Scattering of 22-Mev α Particles by C^{12}†*

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(Received May 4, 1955)

The elastic and inelastic scattering of 22-Mev α particles by carbon has been observed at a number of angles. Groups corresponding to the excitation of C^{12} to the known 4.4-, 7.7-, and 9.6-Mev levels were found. There was no evidence for the higher states reported by others, except possibly at $\sim$12.7-Mev excitation. A strong angular dependence and a marked lack of symmetry around 90° was observed. The excitation function for $E_\alpha = 20.4$ to 22.6 Mev indicates a resonance at $E_\alpha = 21.85 \pm 0.1$ Mev, and the angular asymmetry indicates that there is at least one other level of opposite parity in this region. The Q-value for the second excited state was measured to be -7.64 ± 0.07 Mev. By looking for the appropriate C^{12} recoil ions it was established that this state decays to $Be^8 + \alpha$ with $>80\%$ probability.

I. INTRODUCTION

THE inelastic scattering of 22-Mev α particles by C^{12} was chosen as the subject for preliminary investigation with the Indiana University heavy-particle spectrometer because of the simplicity of the level scheme below 10-Mev excitation and the availability of target materials. It was hoped that information might also be obtained concerning some of the levels that have been reported above 10 Mev, and that the angular distribution for various α groups might be determined.

The present information about the level scheme of C^{12} has been summarized by Ajzenberg and Lauritsen.[1] There are well-established levels at 4.431 ± 0.013 Mev and 9.613 ± 0.012 Mev, the energies quoted having been obtained from observation of the $N^{14}(d,\alpha)$ reaction.[2] The existence of a level around 7.5 Mev has, until recently, been open to some question. It is now clearly established and its location given as 7.68 ± 0.03 Mev.[3] A very broad ($\Gamma = 1.6$ Mev) level at 9.7 Mev is reported by Jackson and Wanklyn.[4] Between 10- and 16-Mev excitation almost all of the available information is from the $B^{11}(d,n)$ reaction, which indicates several levels in this energy region.[5]

II. EXPERIMENTAL PROCEDURE

A. Spectrometer

The Indiana University heavy-particle spectrometer is of the point-focusing type with the magnetic field varying as $1/\sqrt{r}$, as introduced by Siegbahn and Svartholm.[6] With some exceptions, principally that the mean radius of curvature for focused particles is 20 in. instead of 16 in., it is a copy of the one designed and built at the California Institute of Technology.[7] The spectrometer may be rotated with respect to the cyclotron beam, so that all angles of observation from 45° counter-clockwise through a minimum of $12\frac{1}{2}$° to 145° clockwise are available. The target chamber, made from two short 15 in. i.d. steel cylinders joined by a sliding O-ring seal, allows these changes to be made continuously without breaking the vacuum (see Fig. 1).

A null-reading, magnetic-balance type of fluxmeter is used to measure the magnetic field. Matched agate knife edges and V-blocks[8] are used to support both the balance beam and weight. The main parts of this balance are located between the counter and the

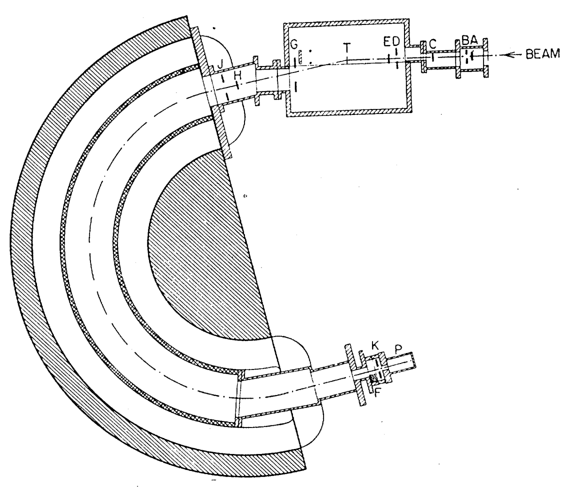

FIG. 1. Schematic cross-sectional view of the target chamber and magnetic spectrometer at the minimum laboratory angle of $12\frac{1}{2}$°. For explanation of the various letters, see text.

† Supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
* Parts of this work have been reported previously by Rasmussen, Miller, Carmichael, and Sampson, Phys. Rev. **92**, 852(A) (1953) and Miller, Rasmussen, and Sampson, Phys. Rev. **95**, 649(A) (1954).
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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[2] R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).
[3] Dunbar, Pixley, Wenzel, and Whaling, Phys. Rev. **92**, 649 (1953).
[4] J. D. Jackson and D. I. Wanklyn, Phys. Rev. **90**, 381(A) (1953).
[5] V. R. Johnson, Phys. Rev. **86**, 302 (1952).
[6] K. Siegbahn and N. Svartholm, Arkiv. Mat. Astron. Fysik. **33A**, Nos. 21, 24 (1946).
[7] Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**, 852 (1950); W. Whaling and C. W. Li, Phys. Rev. **81**, 150 (1951). See also R. Malm and D. R. Inglis, Phys. Rev. **95**, 993 (1954) for a description of another magnet of this type.
[8] Obtained from Voland and Sons, Inc., New Rochelle, New York.

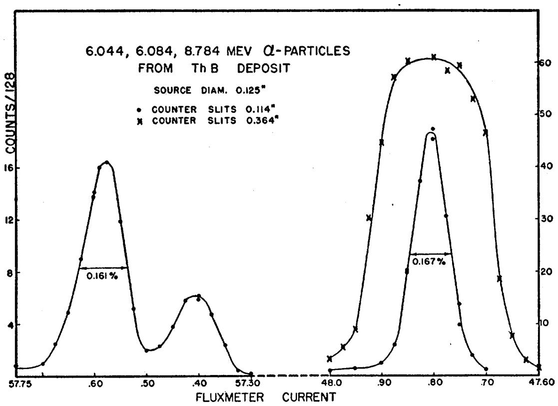

FIG. 2. Natural α groups from a ThB deposit, taken with two different counter slit openings. $K_f = 20\,070$.

magnet exciting coils. The fluxmeter coil proper, supported by an aluminum tube, extends a minimum of two inches into the field region from the edges of the magnet poles. This fluxmeter has, in general, been quite satisfactory, although small temperature effects are observed and there is a noticeable nonlinearity at high fields. The latter effect is a result either of small changes in field shape or of a local inhomogeneity in the field.

Focused particles are detected by a thin-window proportional counter (P in Fig. 1). Adjustable slits (K) allow the counter aperture to be varied. Aluminum foils (F) of nominal thickness 1, 2, 4, 9, 19, 48, and 75 mg/cm^2 can be moved in front of the counter independently to allow rough measurements of particle ranges from 1 to 158 mg/cm^2. A 0.06-in. copper sheet can also be inserted so as to block the counter window completely.

Figure 2 shows the three most prominent α groups from a ThB deposit, as observed with this instrument. The sharp curves have a momentum width about equal to the theoretical width[9] of 1/600 predicted for the source and counter sizes employed. The broader curve, taken with wider counter slits, corresponds to the usual experimental conditions and is the one used to establish the basic energy scale. Since the fluxmeter current I_f is proportional to $1/B$, the energy calibration may be given in terms of a constant $K_f = EI_f^2$. If one uses 8.776 Mev for the (relativistic) energy of the ThC′ α group, $K_f = 20\,070$. During the course of these experiments the fluxmeter was modified, so that a different constant (given in the captions) is to be used for some of the later figures.

B. Cyclotron Beam Focusing

The external cyclotron beam passes through a focusing magnet, the cyclotron shielding, and an analyzing magnet before it reaches the target chamber. The focusing magnet, designed by Professor N. Svartholm and Dr. F. E. Steigert, consists of two consecutive 12° sector magnets which give opposite deflections and produce radial focusing with minimum beam displacement. It changes the divergent incident beam into one that is slightly converging. The homogeneous-field analyzing magnet provides a 32° beam deflection and brings the beam to a focus approximately at the set of slits marked C in Fig. 1. The slits marked B limit the vertical extent of the beam. Under usual operating conditions, the beam at the target position is $\sim\frac{7}{32}$ in. high and $\sim\frac{5}{16}$ in. wide with a horizontal angular divergence of $\sim 1°$. At times, the beam spot has been found to be much narrower than this, apparently as a result of variations in cyclotron operating conditions. The energy and spread in energy of the useful beam are determined partly by the cyclotron fringing field and partly by the analyzing magnet. As estimated from the widths of scattered peaks, the spread in energy of the useful α-particle beam varies from $\sim$75 to $\sim$150 kev, depending on cyclotron conditions. The mean energy of the beam may also vary by an appreciable amount from day to day. These variations were limited to a certain extent by placing a set of adjustable slits between the cyclotron and the focusing magnet.

C. Targets

For experiments of this nature thin target backings are required. After some preliminary attempts to use gold or aluminum leaf, backings made by evaporating a semitransparent layer of aluminum onto thin ($\sim$1400 A) Zapon lacquer films were adopted. By keeping the film on the metal frame upon which it was originally picked up, it was possible to get very smooth targets which stood up quite well under bombardment after minor initial wrinkling at the beam spot. About 0.1 mg/cm^2 of carbon was added to these films by spraying them with a dilute colloidal suspension of graphite in water or water-alcohol mixture.[10] The total thickness of the targets and, in some cases, the backing thickness (which proved to be almost negligible) were measured by observing the energy loss of ThC′ alphas. It was also possible in this way to estimate the target uniformity, which was generally satisfactory although not quite as good as desired.

III. RESULTS

A. Observed α Groups

The elastic α group and groups corresponding to the excitation of C^{12} to its first three excited states were found at a number of angles. Typical curves are given in Fig. 3. These curves were taken with the $\frac{1}{2}\%$ "window" of Fig. 2. Almost all of the observed width of each peak is due to the variation of the emitted

[9] D. L. Judd, Rev. Sci. Instr. 21, 213 (1950).

[10] Aquadag, a product of the Acheson Colloids Corporation, was used. Their alcohol suspension would probably have been more satisfactory.

particle energy over the finite acceptance angle of the spectrometer. Target thickness and inhomogeneiety and the energy spread of the incident beam also contribute to some extent to the observed peak widths. No detailed analysis of the separate contributions has been attempted, although the effect of varying single factors has been observed.

It seemed of interest to attempt a fairly accurate measurement of the location of the state at ~7.7 Mev. An angle (79° lab) was chosen at which the α groups leaving C^{12} at 7.7 Mev and 4.43 Mev fell close to the calibration points furnished by a ThB deposit. The beam energy was calculated from the location of the 4.43 group. The lower energy α group then gave a calculated level energy of 7.64 ± 0.07 Mev, with the largest part of the probable error resulting from the widths of the peaks. Corrections for target thickness and relativistic effects were made, although the net result of these was small (~25 kev) since they also come into the beam-energy determination.

Since work in this laboratory and elsewhere[11,12] suggested a possible 7-Mev level in C^{12} (distinct from the 7.68-Mev state) which decayed either by γ-ray or pair emission, a search for the corresponding α group was undertaken. Weak groups were observed at some angles, but the shift with angle indicated that C^{12} was not the scattering nucleus. If such a level in C^{12} exists, it is excited in this reaction with less than 0.005 times the intensity of the 4.4-Mev level at a laboratory angle of 55°.

No other extended search for levels below 10 Mev was made. However, a search for the higher levels reported in the $B^{11}(d,n)$ reaction[5] was carried out at forward angles. The continuum of alphas from $C^{12*}\rightarrow Be^8+\alpha$ made the detection of weak alpha groups difficult. As a result, no evidence for the higher states was found except for one group at $12\frac{1}{2}°$ (lab) (see Fig. 4) which may correspond to a C^{12} excitation of around 12.7 Mev. Other groups would have been observed if they had an intensity greater than about 5–10% that of the group to the 9.61-Mev state. The very broad group at $12\frac{1}{2}°$ results from the scattering of alphas by hydrogen contamination in the target (this group did not interfere at other angles, since it cannot occur at angles >15°). The continuum of α's from Be^8 also would have obscured the very broad level at ~9.7 Mev reported in the $C^{12}(n,n')3\alpha$ reaction by Jackson and Wanklyn.[4] It is only possible to say that such a broad level is excited with less than $\frac{1}{2}$ the probability of the sharp 9.6-Mev level.

B. Angular Distributions

It became apparent early in the course of these investigations that none of the observed α groups was

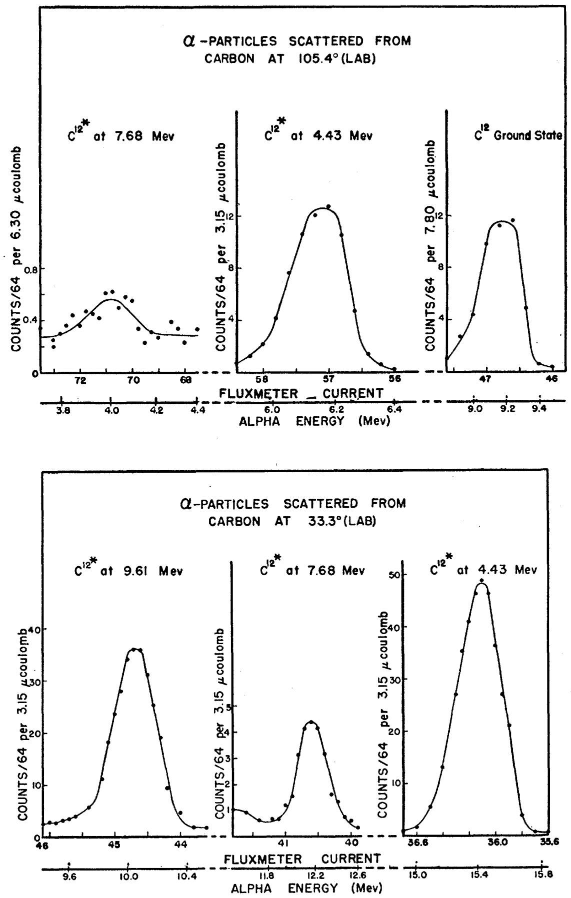

FIG. 3. Typical elastic and inelastic α groups scattered from carbon at the angles noted. $K_f=20\,070$.

isotropic. Cross sections at quite a few angles were obtained before it was discovered that there were significant variations in intensity with small changes in beam energy as well as with changes in angle. To check on these effects, thick-target excitation functions (discussed below) were then run, and the results made it clear that significant angular data would require closer control of the beam energy than was feasible. However, certain qualitative statements about the angular distributions can be made for incident α energies of ~22 Mev, the angles given being c.m. angles and the cross sections being in mb per 4π steradians.

(a) None of the four α groups investigated is symmetric around 90°.

(b) The α groups leaving C^{12} excited to 4.43 and 9.61 Mev show a fairly smooth variation of cross section with angle. The 4.43 group rises to a backward (150°) maximum about 5 times as high and a forward (30°) maximum about 3 times as high as the minimum of ~100 mb at 115°. A forward (30°) maximum over 10 times the flat (~60 mb) distribution from 70° to 120° is observed for the 9.61 group.

[11] N. S. Wall and J. R. Rees (private communication).

[12] G. Harries and W. T. Davies, Proc. Phys. Soc. (London) **A65**, 564 (1952); G. Harries, *ibid.* **A67**, 153 (1954).

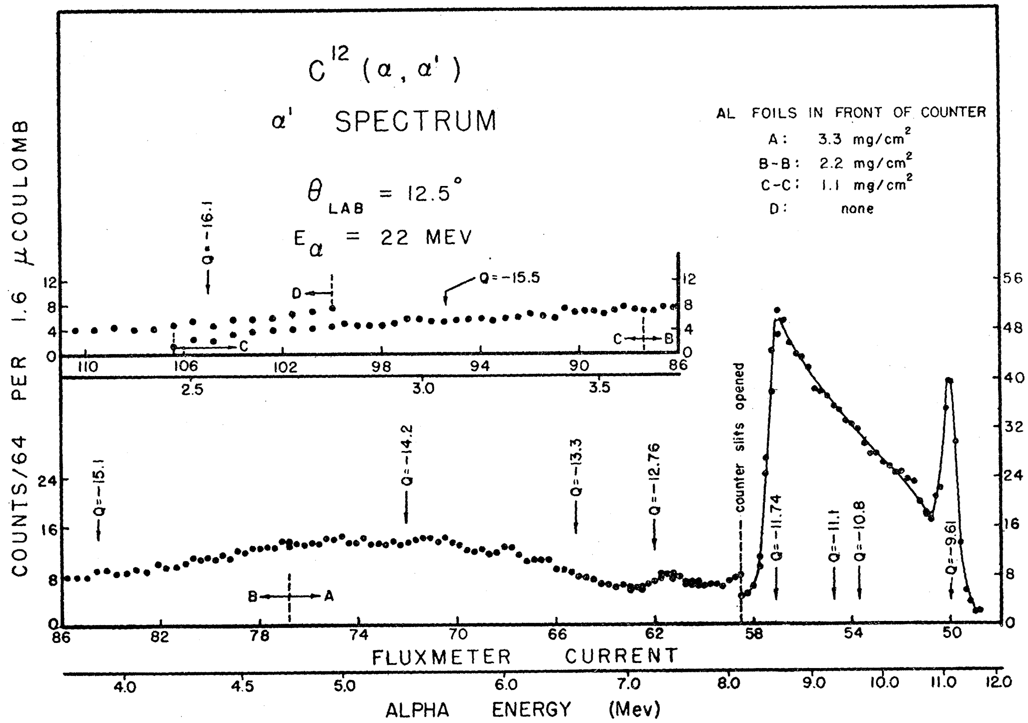

FIG. 4. Search for states in C^{12} above 9.6 Mev. See text for detailed discussion. States reported by others should fall approximately at the positions marked by arrows. The break near fluxmeter current 58 resulted from opening the counter slits to 0.614 in. to give a higher counting rate. Aluminum foils were placed in front of the counter as noted to stop C^{12} ions (compare Fig. 7) and singly-charged α particles. The double curve between 100 and 106 probably results from some doubly-charged α's being missed with the 1.1 mg/cm² foil in front of the counter. $K_f = 27\,850$.

(c) Very rapid variations of cross section with angle are exhibited by the elastic group and that leaving C^{12} excited to 7.7 Mev, changes by a factor of 5 or more for angular changes of 10°–15° being observed. The elastic cross section is ~1000 mb at 60°, while from 75° to 150° it averages ~40 mb. The 7.7-Mev cross section varies from ~3 mb to ~25 mb with an average value of ~15 mb.

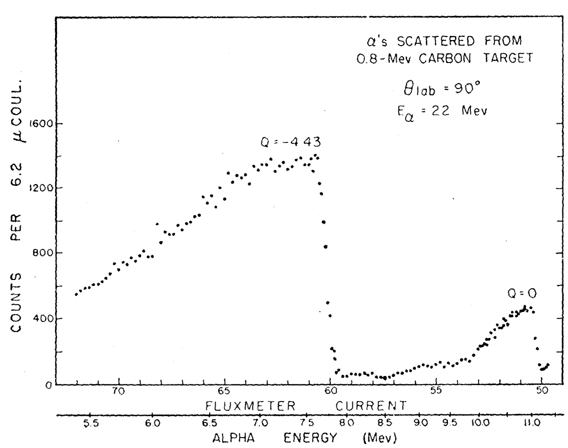

FIG. 5. Alpha particles scattered elastically and inelastically ($Q = -4.43$ Mev) from a semithick carbon target. $K_f = 27\,990$.

C. Excitation Function

The variation with energy of the cross section for elastic scattering and for inelastic scattering to the first excited state was obtained for beam energies between 20.4 and 22.6 Mev. A semithick target, of thickness 2.6 mg/cm² or 0.75 Mev for 22-Mev α's at normal incidence, was prepared in the same manner as the thin targets. The spectrometer was located at 90°, with the acceptance aperture closed down to give somewhat better resolution. The target was placed at 45° to the beam and was observed in reflection, i.e., the side on which the beam was incident also faced the spectrometer. Incident beam energies of 22.65, 22.40, and 22.0 Mev were obtained by small displacements of the cyclotron dees and the deflector. An energy of 21.4 Mev was obtained by placing an aluminum foil in the path of the beam just outside the cyclotron. Typical curves obtained in this manner are shown in Fig. 5. The data was analyzed by the method of Snyder *et al.* (reference 7, p. 866) to give the excitation functions of Fig. 6. No attempt was made to correct for straggling in energy loss or angle, and the target was not perfectly smooth and homogeneous. For these, and possibly other reasons, the various runs do not join together as smoothly as might be desired. However, the method used to obtain large changes in beam energy was so

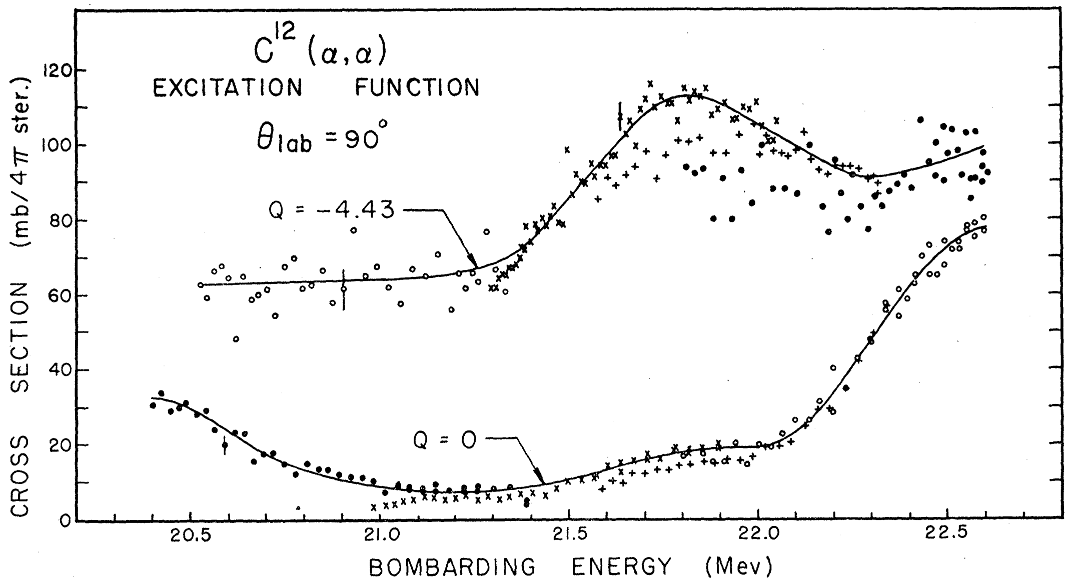

FIG. 6. Excitation functions for $C^{12}(\alpha,\alpha)C^{12}$ and $C^{12}(\alpha,\alpha')C^{12*}$ resulting from analysis of the curve of Fig. 5 and three other similar curves. The solid curves represent our best estimate of the true excitation functions.

hazardous to proper cyclotron dee adjustment that it seemed better not to attempt to repeat the experiment. It should be noted that the initial 200-kev rise of Fig. 5 does not represent the effective resolution for the excitation function, since an α particle that loses 90 kev in the target before being elastically scattered loses more energy before emerging and appears 200 kev lower in the observed spectrum.

D. C^{12} Recoils

At forward angles, even with the 1.8-mg/cm² mica counter window used in the early part of these experiments, pulses very large compared to maximum α pulses were observed. The range of these particles was small compared to that of an α particle of the same $Bze\rho$, suggesting that these were C^{12} recoil ions.

Since the mica window was cutting off at about 12-Mev ion energy (in the sense that the pulses became so small that they were difficult to distinguish from alphas), a 1.1 mg/cm² nickel window with pinholes filled by very thin Zapon lacquer was substituted. The cut-off with this window was below 8.45 Mev. The 6^+, 5^+, and 4^+ charge states of these ions were then found at lab angles of $12\frac{1}{2}°$ and 24° for both elastic recoils and for recoils which had been excited to 4.43 Mev. Typical curves are shown in Fig. 7. By changing the angle between the target and the direction of observation, and noting the shift of the low-energy side of the peak, it was found that an "Aquadag" target that was 40-kev thick for 8.8-Mev α's was approximately 0.5-Mev thick for 13.6-Mev carbon ions. Information on the intensity ratios of ions with various energies in different charge states is given in Table I.

Portions of the spectrum where recoils that had been excited to 9.6 Mev should be observed were scanned. Nothing was found, as would be expected from the instability of this state to α emission. Because of the astrophysical interest in the 7.7-Mev state[3] and its mode of decay, a more extended search was made for recoil C^{12} nuclei which had been excited to 7.7 Mev and had then decayed to the ground state of C^{12} rather than to $Be^8+\alpha$. The intensity to be expected was determined by observing the corresponding inelastic α group (both singly and doubly charged) in the backward direction. This gives the predicted curve of Fig. 8, assuming 100% decay of the 7.7-Mev state to the ground state of C^{12}. A similar experiment comparing the observed recoil C^{12} ions that had been excited to the 4.43-Mev state and the corresponding inelastic backward α's gave agreement to within 6%, thus checking the experimental method. The recoil C^{12} ions starting in the 7.7-Mev state would have an energy of 11.76 Mev, which is well above the cutoff for the nickel window (a clean peak for 8.45-Mev C^{12} recoil ions was obtained with a similar window).

TABLE I. Relative number of C^{12} ions in various charge states.[a]

C^{12} energy (Mev)	Ionic charge 6^+	5^+	4^+	3^+
11.3[b]	15	50	32	3
12.4[c]	22	57	21	...
13.1[b]	26	53	22	...
14.6[c]	29	52	...	...
15.6[c]	44	(37)	19	...

[a] For this data, the spectrometer was looking at the "Aquadag" face of the target.
[b] Data obtained in the course of a single run. Probable error, ±5%.
[c] Data collected over the course of several days running. Probable error, ±10%, but considerably larger errors cannot be ruled out. The value in parentheses is especially questionable.

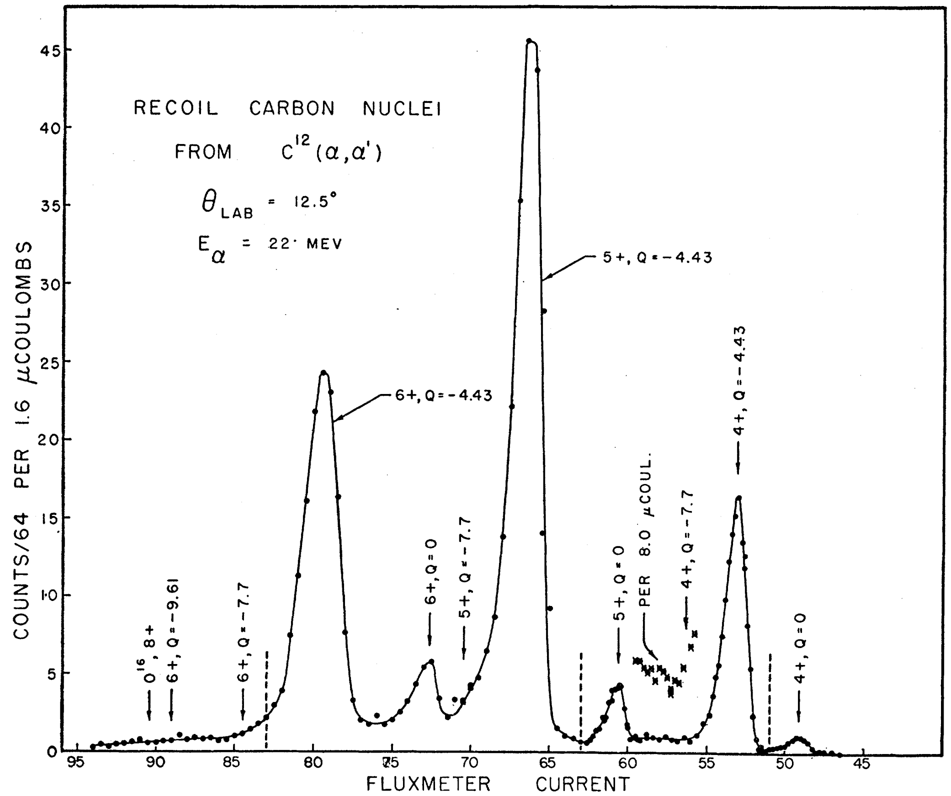

FIG. 7. Spectrum of recoil C^{12} ions. Only pulses larger than those resulting from α particles were counted. The arrows indicate the calculated locations for various possible ions. The vertical dashed lines represent data taken on different days and thus possibly with slightly different beam energies. $K_f = 27\,800$.

As shown in Fig. 8, no evidence for recoil C^{12} ions starting in the 7.7-Mev state was found. The background counts that were obtained in this region most probably represent C^{12} nuclei that have undergone large changes in energy or angle in the target, although a few singly charged α's may have been counted also.

IV. DISCUSSION

At the rather high energies involved, it is not clear that the excitation function of Fig. 6 has any significant bearing on the properties of the compound nucleus, O^{16}. On the other hand, there does not seem to be any other picture of the reaction process that will explain the features of this data, so that the compound nucleus point of view will be adopted with the reservation that it may be completely irrelevant. On this basis, then, the inelastic scattering indicates a resonance at $E_\alpha' = 21.85 \pm 0.1$ Mev (O^{16*} excitation $= 23.55$ Mev) with a width of around 0.4 Mev. The lack of symmetry around 90° in the angular distributions shows that there is at least one other level, of opposite parity, in the neighborhood of 22 Mev (which the data easily allows). However, Wolfenstein's calculations[13] would indicate that there cannot be a large number of additional levels, since this should result in symmetry about 90°. Interference between a few close levels could also result in the sensitive dependence of the angular distributions on energy that was noted. The additional detail shown by the elastic-scattering data would be expected from the interference between resonance and other possible modes of scattering. This can, in principle, give additional information, but the accuracy of the present data is obviously not great enough to justify a detailed theoretical analysis. To illustrate the possible difficulties of such a calculation, it might be pointed out that rather high angular momentum transfers are possible, the barrier height being equal to the available center-of-mass kinetic energy for $L \sim 7$.

The level observed by Newson[14] should occur at $E_\alpha = 22.40$ Mev, where the inelastic curve of Fig. 6 shows a slight dip. The energy difference would seem to be outside experimental error; possibly this higher level is one that cannot be formed by two $J=0$ particles.

One rather striking feature of the present experiment is the contrast between the ease with which the first three excited states of C^{12} are observed and the failure to find what would seem to be well-established higher levels starting ~ 1.5 Mev above 9.61 Mev. In this connection, it should be noted that there is sufficient energy available to excite C^{12} to 16.5 Mev while the barrier for s-wave α particles is ~ 3 Mev. We have been unable to discover any reason for this apparent cutoff.

From the recoil data given in Fig. 8 and from other similar data, it is estimated that there is a greater

[13] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).

[14] H. W. Newson, Phys. Rev. **51**, 620 (1937).

TABLE II. Calculated lifetimes for 7.7-Mev state of C^{12} for various possible spin and parity assignments. See text for assumptions employed in the calculations.

Spin and parity	Electromagnetic radiation	Electromagnetic lifetime (sec)	α lifetime (sec)
0^+	3.25-Mev $E2$	8×10^{-13}	7×10^{-17}
	7.7-Mev π	10^{-11}	
1^-	7.7-Mev $E1$[a]	3×10^{-15}[b]	4×10^{-15}
	3.25-Mev $E1$	4×10^{-14}[b]	
2^+	3.25-Mev $M1$	10^{-15}	5×10^{-12}
	7.7-Mev $E2$[a]	9×10^{-15}	
3^-	3.25-Mev $E1$	4×10^{-14}[b]	5×10^{-7}

[a] Not observed.
[b] Includes inhibition by an arbitrary factor of 10^3 because of the isotopic-spin selection rule.

than 80% probability that the 7.7-Mev state of C^{12} will decay to $Be^8+\alpha$. This is in contradiction to the recent work of Uebergang[15] who finds that the state decays predominantly by cascade γ radiation (7.7-Mev γ radiation has not been observed[16]). It may be that these two modes of decay have probabilities of the same order of magnitude, although this would seem rather unlikely. In an effort to clarify this point, calculations of the relative probabilities for the emission of an α particle (leaving Be^8 in its 0^+ ground state) and for decay by electromagnetic radiation have been made and are summarized in Table II.[17] The radius of the system $Be^8+\alpha$ was taken as $1.45(8^{\frac{1}{3}}+4^{\frac{1}{3}})\times10^{-13}$ cm and the reduced width, γ_α^2, of the decaying C^{12} state was taken as $\hbar^2/\mu R$. Lifetimes for γ radiation were calculated from the formulas given by Blatt and Weisskopf[18] and that for nuclear pair emission (the 0^+ to 0^+ transition) was estimated from the measured value for the O^{16} pair state[19] and the W^5 theoretical dependence.[20] The probabilities for electric-dipole transitions were reduced by an (arbitrary) factor of 10^3, to allow for the isotopic spin selection rule forbidding $\Delta T=0$ transitions in $N=Z$ nuclei.[21] The only spins and parities of the C^{12} state that must be considered are either even-even or odd-odd.[22]

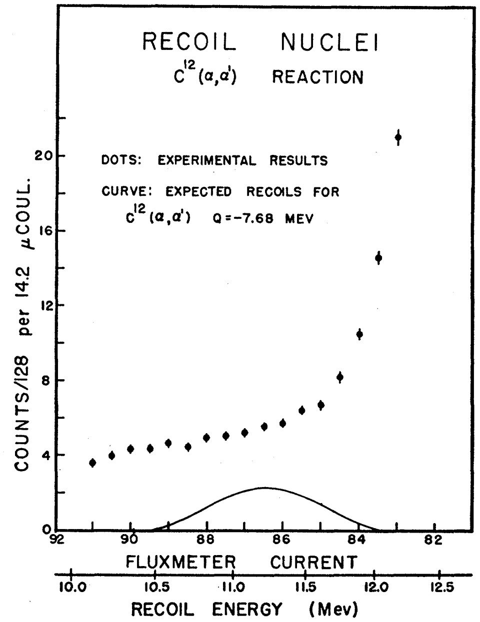

FIG. 8. Search for recoil carbon ions which had been excited to 7.7 Mev and then decayed to the ground state. The dots represent experimental points, while the solid curve represents the shape of the curve expected judging from the corresponding observed backward inelastic α's. The rapid rise at the right is a tail of 6^+, $Q=-4.43$ recoils. Background counts in this region are scattered C^{12} ions plus possibly a few singly-charged alpha particles (compare with Fig. 7). $K_f=27\,960$.

Since observed α widths vary from the limit $\hbar^2/\mu R$ to ~0.001 of that limit,[23] and since γ-ray widths vary from somewhat larger to very much smaller than the values given by the Blatt and Weisskopf formulas, we conclude from Table II only that spin and parity assignments of 0^+, 1^-, or 2^+ for the 7.7-Mev state of C^{12} are all consistent with the experimentally indicated competition between α and γ decay.[24]

V. ACKNOWLEDGMENTS

The authors would like to express their appreciation to Mr. O. E. Johnson for aid in construction of the magnetic spectrometer, and to Dr. B. M. Carmichael, Dr. N. S. Wall, and Mr. J. R. Rees for aid in taking the data. Helpful discussions of the results with Professor E. J. Konopinski, Dr. N. S. Wall, Dr. N. C. Francis, and Professor K. W. Ford are also gratefully acknowledged.

[15] R. G. Uebergang, Australian J. Phys. **7**, 279 (1954).
[16] Beghian, Halban, Husain, and Sanders, Phys. Rev. **90**, 1129 (1953).
[17] Similar results were reported by E. E. Salpeter, Phys. Rev. **98**, 1183(A) (1955).
[18] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[19] Devons, Goldring, and Lindsey, Proc. Phys. Soc. (London) **A67**, 134 (1954).
[20] J. R. Oppenheimer and J. Schwinger, Phys. Rev. **56**, 1066 (1939).
[21] L. A. Radicati, Phys. Rev. **87**, 521 (1952); M. Gell-Mann and V. L. Telegdi, *ibid.* **91**, 169 (1953).
[22] Our observation of this state in C^{12} rules out 0^- completely, and other even-odd or odd-even states could not decay to the 0^+ ground state of Be^8. Decay into three alphas, it would seem, would involve considerably smaller barrier penetration probabilities since the available energy would be more evenly distributed among the three alpha particles. One would also expect decay to the "tail" of the broad 2^+ first excited state of Be^8 at ~2.9 Mev to be quite weak.
[23] See, for example, R. W. Hill, Phys. Rev. **90**, 845 (1953); J. W. Bittner and R. D. Moffat, *ibid.* **96**, 374 (1954).
[24] J. Seed, Phil. Mag. **46**, 100 (1955), has recently reported a $\gamma-\gamma$ correlation experiment which indicates a definite preference for 0^+. However, he also states that he cannot definitely rule out 3^+ or $4^\pm$, in which case it would seem difficult to rule out 1^- or 2^+.