(p,n) Angular Distributions from Mirror Nucleus Targets: C^{13}, B^{11}, and Be^9†

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Neutron angular distributions from the (p,n) reactions in C^{13}, B^{11}, and Be^9 have been measured using a long-counter detection technique in conjunction with the Livermore 90-inch variable-energy cyclotron. Proton energies ranged from threshold (2.0 Mev to 3.2 Mev) up to 5.7 Mev. The aim here was to find qualitative experimental evidence bearing on the direct reaction mechanism proposed by Bloom, Glendenning, and Moszkowski wherein the (p,n) reaction connecting the ground states of mirror nuclei should go via a direct mode which is derived principally from the residual two-body interaction between the incoming proton and the bound neutron (or neutrons). It is found that the experimental evidence supports this hypothesis in that the angular distribution changes slowly in the direction of increasing complexity with increasing energy, largely ignoring the occurrence of resonances except in their immediate vicinity. Also a tentative grouping by pairs of the (p,n) angular distributions for (C^{13}, N^{15}) and (Be^9, B^{11}) shows marked similarities between the members of each pair in conformity with the twin-reaction picture stemming from the same theory. Finally, preliminary results are presented of an IBM-704 computation program using a distorted-wave Born approximation theory formulated originally by Glendenning. The comparison between theory and experiment, although based on early returns, is in general encouraging. It is found that a triplet-singlet interaction strength ratio is required here which is about $\frac{2}{3}$ of that derived from the Gammel-Thaler phenomenological potential. However, in view of the basic differences between the free and the bound two-body problem it is felt that more knowledge will be required in order to properly compare the present results with the free-scattering analyses.

INTRODUCTION

The exploitation of the direct-interaction process as a means of determining spins and parities of nuclear states is now so well advanced as to be termed standard in the repertoire of low- and medium-energy techniques.[1] In this paper, we propose to adduce qualitative experimental and theoretical evidence for yet another useful aspect of direct interaction, namely, the investigation of the effective two-nucleon force in nuclei.[2] As has been suggested,[2,3] this particular kind of investigation is most simple in the case of mirror nuclei reactions,

$$_zX_{z+1}+p \rightarrow {}_{z+1}X_z+n. \qquad (1)$$

The detailed nature of the simplifications is described elsewhere.[2] Here we content ourselves with a brief recapitulation of the main theoretical results. First of all, the fact that we are dealing with mirror nuclei means that this process is dominated by that part of the p-n interaction which exchanges the charge between the two nucleons (considering only central forces). This plus the fact that we are dealing with ground states, where spins and parities are well known and wave functions can be reasonably estimated, makes it possible to calculate a cross section having an explicit and (hopefully) simple dependence on the p-n interaction inside the nucleus. It should be further noted that the charge-exchange part of the central force will in general be spin-dependent. Thus we can choose a force representation in terms of singlet and triplet components and the angular distributions will then depend on the relative strength of the two. More refined considerations, as for instance, the particular interest of such targets as C^{13}, B^{11}, N^{15}, O^{17}, etc., whose structures closely approximate the form of two closed shells (or subshells) plus or minus one extra core nucleon, are treated elsewhere.[2]

It is surprising to find that the amount of experimental information available which might throw light on the kinds of problems just described is quite sparse. The reasons for this are not hard to find, however. For instance, we note that a total excitation cross section (at high energies) in the case of $C^{13}(p,n)N^{13}$ (ground state) has been made recently at Livermore.[3] But the problem is that C^{13} is quite unique as a target on which such single-state excitation measurements (residual radioactivity counting) can be made, since in all other nuclei at least one state besides the ground state is stable against neutron emission. For other mirror-nuclei targets the only immediately accessible experimental data (yet to be taken) bearing on the question at hand are the (p,n) angular distributions, preferably at energies where wave-distorting effects are small. However, as has been clearly demonstrated,[4,5] final-state and initial-state interactions produce very large effects in the angular distributions as long as the potential between the nucleons and the nucleus is comparable with the energy of the reaction. This latter situation exists essentially for all energies where it is practical to separate ground-state neutrons from neutrons leaving the residual nucleus in other states, such separation being performed usually by time-of-flight or by staying below energies capable of exciting anything but the ground state. We are thus left in the difficult situation where the angular distributions can really be done by

† This work was performed under auspices of the U. S. Atomic Energy Commission.

[1] See S. T. Butler, N. Austern, and C. Pearson, Phys. Rev. **112**, 227 (1958); this paper gives a very complete compendium of references (to date) on both experimental and theoretical work in this area.

[2] S. D. Bloom, N. K. Glendenning, and S. A. Moszkowski, Phys. Rev. Letters **3**, 98 (1959).

[3] S. D. Bloom, R. M. Lemmon, and S. A. Moszkowski, Bull. Am. Phys. Soc. **3**, 418 (1958).

[4] C. A. Levinson and M. K. Banerjee, Ann. Phys. **3**, 67 (1958).

[5] N. K. Glendenning, Phys. Rev. **114**, 1297 (1959).

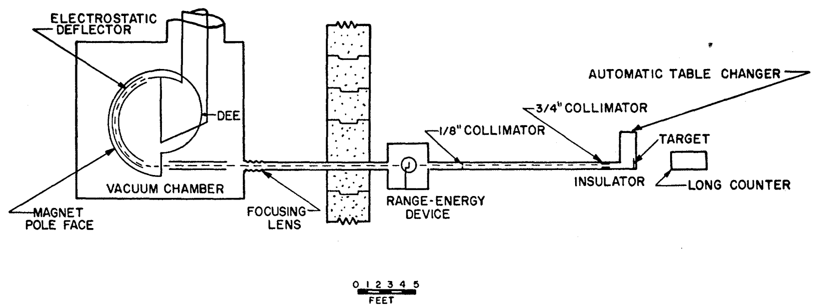

FIG. 1. Schematic diagram of experimental layout. View of the cyclotron is from the side, as the plane of the dee is vertical.

simple techniques (e.g., with long-counters) only at energies *in the vicinity of threshold*. Although this is certainly a severe limitation it is still far from a hopeless one, since there is no basic reason why the direct process should be any less prevalent near threshold than it is at higher energies, aside from kinematic factors. One effect, however, does intrude at low energies which is not much in evidence at high energies. It is the coherent interference between resonances and direct effects. But these effects need not be too disturbing if one avoids as much as possible the vicinity of resonance peaks, as suggested by Butler and others.[6]

In the work to be described here the (p,n) angular distributions were measured for C^{13}, B^{11}, and Be^9 targets, using a long-counter technique (see below) in conjunction with the Livermore variable-energy 90-inch cyclotron. The experimental results were given some time ago,[7] the interim having been spent in getting a concomitant theoretical computation underway.[8] Since last year some (p,n) angular distribution for the case of $C^{13}(p,n)N^{13}$ in the energy range 3.57 Mev to 4.60 Mev have appeared[9] which generally confirm the findings here. Since this latter work was performed on a Van de Graaff accelerator, with better than a factor of ten improvement in energy resolution over the cyclotron, one might expect that resonance effects would not "average" out as effectively as would be desired for the purposes involved here. For this reason the two sets of data are not directly comparable, though it would still be interesting to extend the Van de Graaff work right down to threshold to check the strong forward-angle sloping found in the present work. Because of the flat-energy response of long-counters the cyclotron measurements were necessarily confined to low-energy protons, as described above. (However, in a separate experiment a large body of time-of-flight data has been collected in the case of C^{13}, Be^9, and N^{15} for proton energies ranging from 6–13 Mev. A report on this work is in preparation.[10]) Theoretical calculations with distorted wave functions have been made and are also presented here. These calculations although illuminating and helpful in indicating the direct nature of the process are to be considered as somewhat tentative in nature since certain assumptions are made in the theory which may not be completely tenable at these low energies. The general features of the results and their comparison with the theory are discussed fully for each case at the end of this paper. Suffice it to say that the suggestion of direct reaction dominates the (p,n) process from threshold on. It remains for future experiments, particularly at higher energies, in conjunction with more detailed theoretical calculations to verify the preliminary evidence presented here.

EXPERIMENT

The experimental setup is shown in Fig. 1. The Livermore 90-inch cyclotron provides a beam of protons variable in energy from 2.6 to 13.8 Mev. The beam is collimated by an elliptical tantalum collimator so that a circular spot is produced at the target which is angled at 30° with respect to the proton beam. The first collimator has an $\frac{1}{8}$-in. major axis and $\frac{1}{16}$-in. minor axis elliptical opening. It is located at a distance of 13 ft from the target so as to obtain a large inverse square law reduction of background at the detector. The second collimator is located 2 ft from the target and has an elliptical opening of $\frac{3}{4}$-in. major axis and $\frac{3}{8}$-in. minor axis, which is sufficiently large to transmit most of the proton beam at that point. The beam strikes targets which are thin deposits (≈ 1 mg/cm^2) of elements evaporated on 10-mil tantalum disks. Cooling is achieved by means of an air stream directed against the outside of the target which is exposed to atmosphere. Targets are changed automatically by means of a remote positioning device. The final 2 ft of beam pipe and the target changer form a Faraday cup which is insulated from the rest of the beam pipe. The final 10 ft of beam pipe is made of 30-mil aluminum to minimize neutron scattering and background. Neutrons are detected by means of a BF_3 long-counter whose front face is about 2 ft from the target. This counter is mounted on a cart which pivots in a horizontal plane about the target position as a center. The angle between the proton beam and the counter is controllable from a remote

[6] S. T. Butler, Phys. Rev. **106**, 272 (1957); N. Austern, S. T. Butler, and H. McManus, *ibid.*, **92**, 350 (1953).
[7] S. D. Bloom and R. D. Albert, Bull. Am. Phys. Soc. 4, 321 (1959).
[8] N. K. Glendenning and S. D. Bloom (to be published).
[9] J. K. Bair, H. O. Cohn, and H. B. Willard, Phys. Rev. **119**, 2026 (1960).
[10] J. D. Anderson, C. Wong, S. D. Bloom, J. W. McClure and B. D. Walker, Phys. Rev. (to be published).

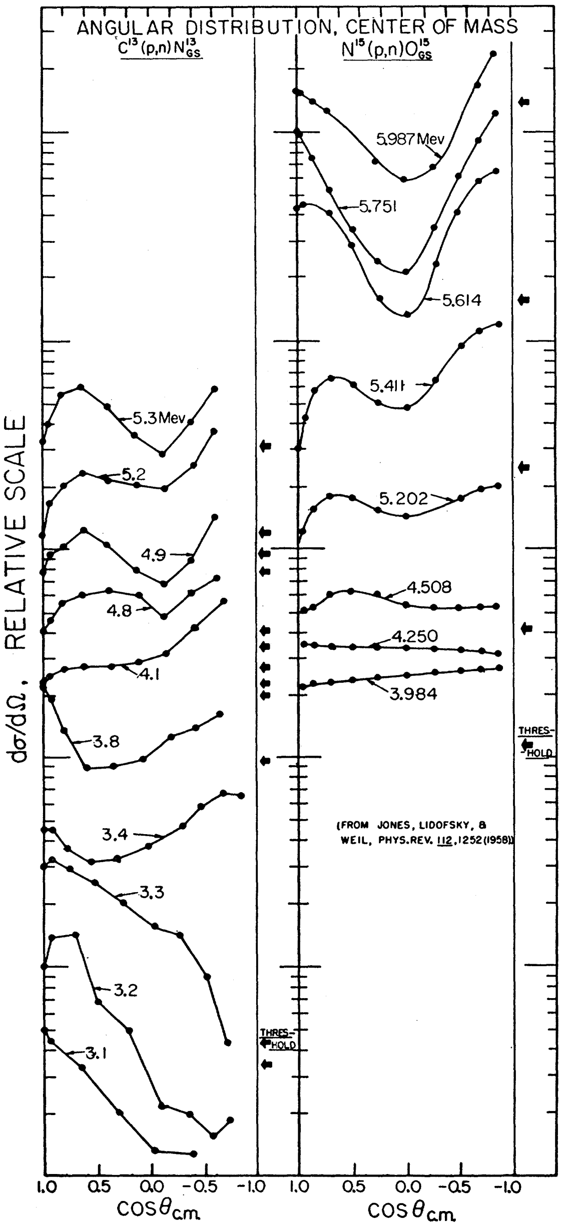

FIG. 2. Comparison of experimental results for "twin" reactions $C^{13}(p,n)N^{13}{}_{GS}$ and $N^{15}(p,n)O^{15}{}_{GS}$. The data for the latter (see reference 9) have been replotted to match the conventions used in this paper. Data taken right at resonance have been omitted from the N^{15} results shown here.

point in the cyclotron control room to better than 1 degree in accuracy and reproducibility.

The energy response of the neutron detector, which was a shielded long-counter of the Hanson-McKibben type,[11] was measured at 2 points using neutron sources of 1.5- and 4.5-Mev average energies. The 2 sources (polonium-beryllium and mock fission), which were calibrated to better than 5% accuracy by the Bureau of Standards, gave results that agreed to within 7% accuracy. Combining these results with measurements by Hanson and McKibben[11] for the same type counter indicates that its energy response was flat to within 15% between 23-kev and 5-Mev neutron energy. Operation of the counter was stable and reproducible over a period of several months.

Targets were prepared by evaporating the target material on 10-mil polished tantalum backings. The deposits were about 2 in. in diameter and weighed about 1 mg/cm^2. Thicknesses were obtained by weighing the 3-in.-diameter backing on a microbalance before and after each deposition. The filament-to-target distance was sufficient to ensure that less than 1% variation in target thickness could be caused by geometric factors.

The experimental measurements were carried out by counting for a given amount of charge collected on the Faraday cup. Typically, the procedure was to increase the angle from 0° in alternate 30° steps so that determinations were obtained in 15° intervals. The cyclotron current averaged about 0.25 microampere. The beam intensity permitted determinations to be made with about 3% statistical error in only a few minutes.

The energy of the proton beam was monitored regularly by a differential range-energy determination device to better than 100-kev accuracy. Backgrounds were determined by inserting blank tantalum backings into the beam at the target positions. Corrections obtained in this manner were generally small compared to the data count.

RESULTS

Bloom, Glendenning, and Moszkowski[2] have pointed out that for (p,n) reactions on mirror nuclei a target nucleus consisting of a doubly closed shell plus one neutron is essentially equivalent to a doubly closed shell minus one proton, from the direct mode point of view, provided the hole and the particle are in the same state. Accordingly we have, for the purposes of discussion here, grouped the results into pairs. First we compare our results for $C^{13}(p,n)N^{13}{}_{GS}$ with the data for the "twin" reaction, $N^{15}(p,n)O^{15}{}_{GS}$, taken by Jones, Lidofsky, and Weil,[12] since there are some grounds for believing that C^{13} may have the structure of a closed subshell of $(p_{\frac{3}{2}})$ nucleons plus one neutron in a $(p_{\frac{1}{2}})$ state.[13] N^{15} ought to be well approximated by a $(p_{\frac{1}{2}})$ proton hole designation. $Be^9(p,n)B^9$ we have grouped with $B^{11}(p,n)C^{11}{}_{GS}$, taking the point of view that Be^9 could possibly be regarded as a relatively inert Be^8 core (consisting perhaps of two alpha particles[14] a considerable fraction of the time) with a $p_{\frac{3}{2}}$ neutron outside this core. B^{11}, by the same arguments as used for C^{13},

[11] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

[12] K. W. Jones, L. J. Lidofsky, and J. L. Weil, Phys. Rev. **112**, 1252 (1958).

[13] M. K. Banerjee and C. A. Levinson, Ann. Phys. **2**, 499 (1957).

[14] William T. Pinkston, Phys. Rev. **115**, 963 (1959); J. S. Blair and E. M. Henley, *ibid.* **112**, 2029 (1958).

may be regarded as having the structure of a proton hole in the $p_{\frac{3}{2}}$ state. Whereas the B^{11} assignment is based on some good theoretical and experimental grounds,[13] the case for Be^9 is, in fact, almost totally hypothetical. Therefore, we should like to emphasize that the grouping together of these two latter cases is very tentative.

$C^{13}(p,n)N^{13}{}_{GS}$ and $N^{15}(p,n)O^{15}{}_{GS}$

Our results and the results of Jones, Lidofsky, and Weil[12] (replotted to match our type of display) are shown in Fig. 2. The ordinate for the angular distribution for these curves (and for Fig. 3 as well) is logarithmic and the plots for the various energies have been displaced vertically quite arbitrarily to facilitate convenient comparison between the "twin" reactions on C^{13} and N^{15} (similarly for Be^9 and B^{11}). The horizontal scale is $\cos\theta$ (angle between incoming proton and outgoing neutron) in the center-of-mass system. The solid arrows along the vertical scale indicate the position of known resonances and are interpolated between the 0° cross-sectional values (e.g., the 2.30-Mev resonance in $Be^9(p,n)$ in Fig. 3 is placed about one-third of the way between the points at $\cos\theta=1$ corresponding to proton energies of 2.2 Mev and 2.5 Mev).

Concentrating our attention on the results for C^{13} alone (Fig. 2) for the moment, it seems quite clear from the onset of the (p,n) reaction at threshold to the highest energy measured here that a gradual change in the angular distribution in the direction of increasing complexity with increasing energy is the basic characteristic of the results. The somewhat surprising forward slope beginning at threshold disappears at around 4.4 Mev, where a kind of inversion in the angular distribution seems to occur since it begins to dip sharply at 0°. It is useful now to compare the C^{13} results with the Jones *et al.*[12] results for N^{15}. Unfortunately, the results for the first 250 kev above threshold for N^{15} are not published, so we cannot say whether $N^{15}(p,n)O^{15}$ also exhibits the same forward sloping in this region that $C^{13}(p,n)N^{13}$ does, although, in view of the difference in threshold, similarities at these low energies would not necessarily be expected (see below). However, the striking similarity of the two angular distributions at those energies at which both have been observed is very obvious. The curves have been compared at roughly the same center-of-mass energy, but it must be borne in mind that there are differences between the two cases which can and should manifest themselves, particularly at the lowest energies. These are discussed below. For $N^{15}(p,n)O^{15}$, it will be noted that the dip at 0° disappears above 5.7 Mev. It is now known that this behavior also characterizes the (p,n) reaction in C^{13}, the dip being replaced by a rise for energies above 6.0 Mev.[10]

The effect of resonances on the C^{13} data can perhaps be discerned in the data taken at 5.2 Mev. In general, because of the fact that the energy resolution of the cyclotron is broad (≈ 100 kev) compared even to the neutron widths encountered here, it is not to be expected that large discontinuities in the angular distributions at or in the vicinity of resonances should manifest themselves clearly. On the other hand, in the case of the $N^{15}(p,n)O^{15}$ investigation, which was performed using the Columbia 6-Mev Van de Graaff accelerator, these discontinuities should and do manifest themselves very strongly indeed. Angular distributions taken by Jones *et al.*[12] right at the peak of sharp resonances are eliminated from the presentation in Fig. 2, but one may easily verify this point by looking at the original

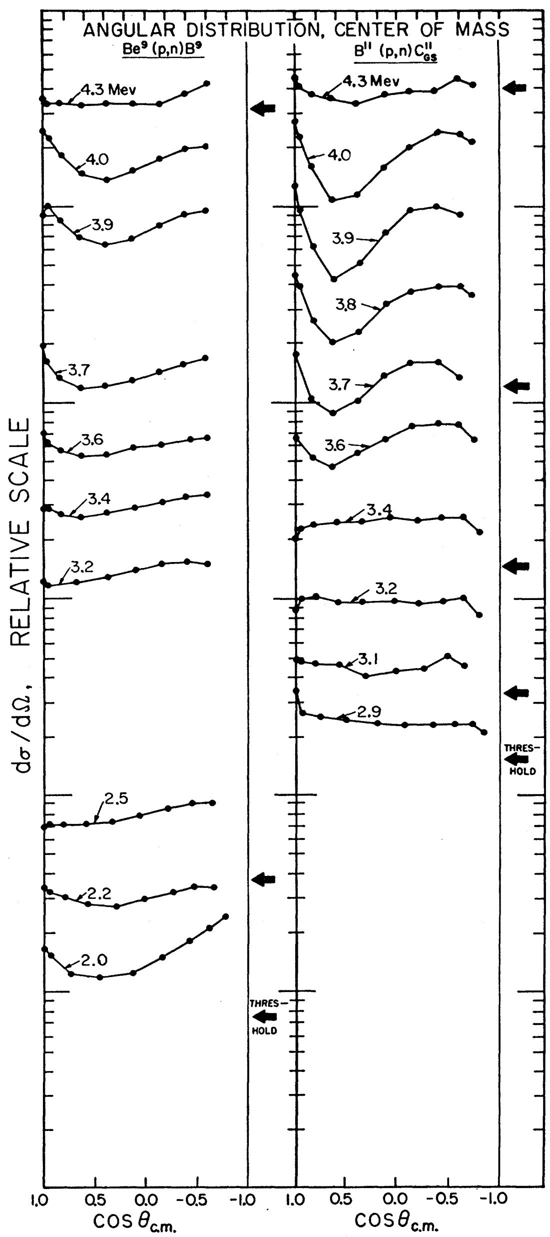

FIG. 3. Comparison of experimental results for "twin" reactions $Be^9(p,n)B^9$ and $B^{11}(p,n)C^{11}{}_{GS}$.

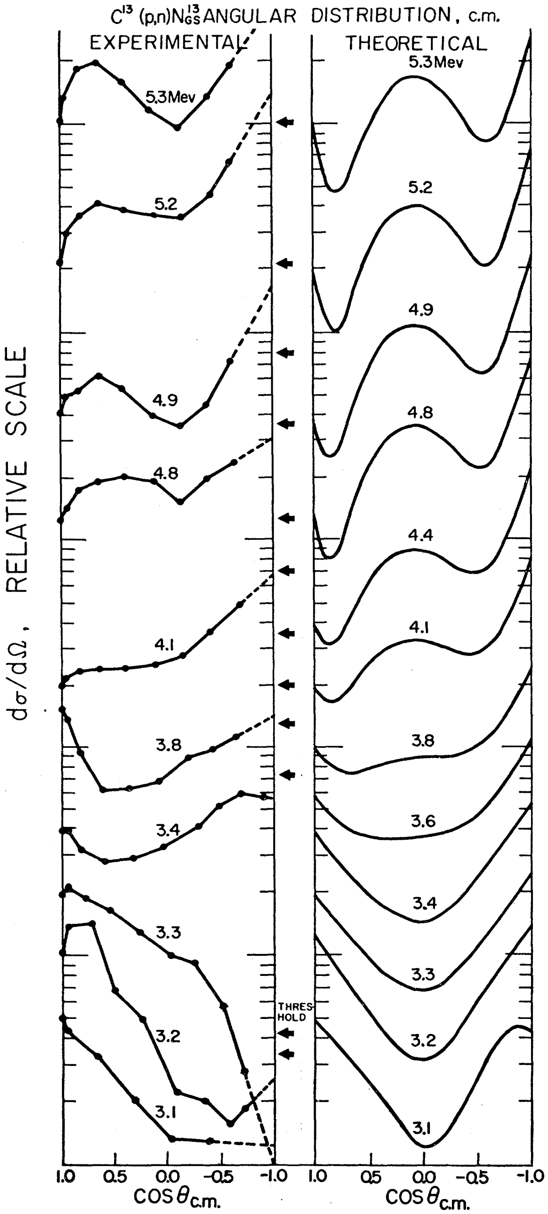

FIG. 4. Comparison between preliminary theoretical results and experimental results in the case of $C^{13}(p,n)N^{13}{}_{GS}$.

curves.[12] The quick disappearance of the effect of these resonances on both the low- and high-energy sides is quite dramatic and strongly supports the validity of the suggestion[6] mentioned earlier.

$Be^9(p,n)B^9$ and $B^{11}(p,n)C^{11}{}_{GS}$

We begin the discussion here by noting that of all the measurements we have made the ones on Be are the most vulnerable to both the theoretical criticisms already given above and the experimental limitations mentioned in the introduction. In the case of Be^9 it happens to be that the energy threshold in the laboratory system for the $(p;p,n)$ process[15] is 1.859 Mev, which is 200 kev *lower* than for the (p,n) process which we are most interested in observing. It is quite clear that the distortion of the (p,n) angular distributions by the breakup process, particularly at the (p,n) threshold, could be very large. This might account for the relatively anomalous behavior at 2.0 Mev (Fig. 3), where the departure from isotropy, characteristic otherwise, near threshold, of both $Be^9(p,n)$ and $B^{11}(p,n)$, is very marked. Also, there is the possibility of contamination in the angular distribution of the controversial state at 1.4 Mev in B^9. However, in this latter case the very questionability of the state indicates a small cross section, and the likelihood of its affecting the present experiment seems small. The breakup process, as soon as one has raised the proton energy out of the immediate vicinity of the (p,n) reaction threshold, may also contribute little to the total number of neutrons, since preliminary measurements[10] indicate that at these energies, at least, the relative contributions of $(p;p,n)$ and (p,n) favor the latter rather heavily.

Keeping all these exceptions in mind, it is still striking to compare $Be^9(p,n)$ and $B^{11}(p,n)$ at the same center-of-mass energies for the energy range covered here. From isotropy at threshold and immediately above, except for the possibly anomalous 2.2-Mev data in Be^9 (already noted), to the pronounced forward peaking and its simultaneous disappearance in both targets the similarity of the two cases seems almost too close not to be at least partly fortuitous. However, since we already know (see Fig. 2) that threshold behavior need not necessarily be isotropic, the similarity at lower energies would be difficult to attribute completely to fortune, and the almost identical evolution with increasing proton energy renders this interpretation even less likely. It would seem therefore, that the direct-interaction hypothesis, via the particular mode described above, is also strongly supported here.

THEORETICAL CALCULATIONS

The basic method of calculation utilized here is the one described and applied in great detail by Levinson and Banerjee[15] and also by Glendenning.[5] Here we have used the latter approach wherein the free-distorted wave functions of the Born approximation are generated by a square well with a uniform imaginary part. In his original work Glendenning[5] used a simple Gaussian interaction between the free and the bound nucleon with no exchange character, whereas Levinson and Banerjee[15] in their work used the Serber exchange mixture,

$$V_{12}=\tfrac{1}{2}(1-P^{\sigma}P^{\tau})V(|\mathbf{r}_1-\mathbf{r}_2|), \qquad (2)$$

where the subscripts 1 and 2 refer to the two nucleons whose force law is under consideration. We have chosen to express the Serber exchange mixture in terms

[15] C. A. Levinson and M. K. Banerjee, Ann. Phys. 2, 471 (1957).

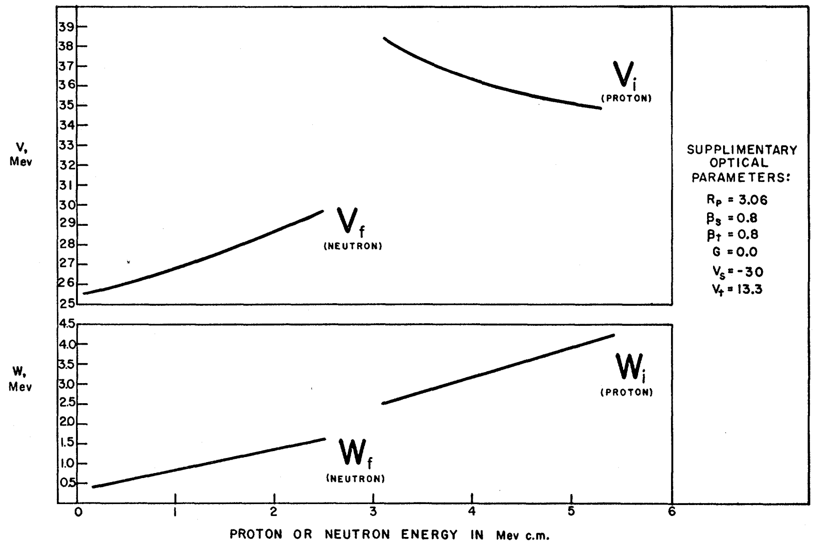

FIG. 5. Optical parameters used in calculating distorted-free wave functions for the theoretical angular distributions shown in Fig. 4. See text for meaning of symbols.

of the ordinary spin-exchange operator, P^σ, and the isotopic spin-exchange operator, P^τ, the definitions for these being taken as given, e.g., by Blatt and Weisskopf.[16] It was found by Levinson and Banerjee[15] that the exchange integrals contribute little to the total inelastic cross sections. For the (p,n) reaction, the charge-exchange part of V_{np} contributes a direct integral in the space coordinates while the exchange integral is associated with the charge-nonexchange part of the p-n interaction and arguments based on the poor overlap of wave functions for the nonexchange contribution to the (p,n) cross section have already been made[2] showing that here this contribution must also be small. However, it was found impossible to produce theoretical curves resembling the experimental results at all without taking into account spin-exchange forces. Thus the neutron-proton force was taken to have the form,

$$V_{np}=(V_{\sigma\tau}P^\sigma+V_\tau)P^\tau, \tag{3}$$

i.e., a spin-exchange component plus a spin-nonexchange component, all multiplied by the isotopic spin-exchange operator. While it is felt that this form adequately takes care of the central forces, the neglecting of the tensor force is another matter and probably will require some emendation in future work (see below). Equation (3) may, of course, be re-expressed in terms of singlet and triplet spin-projection operators, and this in fact was done in the actual computations. In Fig. 4 we show a comparison between this theory and experimental results. The calculation was made on an IBM-704 digital computer. Because of the semilog representation of the ordinate $(d\sigma/d\Omega)$ shapes are preserved at all vertical positions. The ordinate values are only relative at a given energy and should not be interpreted as giving the total cross section (when integrated), either relatively or absolutely. The parameters for the optical-model wave functions used for this particular calculation are shown in Fig. 5. An optical-well radius value of $R_P=1.30(A)^{\frac{1}{3}}\times10^{-13}=3.06\times10^{-13}$ cm was used, and in the very preliminary parametric search which the results of Fig. 5 represent, the variation in V (real part of the potential) was considered as adequately taking into account all possible variations in R_P. This is exactly the same procedure followed by Levinson and Banerjee[4] as well as Glendenning[5] and it is based on the fact that both the magnitude and the differential shapes of the theoretically predicted cross sections are essentially sensitive only to the product $VR_P{}^2$, rather than V and R_P separately. This point has been checked by actual computation and will be discussed in another paper.[8]

The following equations give the relevant mathematical formulas with the definition of symbols used in the calculations under discussion here:

$$\frac{d\sigma}{d\Omega}=\left(\frac{k_p}{k_n}\right)\left(\frac{m}{2\pi\hbar^2}\right)^2|\langle f|V_{np}|i\rangle|^2, \tag{4}$$

$$\begin{aligned} V_i(r)&=V_i+iW_i, \quad r\leq R_P \\ V_i(r)&=0, \quad r>R_P \end{aligned} \tag{5}$$

$$\begin{aligned} V_{np}(r_{np})&=\left[V_s\left(\frac{1-\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{4}\right)-V_t\left(\frac{3+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{4}\right)\right], \\ V_s&=V_{s0}\exp(-\beta_s r_{np}{}^2),\quad V_t=V_{t0}\exp(-\beta_t r_{np}{}^2). \end{aligned} \tag{6}$$

Equation (4) is simply the Born approximation, where $\langle f|$ and $|i\rangle$ refer to the final- and initial-state wave functions (see reference 2 for the explicit form of the totally symmetrized wave functions as well as symbol definitions not given here). The free-state wave functions for the initial state protons (p) and final-state

[16] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 160.

neutrons (n) are the solutions to Schrödinger's equation with the perturbing potentials of Eq. (5). Omitted was the explicit form for the potentials characterizing the final state interaction because it is the same as for the initial state, with the exception that the subscript "f" replaces the subscript "i". With the exception of R_P, initial and final state potential parameters could be and were varied independently. No account was taken in this calculation of the Coulomb distortion. The form of the perturbing potential (V_{np}) causing the reaction in question is given in Eq. (6), where s refers to the singlet-projection operator, $(1-\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)/4$, and t refers to the triplet-projection operator, $(3+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)/4$. For all the computations done here V_t and V_s were assumed to have the same range. However, it was found that a variation in the range of either V_t or V_s could be effectively compensated for by changing the strength of the amplitude, again in accordance, roughly speaking, with the VR^2 law. The surface reaction assumption was made in this calculation as in the earlier work by Glendenning,[5] although the site of the reaction surface was one of the variable parameters. This site could be chosen on any sphere *outside* R_P, the potential boundary, which was the same for both the initial and final states. Harmonic oscillator wave functions were used for the bound states, as is customary in shell-model calculations.

Theory and experiment cannot be said to be in precise agreement at this stage. However, there are many remarkable resemblances characterizing the comparison of theoretical and experimental results as shown in Fig. 4 which could hardly be a result of accident. Ignoring for the moment the pronounced backward rises predicted by the theory just above threshold (3.2 Mev to 3.6 Mev) we see that beginning at threshold both theory and experiment exhibit pronounced rising of the differential cross section in the forward directions, which changes gradually in about the same way in both sets of curves to a large humping around 90° in the theory and 45° or so in the experiment. The theory exhibits a sharp forward peaking at energies above 4.1 Mev not shown in experiment; however, present indications are that this is due at least as much to the very preliminary nature of the search for the best parameters[8] as it is to inadequacies in the basic computational approach. However, the backward rises in the theoretical curves which occur in the theory just above threshold, remarked earlier, might well be due to theoretical inadequacies which, for instance (see above) include ignoring of the Coulomb forces occurring in the initial state as well as the known "softness" of the nuclear edge in both initial and final states. Such effects are bound to be of particular importance for the lowest energies. The "soft" nuclear edge, in fact, is significant at all energies of interest here in that it leads to an enhancement of reaction cross sections in general as compared to what might be expected from a square well, such as we have used here. Thus in this case, as well as in inelastic scattering,[5] in order to fit the observed cross-sectional magnitudes unbelievably high values for the nucleon-nucleon interaction strength would have to be assumed. For this reason it will be necessary to wait for a more elaborate computational program before total cross sections in theory and experiment can be reconciled. It is worth noting that this is achievable since in the Levinson and Banerjee[15] work such a program, taking into account not only Coulomb effects and the rounded well but several other more subtle effects, did come within a factor of two or so of the free-scattering nucleon-nucleon interaction strengths.

The triplet-singlet strength ratio, V_t/V_s [see Eq. (5)], which seems to be required in the present computation[17] is about +0.4, though we would like to note that a much more thorough investigation of this quantity both at these energies and higher energies is in progress.[8] The corresponding ratio for the central-force components of the phenomenological two-body potential derived by Gammel and Thaler[18] may be estimated by making a normalization of their potential amplitudes[17] to a single Yukawa range. This was done here by again invoking the VR^2 law for the two-body force (see above). The procedure must be regarded as very approximate, however, because of the presence of the repulsive core beginning at 0.4 fermis in all the potential components used by Gammel and Thaler.[18] The result with this method nonetheless is +0.6, which is certainly comparable to +0.4, as measured here. It is felt that the computation, although necessarily rough, still has guidance value in that it at least indicates no gross discrepancies between our parameters and the free-body parameters. However, one cannot *finally* compare these two quantities without at least taking into account the fact that the Gammel-Thaler potential included a strong tensor part, whereas in the present work no such force was included in the analysis. Furthermore it must be recalled that in the present work, the *p-n* force was measured *in* the nuclear medium, rather than in the free state. The expectation is that these two situations may well lead to important differences in the effective forces observed.[19]

It is hoped to improve in general the procedure for comparing results from different analyses in the near future.[8] One real improvement which might be mentioned here would be to calculate the free-scattering triplet-singlet strength ratio with the diagonal matrix

[17] The relations between (V_t,V_s) in the present approach and the central-force components used by Gammel and Thaler (reference 18) are as follows:

$$V_t=({}^3V_c{}^+-{}^3V_c{}^-)/2,\quad V_s=({}^1V_c{}^+-{}^1V_c{}^-)/2.$$

Thus the triplet-singlet strength ratio in terms of the Gammel-Thaler components is given by

$$V_t/V_s=({}^3V_c{}^+-{}^3V_c{}^-)/({}^1V_c{}^+-{}^1V_c{}^-).$$

[18] J. L. Gammel and R. L. Thaler, *Progress in Cosmic-Ray Physics*, edited by J. G. Wilson (Interscience Publishers, New York, 1960), Vol. 5, p. 99; see also K. A. Brueckner and J. A. Gammel, Phys. Rev. **109**, 1023 (1958).

[19] S. A. Moszkowski and B. L. Scott, Ann. Phys. (to be published).

elements for the free-scattering potential components. This should pretty much obviate the range-normalization problem described above. Such a calculation, as a function of energy, is now in progress.[20]

Speaking broadly, it is felt that the results to date of our analysis are encouraging, particularly in view of the strictly exploratory nature of both the theoretical and experimental effort described here. Furthermore it is felt that the points made concerning the inadequacies of the present approach in the preceding paragraph are the only major ones distinguishing our evaluation of V_{pn} from free-body calculations, and methods for remedying most or all of them are not difficult to visualize. Thus we feel it is reasonable to say that exploratory as this work may be it still seems to show that the theoretical method and the experiment are well suited to each other and that, by and large, the direct reaction can and very likely will be useful as another tool in the study of the basic nuclear two-body problem.

[20] S. A. Moszkowski and B. L. Scott (private communications).

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$Si^{28}(d,p)Si^{29}$ Reaction*

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The 15-Mev deuteron beam of the University of Pittsburgh cyclotron was used to study the $Si^{28}(d,p)Si^{29}$ reaction. Angular distributions of protons from most of the Si^{29} levels up to an excitation energy of 6.4 Mev were obtained. Good agreement with the 8-Mev deuteron results of Holt and Marsham (at a deuteron energy of 8 Mev) was found, except in a few cases where an $l=2$ distribution showed low-angle peaking in one of the experiments but not in the other. The angular distributions of the 5.94- and 6.19-Mev states in Si^{29}, not previously reported, were obtained. Butler curves with $l=2$ and $l=3$, respectively, were fitted to these two distributions. A somewhat unusual evaporation technique used to prepare the necessary targets from small quantities of SiO_2 with relatively high collection efficiency is described.

I. INTRODUCTION

THE $Si^{28}(d,p)Si^{29}$ reaction has been studied at an incident deuteron energy of 8 Mev by Holt and Marsham,[1] and their experimental results were included in the evidence for the collective behavior of Si^{29} in the study of Bromley *et al.*[2] It is of some interest, however, to perform this experiment at a higher deuteron energy, because the dependence of angular distributions and stripping reduced widths on incident particle energy has been studied in only a few cases. In addition, the use of higher resolution may provide angular distributions to other Si^{29} levels. The work reported here is part of a program carried out in this laboratory to investigate the (d,p) reaction on Si^{28}, Si^{29}, and Si^{30}, and the (d,t) reaction on Si^{29} and Si^{30}. Results of these other experiments will be reported later.

II. EXPERIMENTAL PROCEDURE

The external deuteron beam of the University of Pittsburgh 47-inch cyclotron, whose energy is approximately 15 Mev, is electromagnetically focused and energy analyzed.[3] Charged reaction particles are analyzed by a magnetic spectrometer, which can be rotated about the target. In the present experiment, the reaction protons were detected by means of a nuclear emulsion system.[4]

The targets used were made in this laboratory, as described in the Appendix. One target was made from naturally occuring SiO_2 (92.2% Si^{28}, 4.7% Si^{29}, 3.1% Si^{30}). Other targets enriched in either Si^{29} or Si^{30} were made from SiO_2 enriched in the respective isotope,[5] and

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[5] The enriched SiO_2 was obtained from Isotope Sales Department, Oak Ridge National Laboratory, Oak Ridge, Tennessee.