ation for the numerical SCF tables given by Professor D. R. Hartree and his late father, Dr. W. Hartree; we have found that their numerical data are characterized by an excellent quality: their functions are perfectly smooth and the variation from element to element indicates an outstanding reliability. We sincerely hope that their pioneer work of calculating SCF functions without and with exchange will be continued also in the future by scientists interested in the atomic field.

ACKNOWLEDGMENTS

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Angular Distribution of Photoneutrons from Carbon and Beryllium*

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The photoneutron angular distributions from carbon and beryllium have been measured by using bremsstrahlung of maximum energies of 23 Mev and 18 Mev, respectively. The results are $1+(1.35\pm0.88)\sin^2\theta$ for carbon and $(1.26\pm0.11)+\sin^2\theta$ for beryllium.

INTRODUCTION

PREVIOUS measurements of the photoproton angular distribution from C^{12} using bremsstrahlung of 23-Mev maximum energy have been made by Halpern, Mann, and Rothman.[1] The distribution is of the form $1+a(\sin\theta+0.25\sin\theta\cos\theta)^2$, with a forward peak at about 80° relative to the incident γ-ray beam resulting from dipole and quadrupole interference terms. These results have been interpreted[2] as evidence for an independent-particle description of the giant resonance and LS coupling in the carbon nucleus.

On the assumption of charge independence of nuclear forces, Gell-Mann and Telegdi[3] have shown that the (γ,p) and (γ,n) cross sections in nuclei with $J=0$ and $T_z=0$, for each residual state, must be identical with each other as functions of energy and angle. This prediction is valid if there is no interference between electric dipole absorption and other multipole absorption arising from that part of the interaction Hamiltonian that is a scalar in isotopic spin space.

In this paper a measurement of the angular distribution of photoneutrons from the giant-resonance region of the reaction $C^{12}(\gamma,n)C^{11}$ using 23-Mev bremsstrahlung from the University of Pennsylvania betatron is reported. It was hoped in this way to study the direct emission of photoneutrons and also to check the charge-independence hypothesis. A preliminary measurement[4] indicated a dip in the angular distribution at 90°.

Also reported is a measurement of the photoneutron angular distribution from Be^9 using bremsstrahlung of maximum energy 18 Mev which is below the giant resonance. Guth and Mullin[5] and Czyz[6] have calculated the angular distribution for the reaction $Be^9(\gamma,n)Be^8$, assuming that the Be^9 nucleus consists of a Be^8 core plus a valence neutron in a $P_{3/2}$ ground state. They have obtained a distribution of the form $a+b\sin^2\theta$, arising from electric dipole transitions to S and D states, with the ratio a/b depending on the respective transition probabilities.

EXPERIMENTAL PROCEDURE

The details relating to the formation of a collimated x-ray beam have been presented previously.[7] In this experiment, an additional concrete wall 16 inches thick has been placed between the betatron and the target, about 2 feet from the target and 18 feet from the betaron. This new wall has cut the neutron background by a factor of 5.

The carbon and beryllium targets were cut in the form of 1-inch cubes. Neutrons were detected by a ZnS—paraffin plastic button[8] mounted on an RCA photomultiplier tube. The apparatus was arranged so that the photomultiplier tube could rotate about a center post on which was set the target. There was a

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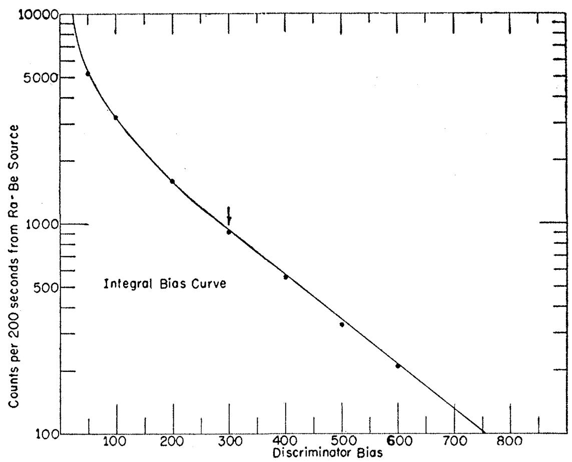

FIG. 1. Bias curve for neutrons from a Ra—Be source. Arrow denotes operating point in this experiment.

distance of 16 centimeters between the detector and the center post, and the solid angle subtended by the detector was 0.083 steradian. The x-ray beam diameter was 1.8 centimeters at the target.

For each angle, sample and background neutrons were counted for a fixed amount of irradiation as measured by an ionization chamber monitor. The monitor was checked frequently against a Victoreen thimble meter. Pulses from the photomultiplier tube were fed successively into a cathode follower pre-amplifier, a Model 100 amplifier, a single-channel analyzer, and a scaler. Figure 1 shows an integral bias curve for this arrangement for neutrons from a Ra-Be source with the operating point used in this experiment shown. The efficiency of the button was 0.3% for Ra-Be neutrons. The electronic circuitry was checked for drift before and after each run by observing the neutron counts from a Ra-Be source located in a standard position. An x-ray beam pulse of 80 microseconds was

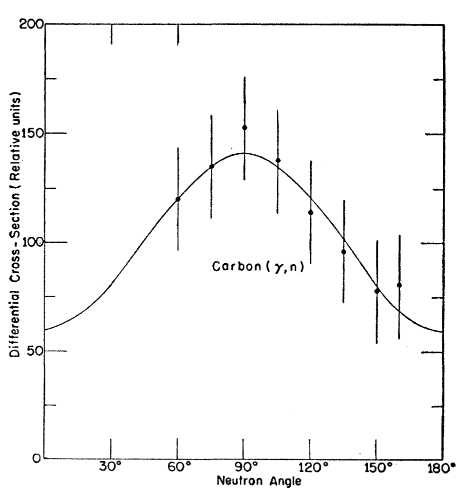

FIG. 2. Angular distribution of neutrons from carbon bombarded with bremsstrahlung of 23-Mev maximum energy.

used to avoid pileup in the scintillator arising from scattered electrons and photons.

Readings were taken at 15° intervals from 45° to 150° and 160°. Pileup difficulties made more forward readings prohibitively long. Because of the low neutron yield from carbon, the signal was only about $\frac{1}{3}$ the background giving an effective counting rate of 0.5 counts per minute. For Be, the signal was about 3.5 times the background.

RESULTS

The angular distributions obtained are $1+(1.35\pm0.88)\sin^2\theta$ for carbon and $(1.26\pm0.11)+\sin^2\theta$ for beryllium. Geometrical corrections resulting from the finite sizes of the target and detector are negligible in

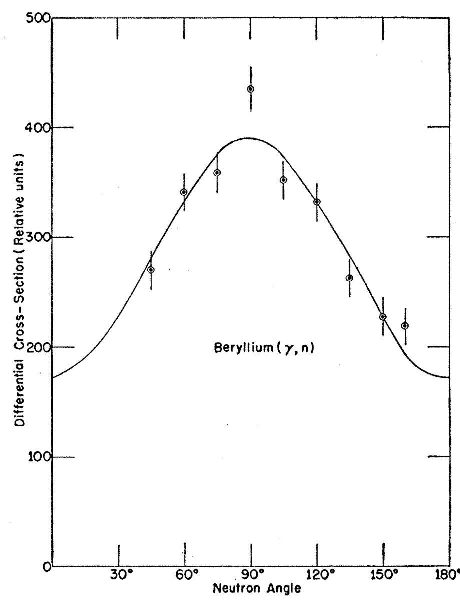

FIG. 3. Angular distribution of neutrons from beryllium bombarded with bremsstrahlung of 18-Mev maximum energy.

this experiment. However, corrections are necessary for neutron scattering in the targets themselves.

The scattering tends to make the observed distribution more nearly spherically symmetric than it actually is. The procedure followed assumed that the neutrons were produced in a small sphere at the center of the target. A small fraction of them, which depends on the total scattering cross section, is removed from each unit solid angle upon scattering. These scattered neutrons then redistribute themselves isotropically. It is expected that any error resulting from the scattering correction are well within the stated errors.

The corrected curves and least squares fits of the data are shown in Figs. 2 and 3.

DISCUSSION

The observed carbon angular distribution is of the form $a+b\sin^2\theta$, which is the same as reported by

Johansson[9] for other, heavier elements and by Dixon[10] for carbon and other elements. In both of these experiments bremsstrahlung of higher maximum energy was used.

Considerable emission of neutrons of nonzero angular momentum from C is indicated in this experiment. This fact seems to show that the photodisintegration does not proceed through a compound nucleus state but through independent-particle states.[2] As indicated in reference 2, an angular distribution of the form $1+\sin^2\theta$ would result from jj coupling in the carbon nucleus, while $1+1.5\sin^2\theta$ would mean LS coupling. Both these distributions fall well within the limits of error of this experiment. Furthermore, an examination of the stated errors in the $C^{12}(\gamma,p)B^{11}$ angular distribution[1] shows that there, also, both types of coupling are consistent with the data. Therefore, no unique coupling assignment is possible on the basis of these two experiments.

The difference in the (γ,p) and (γ,n) angular distributions arises from interference between multipole absorption terms. In proton emission there is interference between dipole and quadrupole absorption, as seen in the forward peak. This effect is not detectable for neutron emission because the neutron, for single-particle transitions, effectively acquires a charge only from the motion of the C^{11} core (neglecting terms involving the spin). For quadrupole transitions the matrix element is reduced by a factor of 24 from that of the proton.[11]

If the small interference term in the (γ,p) angular distribution is neglected, the (γ,n) angular distribution should be the same as the (γ,p) angular distribution of Halpern, Mann, and Rothman,[1] on the assumption of charge independence of nuclear forces. This follows since, in both experiments, the ground and first excited states of B^{11} and C^{11} are the only available residual states. A least squares fit of a curve of the form $a+b\sin^2\theta$ to the (γ,p) data yields the result $1+(1.35\pm1.12)\sin^2\theta$ in agreement with the angular distribution of this experiment. Therefore, the results of the two experiments are consistent with the charge-independence hypothesis.

The result of the present carbon experiment disagrees with the one reported earlier.[4] This discrepancy may be the result of a shift in the maximum energy of the betatron. For the preliminary experiment, the maximum energy was thought to be 22 Mev. Since no accurate calibration of the betatron in this energy range had been made at that time, it is possible that the maximum energy corresponded to a point on the low side of the giant resonance. For the final experiment, the betatron was modified by the addition of coils to increase the yield. For the present experiment, the maximum energy was known to be 23 Mev, which takes in the giant resonance.

The angular distribution for beryllium is a superposition of distributions resulting from photons of all energies up to 18 Mev because of the continuous nature of bremsstrahlung energy. Transitions from the $P_{3/2}$ ground state to the S state, which predominate at photon energies just above threshold, give a large isotropic component to the distribution because of the preponderance of low-energy photons. Higher energy photons cause transitions to the D states with a resultant rise in the angular distribution at 90°.

Hamermesh, Hamermesh, and Wattenberg[12] have observed an isotropic distribution of photoneutrons from beryllium for γ-ray energies of 1.70 and 1.81 Mev and a $1.2+\sin^2\theta$ distribution for 2.76-Mev γ rays. The results for the lower energies correspond, as in this experiment, to the P-S transition. The distribution of this experiment agrees with that for the 2.76-Mev gamma rays. This indicates that the percentages of transitions to the D and S states for bremsstrahlung of maximum energy 18 Mev is about the same as for 2.76-Mev γ rays.

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