Inelastic Scattering of N^{14} by C^{12}

M. L. HALBERT AND A. ZUCKER
Oak Ridge National Laboratory, Oak Ridge, Tennessee*
(Received August 18, 1960)

Inelastic scattering of N^{14} by carbon was studied at 27.3 Mev using two surface-barrier counters to detect both the scattered and the recoil particle in coincidence. The cross section for excitation of C^{12} to the first excited state (4.43 Mev) varies only slightly with angle and averages about 0.5 mb/sr. This is about 15 times greater than the theoretical cross section for Coulomb excitation. The cross sections for scattering to the second, third, and fourth excited states in N^{14} were found to be only 15 to 25% of that for the 4.43-Mev excitation in C^{12}. Scattering to the first excited state of N^{14} was not observed, which is consistent with conservation of isotopic spin.

I. INTRODUCTION

THE general question of how complex nuclei can interact inelastically by means of the nuclear force, yet retain their original identity, is of great interest. Heavy-ion inelastic scattering has not previously been studied at energies above the Coulomb barrier. It therefore seemed worthwhile to extend our recent studies of elastic scattering of 27-Mev nitrogen ions by beryllium,[1] carbon,[2] and aluminum[3] to inelastic scattering as well.

Experimental problems, however, for a while seemed to rule out the possibility of such measurements. Excitation of the projectile as well as the target can occur, and even with the widely spaced levels of a target such as C^{12} (see Fig. 1), better energy resolution is needed than was obtained with scintillation counters. The coincidence method[1] helps enormously but cannot entirely supplant the requirement of good resolution.

With the development of surface-barrier counters counters and their application to heavy-ion detection,[4] it became clear that it was practical to study inelastic scattering. The principal advantages of these counters over scintillation counters for this experiment are excellent pulse-height resolution and pulse-height response proportional to particle energy regardless of the type of particle or its velocity.

Carbon was chosen as the target for several reasons. First, the elastic cross section has been measured; this simplifies the determination of the inelastic cross section and also permits a comparison of the results with theories which connect elastic and inelastic scattering. Second, the inelastic scattering of protons, neutrons, deuterons, and alpha particles by the same states in C^{12} has been studied and comparisons might be informative. Third, C^{12} is a favorable target because its excited states are widely spaced. Finally, a test of the isotopic-spin conservation rule is possible for this target since the initial system has $T=0$, but the first excited state of N^{14} has $T=1$.

* Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

[1] M. L. Halbert and A. Zucker, Phys. Rev. **115**, 1635 (1959).

[2] M. L. Halbert, C. E. Hunting, and A. Zucker, Phys. Rev. **117**, 1545 (1960).

[3] M. L. Halbert and A. Zucker, Nuclear Phys. **16**, 158 (1960).

[4] M. L. Halbert and J. L. Blankenship, Nuclear Instr. and Methods **8**, 106 (1960).

II. EXPERIMENTAL DETAILS

The coincidence method for scattering has been described elsewhere.[1] In this method both the scattered particle and the recoil particle for each event of interest are detected. The counter with the smaller center-of-mass aperture is known as the defining counter. Its output is displayed on a multichannel analyzer which is gated by pulses from the second counter (known as the conjugate counter). Only those conjugate-counter pulses within a certain pre-selected amplitude interval are used for gating. Thus, for any pair of reaction products, precise information is obtained on the pulse height of the particle which entered the defining counter and on its angle of emission from the target; similar though less precise information is obtained for the other particle. This is usually sufficient to identify the reaction unambiguously.

The use of the coincidence method was of particular importance in this experiment because of the large counting rate from other events. Ungated spectra always showed many counts in the regions where none at all should have been expected, and even the most probable inelastic event was almost completely submerged in this background. The coincidence method practically eliminated the background. The effectiveness of the method was such that in one case it was possible to set an upper limit on one inelastic cross section of less than 10^{-5} of the elastic.

Although the basic method of taking data remained the same as outlined previously,[1] a number of important changes have been instituted. These will now be described.

A. Apparatus

The defining counter is a silicon surface-barrier device made of 50 ohm-cm n-type silicon. Bias is provided by a 45-volt mercury battery. A 0.094-in. diameter aperture placed 8.0 in. from the target limits the angular acceptance to a cone of half-angle 0.34 deg.

During the early portion of the experiment, a CsI(Tl)

scintillation counter was used as the conjugate counter. It was replaced by a 150 ohm-cm surface-barrier counter as soon as one of sufficient area ($\sim$1 cm^2) became available. This counter was normally operated with 5 volts bias. Usually a $\frac{1}{4}$-inch diameter collimator located 2.0 in. from the target was placed in front of this counter, making its half-angle of acceptance 3.5 degrees. Occasionally, for certain experimental checks, this counter was used with a different collimator.

The solid-state counters required no magnetic shielding even though the scattering chamber was located in the fringing field of the cyclotron. The iron tubes formerly used to shield the paths of the particles from the magnetic field were found to be unnecessary and were not used, except that the tube shielding the path of the incident beam was retained because it holds the entrance collimator.

The signal from each counter was amplified by a low-noise preamplifier. Pulses from the defining counter were amplified further by a modified *A*-1*D* linear amplifier and were then sent to a 256-channel analyzer. The conjugate-counter pulses were amplified by a *DD*-2 amplifier. A single-channel pulse-height analyzer on the output selected the pulses for gating the multichannel analyzer. The resolving time (2τ) was 0.7 μsec.

When tested with ThC alpha particles (6.06 Mev), the resolution of the defining counter was 1.3% (full width at half maximum). The N^{14} and C^{12} particles entering the counter in this experiment had two to four times as much energy, depending on the angle of scattering. At first sight, it would seem that the resolution for the heavy ions should have been much better than 1.3%. Actually, it was not; at best the elastic peak was 2.5% wide. A large fraction, if not all, of the excess width may be attributed to factors such as beam-energy spread, target nonuniformity, multiple scattering, and the finite geometry. The last two are important because the target is lighter than the projectile and the variation of energy with scattering angle is therefore quite marked.

Figure 2 shows a series of coincidence-gated spectra for the thinnest target with the defining counter at 18.4 degrees (lab). Each was run for the same integrated beam current; somewhat more than an hour of cyclotron time was required per spectrum. The conjugate counter position was varied from 50.2 to 56.2 degrees. The arrows indicate, to an accuracy of $\pm\frac{1}{2}$ channel, the expected peak channel for some of the inelastic events.

The most prominent peak appears to be scattering with $Q=-4.43$ Mev. To verify this, the number of counts in the main peak was added up carefully for each spectrum and plotted as a function of conjugate counter angle, as in Fig. 3. Here the arrows indicate the angles at which the recoil C^{12} ions are emitted for various values of $-Q$. The uncertainty in setting the conjugate counter angles was less than 0.2 degree. The experimental data clearly indicate that the prominent peak is indeed due to the 4.43-Mev scattering events.

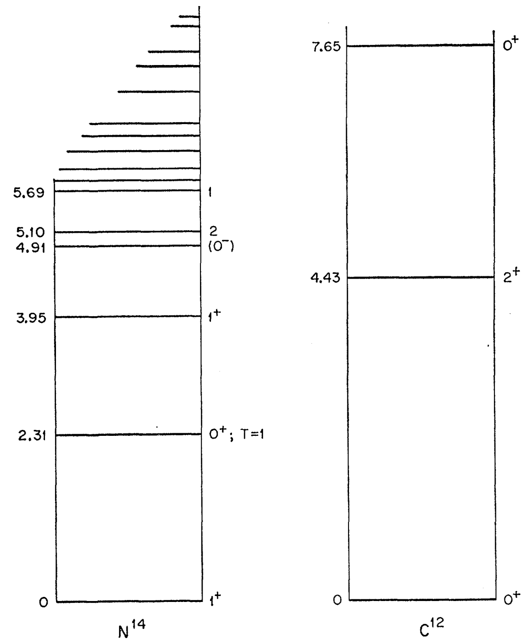

FIG. 1. Energy level diagram for N^{14} and C^{12}, based on the compilation of F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959). All states except the 2.31-Mev state in N^{14} have $T=0$.

B. Beam Energy Measurement

The energy of the incident beam was determined in two ways. In one method[5] the beam entered a chamber containing hydrogen. Protons recoiling in the forward direction were stopped in a nuclear emulsion. From the length of the proton tracks, the beam energy was calculated to be 27.7$\pm$0.3 Mev.

The other method was based on the use of a surface-barrier counter to measure the relative pulse height of nitrogen ions from the beam and of alpha particles of known energy from a radioactive source. The beam passed through a self-supporting evaporated gold film about 100 μg/cm^2 thick oriented at 45° to the beam direction. Nitrogen ions which were scattered through 90° and passed through the gold were detected. The alpha source was placed near the counter.

To obtain the greatest accuracy in comparing the two rather different pulse heights, a null method was adopted which made it unnecessary to establish the linearity or true zero of the multichannel analyzer. The accuracy depended only on the linearity of the preamplifier and of a precision helical potentiometer as a voltage divider in the pulser. First, an alpha spectrum was obtained. Then the test pulses were fed to the preamplifier input and the potentiometer was adjusted so that the test pulses were counted in the same channel of the analyzer. Next the cyclotron was turned on. By reducing the amplifier gain the pulses from the scattered

[5] H. L. Reynolds, D. W. Scott, and A. Zucker, Phys. Rev. **95**, 671 (1954).

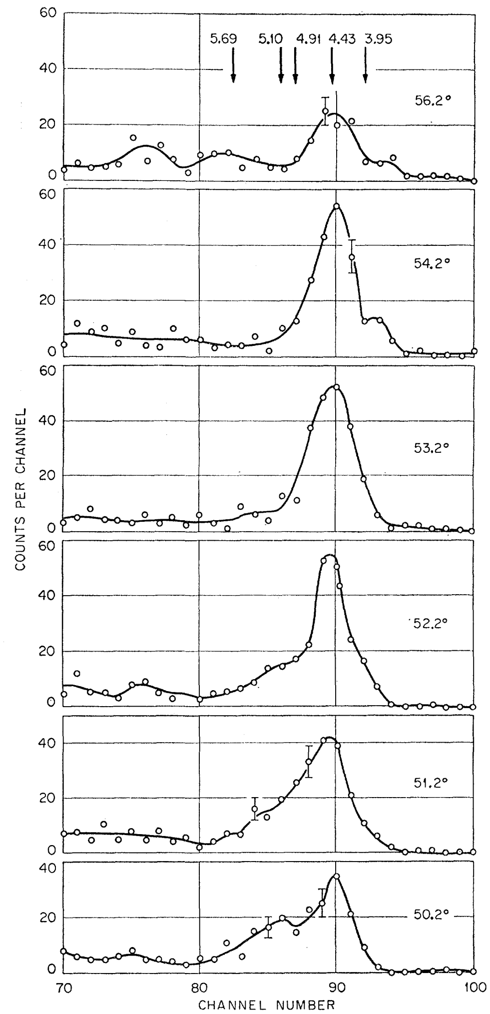

FIG. 2. Coincidence-gated spectra with defining counter at 18.4°. The conjugate counter angle for each spectrum is shown. The arrows indicate the expected peak positions for inelastic events having $-Q$ corresponding to the low-lying states of C^{12} and N^{14}.

N^{14} were placed in the same channel. The cyclotron was then turned off and the attenuator adjusted so that the test pulses matched the N^{14} pulse height exactly. The ratio of the two dial readings on the attenuator gave the ratio of pulse heights, from which the beam energy could be calculated.

By this method the beam energy was found to be 28.1±0.2 Mev. The average of the two energy measurements was taken to be 27.9 Mev.

C. Targets

Most of the experimental data were obtained with two carbon films made from a suspension of colloidal graphite as described earlier.[2] One of these was weighed after bombardment and found to be 0.17±0.03 mg/cm² thick, corresponding to an energy loss for the beam of about 1.2 Mev. The other one fell apart before it could be weighed, but judging from the counting rate was of the same thickness. For these targets the mean energy of scattering was therefore 27.3 Mev.

These targets, although of appreciable thickness and fairly nonuniform, were satisfactory when the energy of the coincident particles was greater than a few Mev. At the extremes of the angular range studied, however, good data could not be obtained from them because the initial energy of the coincident particles was comparable with their energy loss as they left the target. In the later stages of the experiment a carbon film on the order of 0.05 mg/cm² thick, prepared by evaporation,[6] was used. This made it possible to study scattering at angles for which the coincident-particle energy was as low as 2 Mev before leaving the target. With this target, the peaks in the spectra from the defining counter were somewhat sharper. The energy loss in the thin target is estimated at about 0.4 Mev, making the average energy of these scattering events about 27.7 Mev.

D. Effect of γ Decay

The mean lifetime of the 4.43-Mev state in C^{12} is 6.5×10^{-14} sec,[7] so the de-excitation to the ground state occurs essentially at the point of scattering. Should the de-excitation γ ray be emitted at an angle to the direction of motion of the recoiling C^{12} ion, the carbon ion will be deflected slightly. The largest deflection occurs for perpendicular emission from a slow-moving carbon ion. This amounts to a 1.2-degree change in direction for a C^{12} ion of 2 Mev. Since the acceptance angle of the conjugate counter was considerably larger, no difficulty from this effect was expected and none was found.

E. Method of Taking Data

The energy of the coincident particle from inelastic scattering is almost the same as from the elastic. To save time, the elastic scattering with its higher counting rate was used wherever possible for the necessary experimental checks. In detail the procedure was as follows.

For a given defining-counter angle the conjugate counter was first positioned to select elastic scattering only. The window of the single-channel analyzer was narrowed and the intensity variation of the N^{14} elastic peak in the defining-counter spectrum was measured as the window was moved across the C^{12} recoils detected by the conjugate counter. From these data, the expected window position for the inelastic recoils was determined. The window was then opened wide enough to include all the elastic and inelastic recoils with a generous margin of safety and a spectrum obtained for a definite amount of integrated beam current.

[6] G. Dearnaley, Rev. Sci. Instr. **31**, 197 (1960).

[7] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Phys. Rev. **110**, 154 (1958).

This elastic spectrum in the defining counter served three purposes. First, it was useful as a standard against which later elastic runs could be compared as a check that the operating conditions were stable. Such checks were needed because at least half a day and frequently several days were required to collect the inelastic data at one angle. Second, from the position of the elastic peak, the expected pulse heights of the inelastic peaks could be accurately determined. Third, the inelastic counting rate could be easily converted to an absolute cross section since the elastic cross section is known.[2] At the two smallest center-of-mass angles this method of normalization could not be applied because the elastic cross section at these angles had not been previously measured. In these cases the defining counter was simply moved to an angle at which the elastic cross section was known.

The conjugate counter was next moved to the expected angle for the inelastic event under study. Spectra were obtained at this angle and at other nearby angles as described previously for Fig. 2. The number of counts in the peak was summarized as in Fig. 3. This procedure, although very time consuming, was repeated at every scattering angle to confirm the identification of the excited states and also to guarantee that all the coincident particles were being counted (indicated by the plateau of Fig. 3).

III. RESULTS

4.43-Mev state in C^{12}

The predominant inelastic-scattering event at all angles is that leaving N^{14} in its ground state and C^{12} in its first excited state. The differential cross section is given in Fig. 4 with the 27.3-Mev elastic data[2] shown for comparison. The solid dots were obtained with the thin target.

The particle detected in the defining counter from 36.2° to 96.0° was the scattered nitrogen. For the point at 95.8° and the others beyond, the defining counter was positioned to accept the recoil carbon ion because it had the higher energy. The two portions of the data are in good agreement in the vicinity of 96 degrees. The angular resolution was approximately one degree (c.m.).

Since the data were normalized to the 27.3-Mev elastic cross section at each angle, both the systematic and the relative error in the elastic scattering measurement enter. The former makes the magnitude of the cross section uncertain by about 9%, while the latter introduces a 5 to 10% error in the relative cross sections. The standard error in the relative angular distribution for inelastic scattering is perhaps best judged from the scatter of the experimental points, and is about ±10%. Probably most of this uncertainty can be traced to the ambiguities in assigning the counts in the spectra to the various excited states.

The energy sensitivity of the elastic cross section may have an important effect on the normalization of the inelastic curve. Between 23.5 and 27.3 Mev it had previously been found[2] that on the average a 1% increase in energy decreased the cross section by roughly 20%. Since the mean energy of scattering for the thin-target data (27.7 Mev) was about 1.5% higher than for the other data (27.3 Mev), the elastic cross sections used to normalize these points may have been on the order of 30% too large. However, no attempt was made to incorporate such a correction since it cannot be calculated with sufficient accuracy. In the first place, the 30% figure may not apply to energies higher than 27.3 Mev. Secondly, $d\sigma/dE$ varies appreciably with angle because of the structure, and this should not be ignored. Furthermore, the energy dependence of the inelastic cross section is unknown. At angles where the two sets of data overlap, the agreement is usually good. Since the thin-target points include data on angles that could not be studied with the thick targets, it was decided to include these points on the same graph (Fig. 4), but in such a way that they could be easily distinguished from the 27.3-Mev points.

The total area under the experimental curve is 5.1 mb. If the differential cross section is assumed to be flat from 0° to the smallest angle measured, and also from the largest angle out to 180°, then the total cross section is 5.8 mb.

3.95-Mev state in N^{14}

As is clear from Fig. 2, scattering to the 3.95-Mev state occurs with a much smaller probability. This is true at most angles. At the largest angles studied the 3.95-Mev state appeared to be somewhat more important, but the 4.43-Mev state was still dominant. The

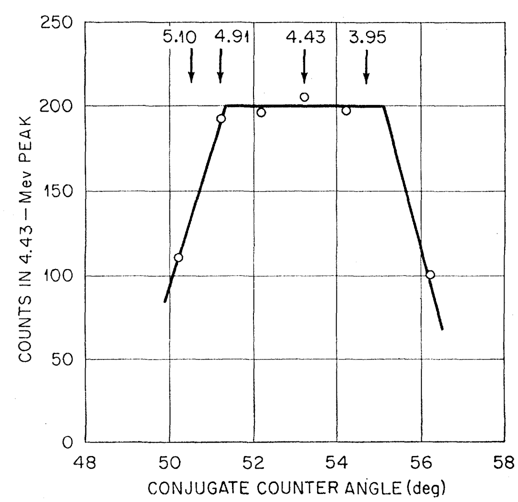

FIG. 3. Area of 4.43-Mev peak with defining counter at 18.4 deg, as a function of conjugate counter angle. The arrows indicate the angles at which the recoil C^{12} ions are emitted for the inelastic events having the values of $-Q$ shown.

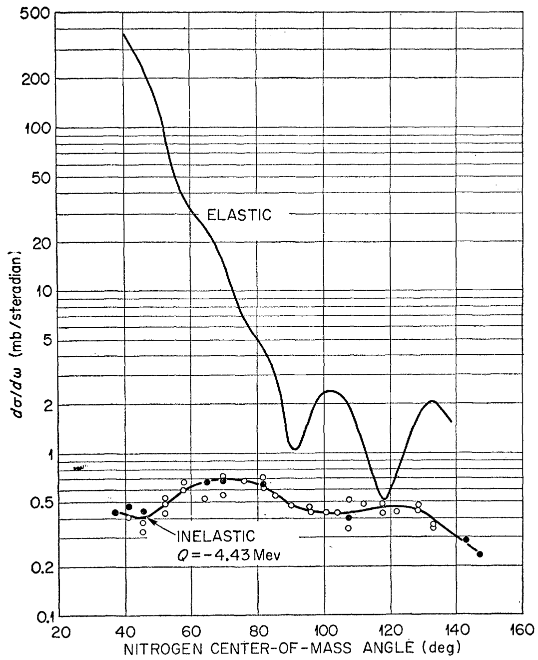

FIG. 4. Differential cross section (center-of-mass system) for inelastic scattering of N^{14} to the first excited state of C^{12}. The mean energy of scattering for the open circles was 27.3 Mev. The solid dots represent data obtained with the thinnest target, for which the mean energy was 27.7 Mev. The upper curve is the experimental cross section for elastic scattering of N^{14} by C^{12} at 27.3 Mev[2].

intensity of scattering to this state is in general on the order of 15% of that to the 4.43-Mev state, so that the differential cross section is approximately 0.07 mb/sr and the total cross section about 0.9 millibarn.

4.91- and 5.10-Mev states in N^{14}

These two states could not be resolved. Their intensity was usually somewhat larger than that of the 3.95-Mev state, very roughly 25% of that for the 4.43-Mev state. Therefore for these states together $d\sigma/d\omega\sim 0.12$ mb/sr and $\sigma_{tot}\sim 1.5$ millibarn.

2.31-Mev state in N^{14}

All states mentioned so far had isotopic spin zero. A systematic search for scattering to the $T=1$ first excited state of N^{14} was made at practically all angles at which the 4.43-Mev scattering was studied. At the proper conjugate-counter angle for $Q=-2.31$ scattering, counts in the correct portion of the gated spectrum were extremely rare and appeared to be randomly distributed rather than peaked at any one pulse height. To set an upper limit on the cross section, all counts found in a 5%-wide section of the spectrum bracketing the pulse height expected for the 2.31-Mev events were assumed to represent scattering from this state.

The upper limit obtained in this way is 5 μb/sr at most angles, so that the total cross section is <60 μb. It should be mentioned that the spectra had to be extremely clean to set this limit. At some angles one count per hour in the correct portion of the spectrum corresponds to a cross section of 2 μb/sr. It did not seem likely that the upper limit could be decreased by longer runs since, as was mentioned, the same density of counts was found in portions of the spectrum where no states can contribute.

Other States

Scattering to the 5.69-Mev and higher excited states was detected, but no attempt was made to measure the cross sections since the states lay too close together in both energy and angle to be resolved.

IV. DISCUSSION

The scattering from the 4.33-Mev state in C^{12}, with the N^{14} remaining in its ground state, shows a notable lack of structure, in marked contrast with the elastic scattering. The little structure that is present shows much larger separation of the maxima than does the elastic cross section.

A comparison of the differential cross section for excitation of the 4.43-Mev state by other medium energy projectiles is given in Fig. 5. In addition to the present results, curves are shown for 14-Mev neutrons,[8] 19.4-Mev protons,[9] 19.1-Mev deuterons,[10] and 41-Mev alphas.[11] Where data at several energies were available, as for protons, deuterons, and alphas, only the highest energy curve was included. The cross sections at lower

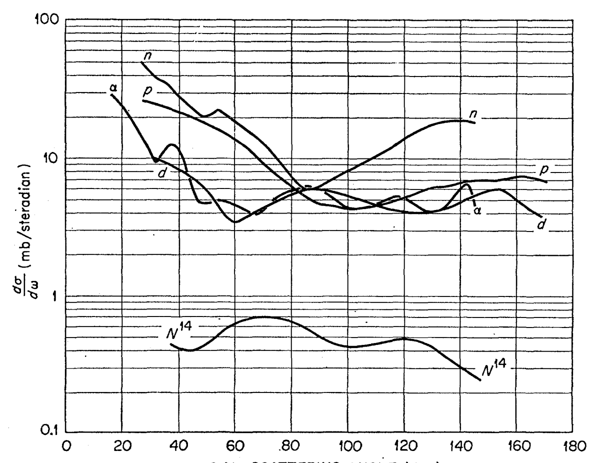

FIG. 5. Comparison of cross sections for excitation of the 4.43-Mev level in C^{12} by various projectiles, as follows: *n*, 14-Mev neutrons[8]; *p*, 19.4-Mev protons[9]; *d*, 19.1-Mev deuterons[10]; α, 41-Mev alphas[11]; N^{14}, 27.3-Mev nitrogen-14 (present results).

[8] J. D. Anderson, C. C. Gardner, J. W. McClure, M. P. Nakada, and C. Wong, Phys. Rev. **111**, 572 (1958).
[9] R. W. Peelle, Phys. Rev. **105**, 1311 (1957).
[10] R. G. Freemantle, W. M. Gibson, and J. Rotblat, Phil. Mag. **45**, 1200 (1954).
[11] A. I. Yavin and G. W. Farwell, Nuclear Phys. **12**, 1 (1959).

energies are generally larger and, for alpha particles, show more pronounced structure.

The most striking feature of Fig. 5 is the large gap, corresponding to a factor of approximately 10, between the N^{14} cross section and all the others. This may be due to the larger number of additional reactions possible with the nitrogen ions than with simpler particles. The number of inelastic scattering processes is larger since the projectile as well as the target can be excited. Furthermore, many transfer reactions are possible with N^{14}. Under favorable conditions the total cross section for each such reaction may be as high as a few millibarns.[12] This point of view implies that a limit exists on the sum of the cross sections for final states consisting of two heavy ions, and that competition is responsible for the small cross section to any one final state.

Another qualitative explanation may be given. The probability of excitation is likely to be larger for close collisions than for distant ones. Simple projectiles can come close to the C^{12} nucleus, excite it, and successfully escape, but if the N^{14} passed close to the C^{12} it would be less likely to be re-emitted.

An obvious mechanism for inelastic scattering is Coulomb excitation. In Fig. 6 the semiclassical theory[13] for $E2$ excitation is compared with the measured cross section. The parameters for this case are $\eta = 4.73$ and $\xi = 1.15$. The reduced transition probability for excitation, $B(E2)$, was obtained from the measured lifetime[7] of the 4.43-Mev state, $\tau = (6.5 \pm 1.2) \times 10^{-14}$ sec, by means of a formula[14] adjusted for the statistical weight of the final state:

$$B(E2) = 5(75/4\pi)(\hbar c/\Delta E)^5 \hbar/\tau.$$

From this formula $B(E2) = (37 \pm 7) \times 10^{-52} e^2$ cm^4. To make the curve coincide with the experimental points, as it does in Fig. 6, it was necessary to multiply the theoretical cross section by a factor of 15. That is, Coulomb excitation is about 15 times too small to explain the data. The total cross section for $E2$ excitation, calculated quantum mechanically,[13] is 0.34 ± 0.06 mb, 17 times smaller than the experimental value of 5.8 mb. It thus seems clear that Coulomb excitation is a relatively unimportant mechanism for scattering to the 4.43-Mev state in C^{12}.

Blair has developed a model for inelastic diffraction scattering which is successful for some alpha-particle scattering data.[15] This theory connects the elastic and inelastic scattering through a nuclear deformation and predicts that the maxima of the inelastic pattern appear at the same angles as the minima of the elastic

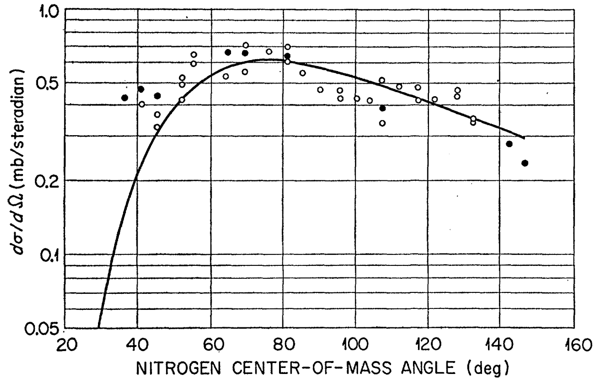

FIG. 6. Comparison of experimental cross section for excitation of 4.43-Mev level in C^{12} by N^{14} (dots and circles) with 15 times the theoretical cross section for $E2$ Coulomb excitation (solid line).

when there is no change of parity. In the data of Fig. 4 the broad inelastic maximum at 120 deg does come at about the same angle as an elastic minimum, but otherwise there is little evidence to bear out the prediction. However, the present result should probably not be regarded as an adequate test of the theory. Considering the approximations needed in its development, it is doubtful whether the theory is really applicable here. For example, the Coulomb field should not be neglected for N^{14} on C^{12} since $\eta = 4.73$. Furthermore, the theory is basically a small-angle theory, but here is must be applied to angles considerably greater than one radian.

The predominance of the 4.43-Mev state may be connected with its collective properties. For the rms charge radius $R = 2.50 \times 10^{-13}$ cm from electron scattering by carbon,[16] the single-particle reduced transition probability is $5.6 \times 10^{-52} e^2$ cm^4. This is about 7 times smaller than the value calculated above from the lifetime, indicating collective enhancement. On the other hand, the excited states observed in N^{14} are commonly thought to be single-particle states. It is interesting to note that the cross section for exciting the single-particle 3.95-Mev level is in fact about 1/7 that for exciting the collective 4.43-Mev level. A similar result has been found in the inelastic scattering of 9.5-Mev protons by carbon[17] and nitrogen.[18]

It was hoped that the upper limit on scattering to the first excited state of N^{14} would provide a test of the validity of the isotopic-spin conservation rule. Ordinarily, one wishes to compare the cross section for a transition allowed by this rule with that for the forbidden transition. For this purpose the allowed transition should be as similar as possible to the forbidden one, but all of the other measured processes

[12] M. L. Halbert, T. H. Handley, J. J. Pinajian, W. H. Webb, and A. Zucker, Phys. Rev. **106**, 251 (1957).
[13] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).
[14] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 595.
[15] J. S. Blair, Phys. Rev. **115**, 928 (1959).
[16] H. Ehrenburg, F. R. Hofstadter, U. Meyer-Berkhout, D. G. Ravenhall, and S. H. Sobottka, Phys. Rev. **113**, 666 (1959).
[17] W. E. Burcham, W. M. Gibson, A. Hossain, and J. Rotblat, Phys. Rev. **92**, 1266 (1953).
[18] R. G. Freemantle, D. J. Prowse, and J. Rotblat, Phys. Rev. **96**, 1268 (1954).

go to final states of spin and parity different from the 0^+ of the 2.31-Mev state. Perhaps the most similar allowed transition is the $Q=-3.95$-Mev transition, which leaves the C^{12} in its ground state and the N^{14} in its second excited state (1^+). The cross section for scattering to the 2.31-Mev state is $<1/15$ that for scattering to the 3.95-Mev state. A similar upper limit (6%) for this intensity ratio was obtained by Watters[19] with 31.5-Mev alphas scattered by N^{14}.

It was pointed out by Hashimoto and Alford[20] in a similar problem that the angular momentum and parity conservation rules should be considered. In this case they would inhibit the 2.31-Mev transition by a factor of about 3. It appears then that although a stringent test of the isotopic-spin conservation rule must be sought elsewhere, within the sensitivity of this experiment the rule is not violated.

[19] H. J. Watters, Phys. Rev. **103**, 1763 (1956).
[20] Y. Hashimoto and W. P. Alford, Phys. Rev. **116**, 981 (1959).

ACKNOWLEDGMENTS

We wish to thank J. L. Blankenship for furnishing the surface-barrier counters, P. H. Stelson for his comments on Coulomb excitation, M. P. Fricke for preparing the evaporated carbon film, G. A. Palmer for assistance in taking data, and A. W. Riikola and H. L. Dickerson for providing the long hours of steady cyclotron operation required for this experiment.

PHYSICAL REVIEW VOLUME 121, NUMBER 1 JANUARY 1, 1961

Lifetime of the First Excited State of N^{14}†

C. P. Swann, V. K. Rasmussen, and F. R. Metzger
Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania
(Received August 26, 1960)

The mean life of the first excited state of N^{14} has been measured by nuclear resonant scattering. The $N^{14}(p,p')$ reaction with an N^{14} enriched gaseous ammonia target was used as the source of Doppler-broadened γ radiation. The value of $(7.3\pm1.8)\times10^{-14}$ sec obtained is a factor of two longer than theoretical predictions based on the wave functions used to explain the anomalously slow C^{14} β decay.

INTRODUCTION

The slowness of the C^{14} β decay seems to be most satisfactorily explained by the chance cancellation of terms in the matrix element.[1–4] Since the electromagnetic decay of the first excited state of N^{14} involves, in the approximation that isotopic spin is a good quantum number, the same nuclear wave functions, a measurement of this decay rate should be of interest. Elliott[3] and Visscher and Ferrell[4] have calculated this rate using wave functions consistant with the β decay. They predict mean lives of 3.75×10^{-14} and 2.88×10^{-14} sec, which may be compared to the extreme *j-j* coupling prediction of 7.4×10^{-15} sec.

Sherr *et al.*[5] and Thirion and Barloutaud[6] attempted to measure this lifetime by the Doppler-shift method. Neither group was able to find a target dense enough to give a detectable reduction in the Doppler shift of the γ ray. They give upper limits for the mean life of 5×10^{-13} and 3×10^{-13} sec, respectively.

Previous efforts to measure this lifetime by the nuclear resonance fluorescence techniques served only to establish a lower limit of 6.6×10^{-15} sec, as quoted by Warburton and Pinkston.[7] Thus the theoretical values are within the experimental limits, but these limits are so wide as to be of little significance.

The theoretical lifetimes are well within the range of lifetimes previously measured by the resonance fluorescence technique, and one might expect it to be easily measurable. That this is not the case is the result of two unfavorable circumstances. First, the statistical weight factor in the resonance cross section for this 1–0–1 transition is only $\frac{1}{3}$ compared, for example, to 5 for the favorable 0–2–0 case. Second, the most suitable source of the 2.31-Mev γ ray appears to be the $N^{14}(p,p')N^{14*}$ reaction which gives a rather low yield even at proton energies several hundred kev above the $N^{15}(p,n)$ threshold. The presence of neutrons in this case is particularly troublesome because of the 2.22-Mev gamma ray resulting from neutron capture in the hydrogen of hydrogenous materials. Indeed, this measurement was only possible because we were able to obtain from F. H. Spedding nitrogen depleted in N^{15} by a factor of about 30. The low γ-ray yield along

† This research was supported by the U. S. Office of Naval Research.
[1] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[2] B. Jancovici and I. Talmi, Phys. Rev. **95**, 289 (1954).
[3] J. P. Elliott, Phil. Mag. **1**, 503 (1956).
[4] W. M. Visscher and R. A. Ferrell, Phys. Rev. **107**, 781 (1957).
[5] R. Sherr, J. B. Gerhart, H. Horie, and W. F. Hornyak, Phys. Rev. **100**, 945 (1955).
[6] J. Thirion and R. Barloutaud, Compt. rend. **240**, 2136 (1955).
[7] E. K. Warburton and W. T. Pinkston, Phys. Rev. **118**, 733 (1960).