I.S. in Table II, except for the case of Sn. For this element, optical[10] and muonic[11] I.S. data are available. The optical I.S. for Sn, while based on accurate measurements, are affected by dubious corrections[12] invented to allow for the specific mass shift, of essentially unknown magnitude. While our results agree qualitatively with Stacey's,[10] it appears preferable to accept our results, and to use them to compute the much-needed specific mass shifts from Stacey's data. We shall discuss this point elsewhere.

Our experiments became possible only through the cooperative attitude of Professor H. L. Anderson, who arranged for the sharing of the equipment, and the untiring help of Dr. G. Rogosa (U. S. Atomic Energy Commission), who coordinated the procurement of isotopically enriched targets. We are also indebted to Professor E. Shrader and Professor H. Newson, who generously lent us isotopes which they needed themselves. We are grateful to Mr. D. White (Argonne National Laboratory) and Dr. K. Haefner for much assistance in preparing usable targets. We gratefully acknowledge the valuable help of Mr. Frank Castorf and Mrs. Serena Torres with programming. Finally, we wish to thank those members of the National Research Council-Chicago collaboration who did not directly participate in this work for sharing their apparatus and programs with us.

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[*] Research supported by National Science Foundation Grant No. GP-6135 (Research).

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[‡] E. I. du Pont de Nemours Fellow, 1966-1967.

[§] National Science Foundation Predoctoral Fellow, 1961-1966.

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DETECTION OF THE SINGLET DEUTERON (đ) AND THE REACTION $\mathrm{Be}^9(p,\text{đ})\mathrm{Be}^8$[†]

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(Received 10 April 1967)

When a singlet deuteron—a neutron and proton in the $S=0$, $T=1$ state, which we designate đ—is emitted in a nuclear reaction, it breaks up almost instantaneously, but not until it is outside the range of interaction with the residual nucleus. Thus, the momentum of the n-p system is conserved, and the momenta of the neutron and proton are the vector sum of the momentum of the original đ plus the momentum of the breakup which must be equal and opposite for the neutron and proton. The total energy available to the system may be divided between the energy of the đ ($E_{\text{đ}}$) and the energy available in the break-up (E_{BU}) in a variety of ways; this is governed by a density-of states function which has been calculated by Simpson,[1] using a theory due to Phillips, Griffy, and Biedenharn.[2]

Attempts to detect singlet deuterons by observing only the proton or only the neutron have been reported by Temmer.[3] In the experiments reported here, the reaction $\mathrm{Be}^9(p,pn)\mathrm{Be}^8$ is studied by detecting the outgoing neutron and proton in coincidence while measuring the proton energy by the pulse height in a solid-state detector and the neutron energy by the time delay between arrival of the proton in that detector and the arrival of the neutron in an organic scintillator. In a two-dimensional display of E_n vs E_p, the transitions to the ground and first excited states of Be^8 appear as two lines corresponding to $E_p+E_n=E_0$, the energy of the incident proton (12 MeV) plus the Q's of the two reactions, −1.7 and −4.6 MeV, respectively. In some fraction of these reactions, the actual reaction is $(p,\vec{d})$, and it is these which we are interested in here.

Let us consider the distribution of E_p along these lines (it would be completely equivalent to consider the distribution of E_n, as their sum is a constant) in the special case where the neutron detector is directly behind the proton detector. Since these detectors subtend a relatively small solid angle, both particles will reach their detectors only if the transverse momentum in the breakup is very small. There is a very low probability of a small transverse momentum if E_{BU} is large, but as E_{BU} decreases, this probability increases. When E_{BU} is very small—below 40 keV in our experimental geometry—the probability of a neutron reaching its detector if the proton reaches its detector becomes unity. Thus the cases where E_{BU} is very small are detected much more efficiently. When E_{BU} is very small, the energies of the neutron and proton are nearly equal, and equal to $\frac{1}{2}E_0$. Thus the distribution of E_p is strongly peaked at $E_p=\frac{1}{2}E_0$, and it is symmetrical about that value since the neutron and proton are completely equivalent. A calculation of this distribution is shown by the curves labeled "calc" in Fig. 1.

In measuring the experimental distribution of E_p, one detects ordinary (p,pn) reactions as well as $(p,\vec{d})$ reactions, so that the former constitute a "background." Some estimate of this background may be obtained by measuring reactions where the neutron and proton are detected at the same angle but on opposite sides of the beam. One might hope that the (p,pn) contributions would be of roughly the same magnitude, but the $(p,\vec{d})$ contribution would be considerably smaller, and would bear no resemblance to the curves in Fig. 1.

Results of measurements of this type at various angles relative to the incident proton beam are shown in Fig. 2. The upper curves correspond to transitions to the ground state of Be^8 where the experimental situation is cleanest. It is clearly seen that the measurements with the two detectors on the same side of the beam bear a striking resemblance to the calculated curves of Fig. 1. They are strongly peaked at $E_p=\frac{1}{2}E_0$, whereas the measurements with the two detectors on opposite sides do not have this feature. If the latter are considered to be a "background," whose rough average is to be attributed to (p,pn) reactions and therefore subtracted off, a good fit to the calculated curves is obtained as shown for two cases in Fig. 1. [The backgrounds used in Fig. 1—labeled "BACKGD"—were estimated with some regard to the wings of the curves and under the assumption that (p,pn) contributions vary smoothly and monotonically with angle, as well as from the data with detectors on opposite sides of the beam. While there is some arbitrariness in the choice of this background, at least it can be said that it was not deliberately chosen so as to get good fits in Fig. 1, and, in fact, better fits could have been obtained by adjusting it.]

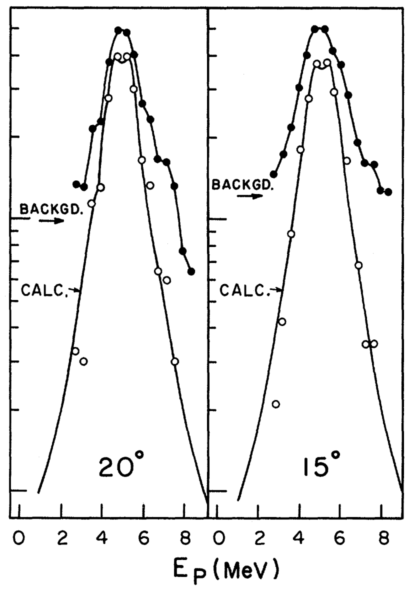

FIG. 1. Energy distributions of protons detected in coincidence with neutrons from the breakup of singlet deuterons with the neutron detector at the same angle as the proton detector. The neutron detector subtends a solid angle of 4.9×10^{-2} sr and the proton detector subtends a much smaller solid angle. Curves labeled "CALC" are calculated, the solid points are data from Fig. 2 at 15 and 20°, and the open circles are obtained from these by subtracting a "background" of events from (p,pn) reactions as discussed in the text.

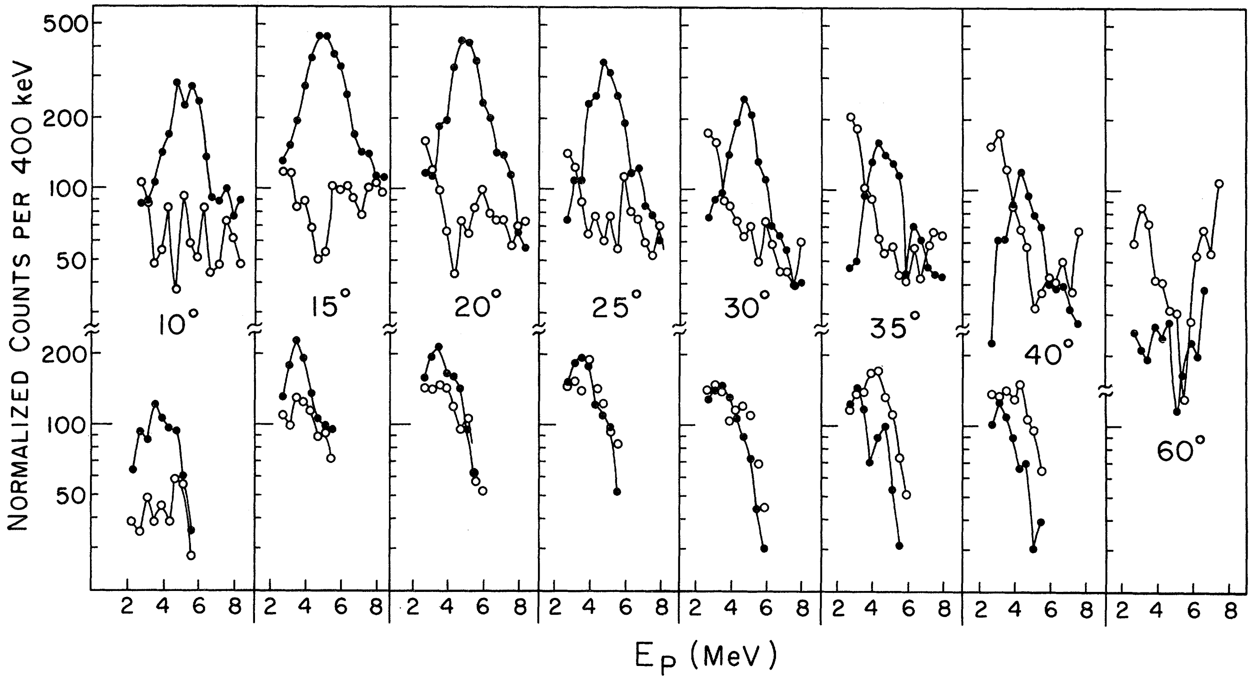

FIG. 2. Energy distributions of protons detected in coincidence with neutrons from reactions Be^9(p,đ) and Be^9(p,pn). In upper curves, the sum of their energies indicate that Be^8 is left in its ground state, and in lower curves this sum indicates that Be^8 is left in its 2.9-MeV excited state. The solid points are data where neutron and proton detectors are at the same angle, and open circles are data where they are at equal angles on opposite sides of the beam. All data are normalized to the same monitor count.

Once we are convinced that the peaks centered at $E_p = \frac{1}{2}E_0$ in Fig. 2 are due to singlet deuterons, it becomes interesting to determine their angular distribution. Utilizing the same method for determining "background" as that used in Fig. 1, the areas under the curves were determined, and the angular distribution labeled "Areas" in Fig. 3 was obtained. Since this method is somewhat sensitive to the assumed "backgrounds," an alternative angular distribution is shown in Fig. 3 in which the intensities were assumed to be proportional to the peak values in the energy distribution, with no background subtracted. It is seen that the two angular distributions agree reasonably well.

Also shown in Fig. 3 is the angular distribution of bound ($S = 1, T = 0$) deuterons from the reaction Be^9(p,d)Be^8 measured in the same experimental setup. According to usual deuteron stripping theories, the (p,d) and (p,đ) angular distributions should be nearly identical, and the cross section for the former should be three times larger ($\sigma \propto 2S+1$). It is clear from Fig. 3 that the angular distributions are quite similar, although not identical. In particular, the angular distribution for d's seem to be peaked at a slightly smaller angle than the angular distribution for đ's. This could be due to a spin dependence in the stripping interaction, or to a difference between the optical model potentials for a 12.5-MeV d and a 10.2-MeV đ, although experimental explanations are not out of the question.

An estimate of the cross-section ratio may be obtained by estimating the probability, P, for detecting the neutron from a đ once the proton is detected. The calculation of P is the same one as was used in obtaining the calculated curves of Fig. 1, but it is much more sensitive to the details of the "density-of-states" function which is not very certain in the region where it was computed in Ref. 1, and which, moreover, must be extrapolated far beyond the range of that computation. Our calculation of P gave it to be 2.1% times the efficiency of the neutron detector. The latter is about 13%, so that we obtain $P \simeq 0.27\%$. Using this, we find that the ratio of d to đ normalized to the same number of monitor counts was 4.25 at 20° and 5.5 at 15°. In view of the uncertainty of the calculation and the uncertainty of the background subtractions in the measurements, this

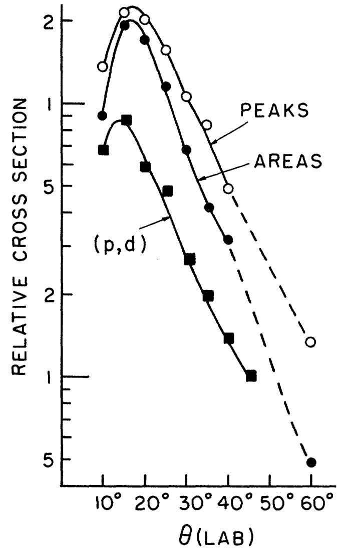

FIG. 3. Angular distributions of đ and *d* from reactions Be^9(*p*,đ)Be^8(g.s.) and Be^9(*p*,*d*)Be^8(g.s.). The upper two curves are for đ; the solid points are determined from areas under the distributions of Fig. 2, and the open circles are from peak heights. The lower curve is for ordinary deuterons.

is not in bad agreement with the predicted ratio of 3.0. That predicted ratio may also, of course, be influenced by the factors cited above as possibly contributing to the differences in the angular distributions.

The data for reactions leading to the 2.9-MeV excited state of Be^8, shown in the lower part of Fig. 2, were much less reliable than those for the ground-state transition. There is a continuum of events from reactions Be^9(*p*, *pn*2*α*), and in some cases, there was not even an observable peak corresponding to the 2.9-MeV state of Be^8. However, at every angle in Fig. 2, there is a peak in the energy distribution of protons at the proper energy−1.45 MeV lower in energy than the peak in the upper curves. There are no such peaks in the data where detectors are on opposite sides of the beam. The angular distribution for these peaks is clearly peaked at the same angle (~17°) as for the ground-state transition, as is expected from the fact that both are $l=1$ transitions. It does not fall off with angle as fast as the angular distributions of Fig. 3, but this can perhaps be explained by contributions from the (*p*, *pn*2*α*) continuum which were clearly large and were not subtracted off. Thus, it seems that (*p*,đ) reactions leading to the 2.9-MeV state of Be^8 were also observed in these experiments.

The authors are happy to acknowledge helpful discussions with G. C. Phillips, J. C. Legg, D. Robson, G. Temmer, E. W. Hamburger, and W. W. Daehnick.

[†] Work supported by National Science Foundation.

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