L. Messiah (private communication).

Activation Energy of Heat Treatment Introduced Lattice Defects in Germanium*

R. M. Baum† and C. S. Hung‡
Purdue University, Lafayette, Indiana
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RECENTLY Dunlap[1] and DeSorbo[2] reported on resistivity measurements of heat-treated germanium single crystals at hydrogen temperatures. They found that the activation energy for thermally introduced acceptors is about 0.03 ev; i.e., considerably higher than for chemical acceptors.[3] Some time ago,[4] at the