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Inelastic Scattering of Protons by C^{12}†

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The yield of inelastically scattered protons from the first excited state of C^{12} was measured as a function of bombarding energy from 5.3 to 7.3 Mev. The angular distribution of these protons was also measured at 6.13, 6.51, and 6.90 Mev. The absolute cross section was obtained by comparison with the known (d,p) cross section. The results indicate that, in this energy range, this inelastic scattering process proceeds largely by way of compound-nucleus formation, which obscures any direct interaction effects that may be present.

I. INTRODUCTION

IN recent years, a number of measurements of the angular distributions of the reaction products from nucleon inelastic scattering and from (n,p) and (p,n) reactions have yielded results that differ considerably from predictions of statistical compound-nucleus theory. For instance, in several cases, where the theory might be expected to be valid, the angular distributions are strongly forward-peaked, whereas the theory gives either symmetry about 90 degrees or isotropy in the center-of-mass system.

Austern, Butler, and McManus[1] have interpreted these angular distributions in terms of a direct collision process between the incident nucleon and one of the nucleons of the target nucleus, and this theory has been qualitatively successful in accounting for some of the observed data. More detailed calculations of this type of process have been in progress by a number of authors,[2-4] and the results of these will appear shortly.

The extent to which the direct interaction process competes with compound-nucleus formation is not presently known. At low bombarding energies ($\lesssim 14$ Mev), we can expect direct interaction to occur throughout the entire nuclear volume because of the comparative transparency of the nucleus at these energies.[5] At higher energies, however, the nucleon mean free path is considerably reduced, and any nucleon that penetrates to within the nuclear radius is more likely to form a compound system, except for some light nuclei. Thus, at these energies, we can expect direct interactions to occur only outside the nucleus. We might therefore expect to find an increasing contribution from compound-nucleus formation with increasing energy. On the other hand, as the bombarding energy is increased, more excited states of the target nucleus become accessible to the decaying compound nucleus, and the excitation of any one level by this mechanism should eventually decrease. It is not clear, therefore, whether in any energy region one mechanism dominates the reaction cross section. In general, we must expect that both processes will be present in these reactions.

In order to determine the contributions to the cross section of the two competing mechanisms and to check the accuracy of direct interaction calculations, it is desirable to separate the two mechanisms. This can be done in either of two ways. First, the angular distributions can be measured at intermediate energies for intermediate weight or heavy (but nonmagic) nuclei, using an incident beam whose energy spread is larger than the widths of any of the compound-nucleus levels that can be excited at these energies. The compound-nucleus process in this case will be incoherent with the direct interaction, and the reaction products from the decay of the compound nucleus will appear as a fairly isotropic background. Any large anisotropies will then be due to the direct interaction process.

Another method by which it should be possible to isolate the direct interaction mechanism is by performing measurements at bombarding energies that correspond to energies in the compound nucleus that lie between well-isolated resonances. In this case, the incident beam should have a small energy spread. Then the contributions to the cross section from nearby resonances will add coherently with the direct interaction. However, if the resonances are sufficiently separated and narrow, their effect will be small and can be estimated from the resonance parameters.

In this paper we report an attempt to measure, by the second of these methods, the direct-interaction contribution to the cross section for the excitation of the 4.431-Mev[6] level in C^{12}. Previous measurements[7-9]

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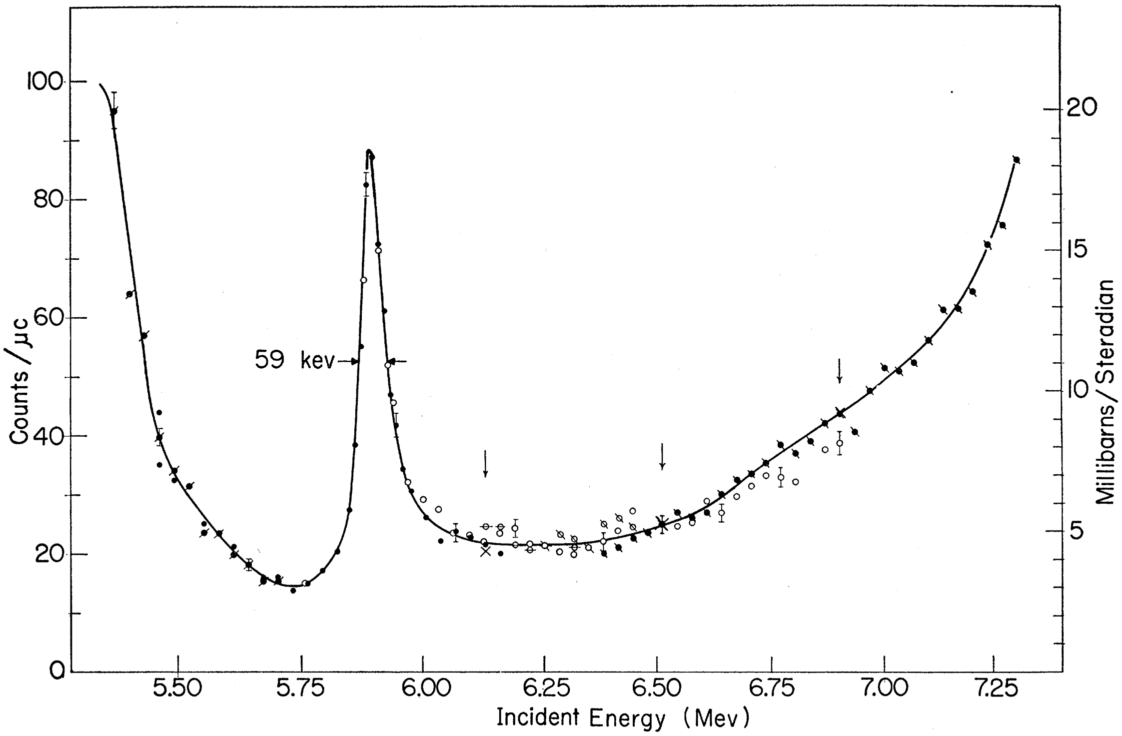

FIG. 1. Yield of inelastically scattered protons from C^{12} as a function of bombarding energy. The three crosses at positions marked by the vertical arrows are data from the nuclear track plates used in the angular distributions at these energies while the other symbols represent different runs with the scintillation counter. Statistical counting errors are indicated on a few representative points.

of elastically scattered protons and of gamma rays from inelastic scattering showed resonances at 4.8 Mev, 5.37 Mev, and 5.90 Mev, with an indication of another resonance at about 7 Mev. Thus, the known levels of the compound nucleus N^{13} appeared to be fairly widely spaced.

Also, the second excited state of the target nucleus C^{12} lies more than 3 Mev above the first. This simplifies theoretical calculations, since the effects of higher states upon the excitation of the first state can be ignored for bombarding energies up to several Mev above threshold. Furthermore, the structure of C^{12} is fairly well understood, and one can have some confidence in making calculations for this nucleus.

II. EXPERIMENTAL PROCEDURES AND RESULTS

Yield Curve

To investigate the direct interaction process, two measurements must be made. First, the inelastic yield must be measured as a function of bombarding energy to determine the location and nature of the resonances. Then, angular distributions must be obtained at some distance from the resonances. In the present work, the yield of protons leaving C^{12} in the 4.43-Mev level was measured at an angle of 45 degrees in the laboratory system for bombarding energies from 5.4 to 7.3 Mev.

The MIT-ONR broad-range spectrograph[10] was used to isolate the proton groups, and counting was done with a scintillation counter mounted at a fixed position on the focal surface. The field of the spectrograph was changed in step with the bombarding energy to keep the proton group centered on the counter. The centering was checked frequently by varying the spectrograph field with a fixed bombarding energy and determining the center of the resulting "momentum distribution." Pulses from counter were amplified and fed to two scalers with biases set to give a single pulse-height channel. A background, caused by the flux of gamma rays and neutrons present in the target room whenever a beam is accelerated, was measured with the protons blocked off from the spectrograph. This background, which never exceeded 10% of the proton counts, was determined as a function of time and subtracted from the total counts for each point.

As shown in Fig. 1, the resonances at 5.3 Mev and 5.9 Mev are observed with a smooth, gradually rising yield above the latter. This curve was taken with an input energy spread of about 0.1% and a target thickness of about 5 kev. The input energy was varied in steps of 30 kev, except in the region of the 5.90 Mev resonance, where 12 kev steps were used. As shown in the figure, the observed half-width of this resonance is 59 kev. Subtracting incident energy spread and target thickness leaves a width of about 55 kev, in agreement with previous measurements. The peak of the resonance lies at 5.891 Mev.

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[10] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. (to be published).

Angular Distributions

Angular distributions were taken at energies of 6.13, 6.51, and 6.90 Mev. These energies are marked by arrows on the yield curve.

At each angle, an exposure was made at each of the three energies on one strip of nuclear track plate. The spectrograph field was varied to separate the three groups. In view of the slow variation in the yield at these energies, the slight variations in input energy (±0.1%) caused by this process of cycling the field of the input magnet introduced a negligible error.

Target stability was checked by repeating a point on the 6.90-Mev curve at the end of the first run, and the over-all reproducibility was checked by repeating three points on this curve in a second run. All input points agreed within 5%.

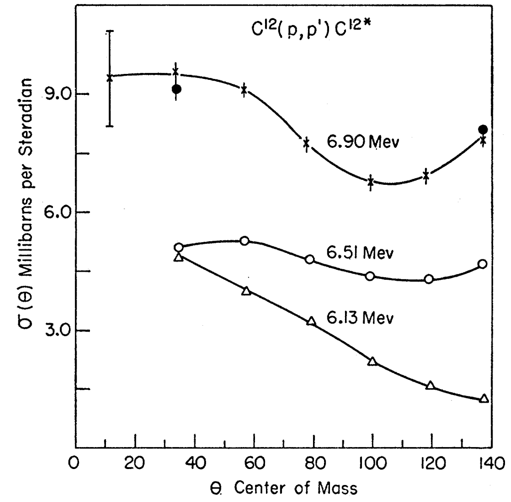

FIG. 2. Experimental angular distributions of inelastically scattered protons from C^{12}. As described in the text, the vertical scale was obtained by comparing the yield with the yield from $C^{12}(d,p)C^{13}$. The three curves are labeled with the bombarding energies at which they were obtained. Only one point at 12 degrees could be obtained because of the intense background from slit edge scattering, and this point has the large uncertainty indicated.

The absolute cross section was determined by comparing the yield of the inelastic protons with the known yield of protons from the $C^{12}(d,p)$ reaction.[11] The comparison was made at 90 degrees with an incident proton energy of 6.90 Mev and an incident deuteron energy of 3.29 Mev. The target was not moved between exposures. The (d,p) yield was measured before and after the (p,p') yield, the two runs agreeing to within 4%.

The angular distributions are shown in Fig. 2, with the absolute differential cross section plotted against center-of-mass angle. Background from slit-edge scattering prevented observation at angles below 10 degrees.

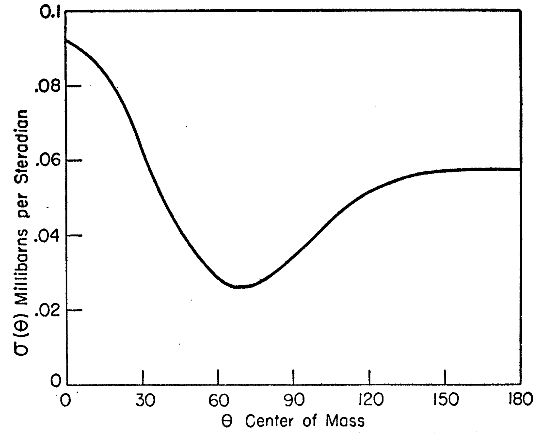

FIG. 3. Theoretical angular distribution of inelastically scattered protons from C^{12} with excitation of the 4.43-Mev level; energy of incident protons is 6.5 Mev.

III. DISCUSSION

The experimental angular distributions bear little resemblance to the theoretical angular distribution for the direct interaction process which is shown for 6.5 Mev in Fig. 3. This curve was computed, using formulas developed in a paper by H. Feshbach and one of the present authors (JRL); the paper is scheduled to appear shortly. The principal assumption involved in the calculation is that the 4.43-Mev level arises from single-particle excitation. Although this curve was computed only at 6.5 Mev (lab energy), the angular distribution does not change very much with changes in energy of a Mev or so.

The most serious discrepancy, however, between the theoretical and experimental curves is in the absolute cross section. It will be noted that the theoretical cross section is two orders of magnitude smaller.

Recent work of Schneider[12] on the elastic scattering of protons from C^{12} indicates the presence of other levels in this region that do not appear in the inelastic yield probably because of a high centrifugal barrier. It is to be noted that the present yield curve, while confirming resonances at 5.3 and 5.9 Mev, gives no indication of a level at 6.65 Mev. It is possible, however, that a broad level somewhere above 7.3 Mev overlapping the broad level reported by Schneider at 6.65 Mev could account for the observed yield.

In any case, it appears that the number and widths of the levels in the compound nucleus for this energy region are sufficient to make compound-nucleus formation the dominant reaction mechanism.

IV. ACKNOWLEDGMENTS

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[12] H. Schneider, Helv. Phys. Acta **29**, 55 (1956).