the behavior of the long-life component found some years ago by Bell and Graham for annihilation in quartz and various other substances.[4] Perhaps the narrow component of the two photons may stem from a simple positron-electron system with v/c sensibly less than 1/137. If the narrow component should be formed only "in parallel" with the long-half-life component, one might expect the narrow fraction to be one-third of the long-half-life fraction of Bell and Graham, which was 0.29.[4] Perhaps a portion of the two-quantum events supposed to arise from the triplet state appear in the narrow component.

The present experiment is being extended to include other materials under various conditions. Preliminary work on teflon, at room temperature, indicates an angular correlation similar to that for fused quartz.

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[4] R. E. Bell and R. L. Graham, Phys. Rev. **87**, 236 (1952); **90**, 644 (1953).

Angular Distribution of Pickup Deuterons for 95-Mev Protons on Carbon, and Implications as to Internal Interactions in Carbon*

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THE angular distribution of the sharp energy group of deuterons observed in this reaction has been analyzed by Born-approximation pickup theory, to give the internal momentum distribution of the picked-up neutrons. The momentum distribution shows relatively strong high-momentum components, and these in turn indicate the presence of a strong short-range interaction in carbon.

A previous brief report[1] described the sharp energy distribution of deuterons observed in this reaction. The sharply defined group has been studied for laboratory angles between 6° and 60°. At the largest angles, the group still is clearly recognizable, although because of the increasing relative intensity of a continuum distribution of deuterons, the absolute cross section to be attributed to the "line" is uncertain to a factor of perhaps two. An energy distribution at 42° is shown in Fig. 1, and Fig. 2 shows the angular distribution of the sharp group.

Following Chew and Goldberger,[2] a Born-approximation calculation of the reaction yields from the angular distribution the internal momentum distribution of the picked-up neutron. CG show that the differential cross section $\sigma(\theta)$ is proportional to $N(\mathbf{n})F(q)$, where $N(\mathbf{n})$ is the momentum distribution density of neutrons of momentum $\mathbf{n}$ and $F(q)$ is a factor which is a function of the internal momentum of the formed deuteron; if one uses a Hulthén wave function for the deuteron then $F(q)$ has a relatively weak angular dependence. In the present case it falls by a factor of about $2\frac{1}{2}$ while the center-of-mass differential cross section is falling by 40, over the angular range covered.

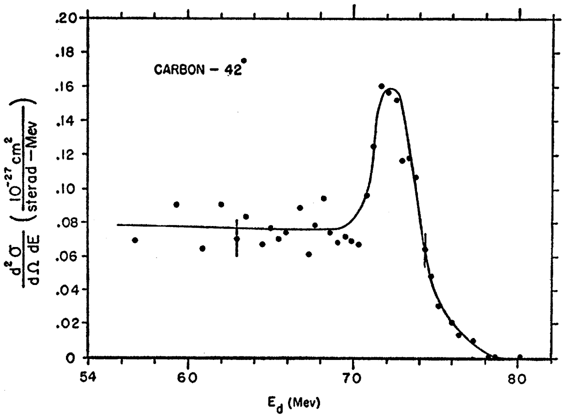

FIG. 1. Energy distribution of deuterons from the $C^{12}(p,d)$ reaction at 95 Mev. Statistical uncertainty is shown for two representative points.

Some discussion is in order with regard to the interpretation of the deuteron pickup results in terms of internal momentum distributions, in view of the fact that in the same type of theory applied by Butler[3] at low energies with very good success, the results do not seem to depend on the internal wave function $u(r)$ of the picked-up nucleon. In fact the effect of Butler's procedure is that the internal contribution to the

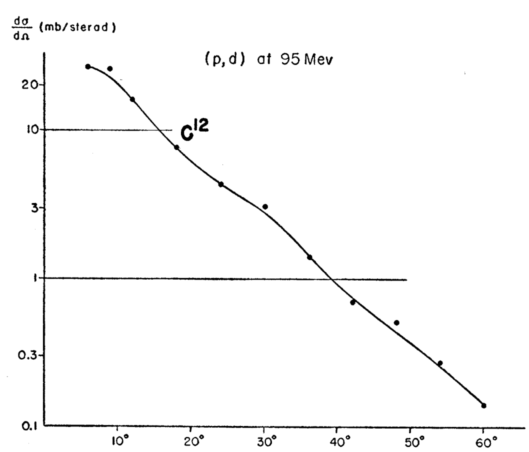

FIG. 2. Angular distribution (plotted *vs* lab angle) of the sharp energy group in the $C^{12}(p,d)$ reaction. The statistical uncertainty for the individual points is about 10 percent. There is additional systematic uncertainty in the separation of the "line" from the continuum—this uncertainty is negligible at small angles, but becomes a factor of about 2 at the largest angles.

overlap integral $\int \exp(i\mathbf{n}\cdot\mathbf{r})u(\mathbf{r})d\mathbf{r}$ is omitted entirely. This omission does not have a dominating effect on the magnitude of the integral,[4] since at low energies the wavelength $2\pi/n$ is not small compared to the nuclear radius, so that a considerable contribution to the integral comes from the region outside the nucleus. Indeed, at low energies it has been pointed out[3] that a variety of different approximations can lead to angular distributions resembling Butler's. At higher energies, on the other hand, the dominant contribution to the integral comes from the region inside the nucleus. It is just for this reason that one may hope the high-energy data can give information on the momentum distribution inside the target nucleus. An incidental characteristic accompanying this dominance of the inner contribution is that minima and secondary maxima become less pronounced, in the angular distribution.

The momentum density obtained from the data of Fig. 2 refers to a single state. If the independent-particle model is valid, this momentum distribution is that of a single-particle orbit, and the corresponding wave function $u(r)$ can be obtained by Fourier inversion. For this, the orbital angular momentum number l must be known. One could identify this l-value as 0 or 1 (the only probable values) if information were available on the behavior of $N(\mathbf{n})$ for $n\rightarrow 0$. The kinematics of the reaction are such that at 95 Mev the value of n even for the forward angles has a minimum corresponding to about 8 Mev kinetic energy, and this does not permit the determination of the behavior of N for $n\rightarrow 0$. Such a determination could be made by using protons of energy about twice the Q of the reaction, so about 30 to 35 Mev; at that low an energy, however, the theory is probably less accurate.

Direct Fourier inversion of the momentum "wave function" $[N(\mathbf{n})]^{\frac{1}{2}}$ to get the configuration-space wave function $u(r)$ is thus not possible unambiguously because of lack of information on the behavior of N outside the range for n of 0.65 to 2.3×10^{13} cm^{-1}, covering equivalent kinetic energies of about 9 to 120 Mev. However, calculations have been made using various reasonable extrapolations at low and high n, and the region covered by the data serves to determine the dominant characteristics of $u(r)$. Namely, the fact that the momentum spectrum falls off as slowly as it does at high n can be accounted for only by a $u(r)$ which has high curvature near the origin. The potential $V(r)$ which is required to produce this u can be obtained by applying the Schrödinger operator to u. The result is that to account for the momentum spectrum in this way requires a $V(r)$ which for $r>1.0\times10^{-13}$ cm is not well determined but may be of the order of -20 to -30 Mev up to $r\sim3$ or 4×10^{-13} cm, but which for $r<1.0\times10^{-13}$ cm drops to a narrow hole of the order of 200 Mev deep. Present analysis indicates that the behavior of $V(r)$ for small r is similar for either of the assumptions $l=0$ or $l=1$; the behavior at large r appears to be given more reasonably on the assumption $l=1$.

These results suggest the interpretation that the potential felt by a nucleon in carbon includes a short-range strong interaction, presumably to be associated with local fluctuations occurring when two nucleons are near each other. It is not clear whether local fluctuations of the strength indicated here can be reconciled with the high degree of success of the independent-particle model.[5] At the same time, evidence of strong correlation effects inside the nucleus has recently appeared in the coincidences observed in high-energy photonuclear reactions.[6]

Some comments are appropriate on the relation of the present results to other information concerning the momentum distribution, and on the validity of the theory. As to the first: the momentum distribution obtained here is substantially in agreement with that obtained by York[7]; the present measurements give more specific information because of the better energy resolution available with a proton beam, and give information out to higher momenta. Relatively strong high-momentum components in carbon have also been inferred by Temmer.[8] The "Chew-Goldberger" (CG) distribution introduced[2] to describe York's results fits the present data but clearly is not to be considered correct at very much higher energies. The CG distribution corresponds to a Hulthén wave function with $\beta=\infty$—i.e., with infinite curvature at the origin. The results of the present note indicate that for internal nucleon kinetic energies above 150 Mev or so the momentum distribution $N(\mathbf{n})$ will fall off more rapidly than the n^{-4} behavior of the CG function. A Hulthén wave function with a finite value of β would give asymptotically an n^{-8} behavior at high n. The falsely high N given by the CG distribution for extremely high momenta does not affect the results of some calculations involving the effect of the momentum distribution, but may affect others, depending on the specific way in which $N(\mathbf{n})$ enters. Thus Lax and Feshbach[9] have obtained good agreement in photomeson production using the CG distribution, but Henley[10] found it to be too strong at high n to agree with the proton-produced meson distribution, and empirically introduced a modified momentum distribution having a stronger cutoff. Cladis,[11] Wolff,[12] and Wilcox[13] have studied the momentum distribution by quasi-elastic scattering of high-energy protons, and have concluded that the CG distribution is unsatisfactory. However, it can be shown that the disagreement they obtain is due to the artificially high value of the CG distribution at high n. From the results of the quasi-elastic experiments the behavior of $N(\mathbf{n})$ can be inferred for internal nucleon kinetic energies up to 30 Mev or so—in this range the results are essentially in agreement with the present results; it is difficult to extract from these experiments information on higher momenta.

As to the validity of the theory, there is unfortunately good reason to believe that just for the high momenta, which are of special interest, the simple theory may become inadequate. The theory is essentially based on the idea that the incoming proton interacts with only one target nucleon at a time. If, however, the high internal momenta occur only when two target nucleons are near each other, then the single-interaction model is inappropriate. Nevertheless, perhaps the qualitative conclusions drawn by the use of this theory have enough validity to be of interest.

* Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[4] Except for a certain large effect at one minimum. See P. B. Daitch and J. B. French, Phys. Rev. **87**, 900 (1952).

[5] In recent work of Brueckner, Eden, and Francis, they answer this question affirmatively.

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Low-Energy Photoproduction of π^0 Mesons from Hydrogen: Total Cross Section*

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TOTAL cross sections for the photoproduction of neutral pions from threshold to 240 Mev have been measured with the use of a liquid hydrogen target. One of the π^0 decay photons was detected in a scintillation counter telescope composed of an anticoincidence counter, a $\frac{1}{4}$-in. Pb converter, and two counters in coincidence separated by a $\frac{1}{2}$ in. thick Al absorber.

The product of efficiency times solid angle for the γ-ray telescope was calculated by a Monte Carlo method with the Illinois digital computer. This calculation included the following: (1) geometry effects arising from the finite size of source and detector, (2) pair production and depth distribution of pair production in the Pb converter, (3) radiation loss and straggling of the pair electrons, (4) ionization loss and straggling of the pair electrons, (5) multiple scattering of the pair electrons, and (6) preabsorption of the photons in material preceding the telescope. Results

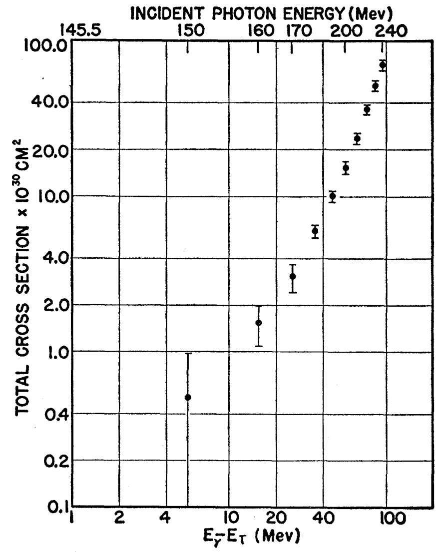

FIG. 1. Values of σ^0_{total} as a function of the difference between incident photon energy in the laboratory system and the threshold energy.

of this calculation are in satisfactory agreement with measured efficiencies of a similar counter at Cornell.[1]

Counting rates at an angle of 85° to the x-ray beam were measured as the betatron energy was increased in 10-Mev steps from 120 to 250 Mev. The photon difference method yielded the counting rate per incident photon as a function of incident photon energy.

This counting rate per photon, $I_{85°}$, is related to the photomeson cross section by integrating the spectrum of decay photons over the detector efficiency.[2] The photomeson cross section is assumed to be

$$\sigma^0(\theta) = A_0 + A_1 \cos\theta + A_2 \cos^2\theta.$$

Then the total cross section is

$$\sigma^0_{\text{total}} = 4\pi[A_0 + \tfrac{1}{3}A_2].$$

In the resulting expression[2] for $I_{85°}$, the term involving A_1 is negligibly small, while the ratio of the coefficient of A_2 to that of A_0 is approximately $\frac{1}{3}$. Thus the data are essentially a measure of σ^0_{total}. Because this ratio is not exactly $\frac{1}{3}$ at all energies, a value must be assumed for the ratio A_2/A_0; but the results are very insensitive to this value.[3] Cross sections presented in Fig. 1 are based on the assumption that $A_2/A_0 = -0.6$.

The logarithmic plot in Fig. 1 shows that between 170 and 240 Mev, σ^0_{total} is proportional to $(E_\gamma - E_T)^{2.2}$, where E_γ is the incident photon energy and E_T the threshold energy. This large exponent is not surprising because σ^0_{total} arises almost entirely from the "enhanced" P-state (isotopic spin$=\frac{3}{2}$, $J=\frac{3}{2}$) of the meson-nucleon system and is extremely sensitive to the corresponding phase shift δ_{33}. When the theoretical connection between σ^0_{total} and δ is established, these measurements may be used to determine δ_{33}.