6. Klinkenberg's table of nuclear shell structure[5] was used for orbital assignments for the ground states of the two nuclides. Ti^{47} is predicted to have a $f_{7/2}$ ground state and Sc^{47} is given the $f_{7/2}$ assignment since it is expected to have the same configuration as Sc^{45}. This predicts an allowed beta transition to the ground state of Ti^{47} and perhaps is not inconsistent with the log ft value of 6.0. The log ft value of 5.3 for the lower-energy beta group indicates that it is an allowed transition. This leads to an assignment of $f_{5/2}$ for the 167-kev state in Ti^{47}. The gamma transition would then be magnetic dipole which has a theoretical K-shell conversion coefficient of about 4×10^{-3}. This would partially indicate the reason for the absence of a detectable conversion line in the beta spectrum. A thinner source might reveal such a conversion line.[6]

The authors wish to express their appreciation to Mr. J. Powers for performing the chemical separations.

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[5] P. F. A. Klinkenberg. Revs. Modern Phys. 24, 63 (1952).

[6] *Note added in proof.*—While this article was in press Lyon and Kahn [Phys. Rev. 99, 728 (1955)] published their results on the decay of Sc^{47}. Their results are in general agreement with those presented in this article.

PHYSICAL REVIEW VOLUME 100, NUMBER 5 DECEMBER 1, 1955

Inelastic Scattering of 19-Mev Protons by O^{16}†

W. F. HORNYAK AND R. SHERR
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

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The NaI scintillation spectroscopy of the proton groups from the inelastic scattering of 19-Mev protons by O^{16} yielded levels in O^{16} at 6.14, 7.02, 8.87, 9.85, 10.34, 11.08, 11.51, 12.02, 12.53, 13.06, and possibly 13.39 Mev, with an error of ±30 kev. The levels at 8.87 and 11.08 Mev are probably 2^- in character and are found to decay by γ rays cascading through the states at 6 and 7 Mev. The relatively weakly excited level at 12.02 Mev is probably accompanied by γ-ray emission. Differential cross sections for most inelastic groups are also given.

I. INTRODUCTION

THE recent experiment of Bittner and Moffat[1] has considerably increased the number of levels in O^{16} below 14 Mev of excitation for which reliable energy and character assignments can be made.[2] The resulting relatively complete level structure has been compared by Dennison to the predictions of the α-particle model.[3] Some degree of correspondence was noted. However, the question of the existence of the predicted $2^{\pm}$ doublets, which has heretofore been the subject of a number of unsuccessful experiments,[4] remained unanswered. The α-particle scattering by C^{12} used by Bittner and Moffat could reach only even-parity even-spin or odd-parity odd-spin states in O^{16} and could therefore not excite the 2^- components of the doublets. In the inelastic scattering of protons by O^{16} there are no *a priori* restrictions of this kind.

II. PROTON GROUPS

An external beam of 19-Mev protons from the Princeton FM cyclotron was used to bombard various oxygen-containing targets. The 60-inch scattering chamber, previously described,[5] was used in these experiments. Although the cyclotron beam energy spread is of the order of a 100–200 kev, the mean energy was regulated to ±10 kev by the use of a "proton range to cyclotron magnet" feedback system.[6] A carefully stabilized scintillation pulse height spectrometer using a thin NaI(Tl) crystal was used to detect the scattered protons. The resolution for 19-Mev protons was approximately 2.5%, full width at half-maximum.

The spectrometer was calibrated for linearity by observations on p-p scattering at various angles. In these runs the target consisted of a thin polystyrene film (2.0-mg/cm² Al equivalent for 19-Mev protons) mounted together with a thin Pt metal foil (2.7-mg/cm² Al equivalent). At each scattering angle the ratio of the pulse heights observed for the protons elastically scattered from H and from Pt were compared with calculated values.[7] Except for relatively small corrections such as for energy loss in the target and scintillation crystal foil covers, this comparison is independent of the absolute beam energy and may be used as a measure of the system linearity.

The results of these measurements are shown in Fig. 1. Here f is a correction factor by which the observed energy must be multiplied to give the true energy. This curve has been arbitrarily normalized to unity at 18.60 Mev. The observed energy is obtained by assuming proportionality between pulse amplitude and en-

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† This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

[1] J. W. Bittner and R. D. Moffat, Phys. Rev. 96, 374 (1954).

[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

[3] D. M. Dennison, Phys. Rev. 96, 378 (1954).

[4] Peterson, Fowler, and Lauritsen, Phys. Rev. 96, 1250 (1954).

[5] J. L. Yntema and M. G. White, Phys. Rev. 95, 1226 (1954).

[6] G. Schrank, Rev. Sci. Instr. 26, 677 (1955).

[7] Corrections for nonintegral mass values and relativistic effects were made.

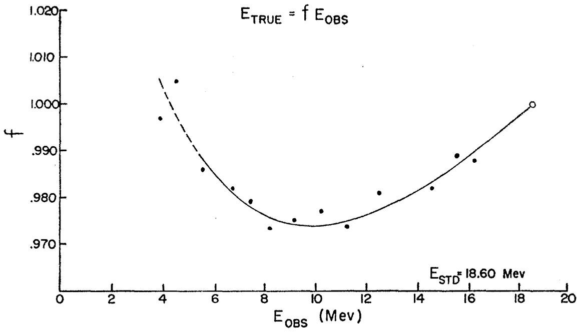

FIG. 1. Energy calibration curve for the NaI(Tl)+6291 Dumont photomultiplier response to protons 4–19 Mev. Multiplier high voltage was 750 volts with shield connected to first dynode; the NaI(Tl) crystal was approximately 5 mm thick.

ergy where the constant of proportionality is determined by the elastic Pt line. The latter was measured coincidently with the other proton groups and since its energy varies only slightly around 18.60 Mev over the entire angular range, it was assumed that $f=1$ for this line. (The use of this Pt group has the added advantage of eliminating changes in gain with angle, through either counting rate or stray magnetic field effects.) The entire nonlinearity was found to reside in the NaI(Tl) crystal-photomultiplier tube response; we have not made tests to determine which of these two components is responsible for this effect.

The absolute beam energy calibration was determined by the aluminum equivalent of the proton range to which the cyclotron was stabilized. The mean range of the average-energy proton entering the regulator was 515 mg/cm² Al. From Bichsel and Mozley's recent precision range-energy determinations,[8] this corresponds to an energy of 18.88 Mev.

Both as a control for the cellulose acetate target (which contains O, H and C) and to obtain an additional check on the spectrometer and cyclotron energy calibration, the scattered proton spectrum for a polystyrene (H and C only) target was obtained. A composite target of 2-mil polystyrene and 0.1-mil Pt foils gave the results shown in Fig. 2 Groups *A* and *B* correspond to the elastic scattering from Pt and C, respectively, while groups *C*, *D*, and *E* correspond to excitation energies of 4.45, 7.66 and 9.64 Mev (all ±30 kev) respectively and are therefore the first three excited states in C^{12}. The Pt foil gives only a relatively weak unresolved continuum of inelastic protons which is indicated in Fig. 2 by dashed line. No attempt was made to assign the groups having energy less than group *E*; the increase in counting rate at low pulse amplitude is partly due to γ-ray background.

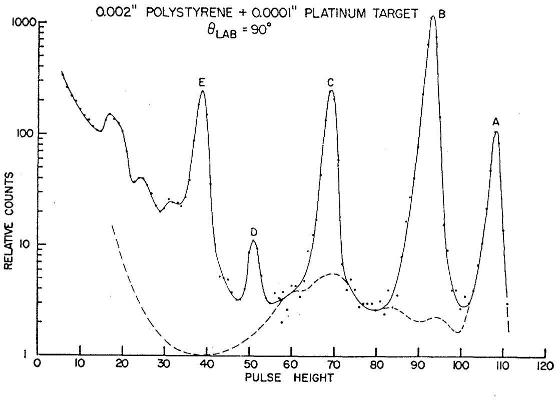

FIG. 2. $C^{12}(p,p')C^{12*}$ reaction at 19 Mev. Detector collimation was 0.73° half-angle, polystyrene and Pt target. The statistics are indicated by the scatter of the points. The inelastic protons from Pt are indicated by the dashed line.

Observations on the $O^{16}(p,p')O^{16*}$ reaction were made using cellulose acetate, PbO_2, and U_3O_8 targets. In the latter cases, the targets were made by drying a slurry of powder and distilled water on 0.1-mil Pt. Some typical runs for U_3O_8 are shown in Fig. 3; the elastic lines have been omitted. The excitation values derived from several such spectra at various angles are summarized in Fig. 4. In addition to the average values, indicated by the dotted lines, the location of the levels with widths less than 500 kev previously found are indicated by short leaders on the energy scales. Group *A* gives an energy excitation of 6.14±0.02 Mev and appears to be mostly the excitation of the 3^- level at 6.14 Mev in O^{16}. The group *B* corresponds to an energy of 7.02±0.02 Mev in O^{16} and appears to be the 6.91 and 7.12-Mev states unresolved. Groups I to IX correspond to levels in O^{16} at 8.87, 9.85, 10.34, 11.08, 11.51, 12.02, 12.53, 13.06, and 13.39 respectively, all ±30 kev. The last group, group IX, may be spurious.

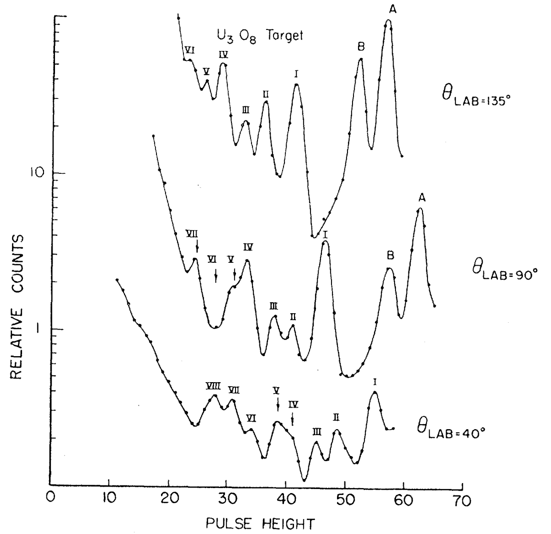

FIG. 3. $O^{16}(p,p')O^{16*}$ reaction at 19 Mev, U_3O_8 target. The three curves have been arbitrarily displaced for clarity. The elastic lines are not shown.

The foregoing excitation energies for C and O involve an assumed correction of +70 kev to the energy of the

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[8] H. Bichsel and R. F. Mozley (to be published).

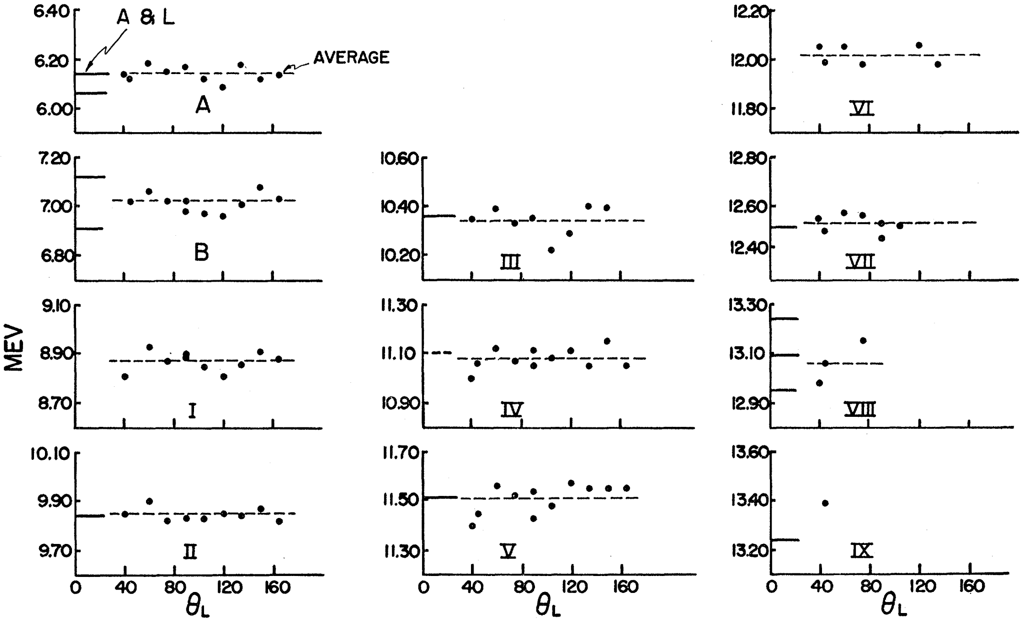

FIG. 4. Summary of excitation energies in O^{16} obtained at various laboratory angles θ_L. The average values are given by the dotted lines, as indicated; the short leaders along the energy scale labeled *A* and *L* (reference 2) locate the level energies previously determined.

incident protons. This correction was made because the uncorrected values for C(4.43 and 9.61) and O(9.84 and 10.36) were consistently high. A correction of this magnitude to the incident energy is within the uncertainty in its determination.

The O^{16} groups were observed at 10 angles between 40° and 160° in the laboratory system. Figure 5 shows the resulting differential cross sections, including elastic scattering. Table I gives the total integrated cross sections.

III. GAMMA RAYS

The γ-ray scintillation spectrum of a cellulose acetate target, observed in a NaI(Tl) crystal 2 in. high and $1\frac{3}{4}$ in. in diameter, is shown in Fig. 6. The 4.43-Mev γ ray from C^{12*} was used as an energy calibration and checked against a Na^{22} source. In addition to the expected 6- and 7-Mev γ rays from O^{16*}, three lines appear at lower energy which can be interpreted as the full energy, one and two escape annihilation peaks of a single γ ray of energy 2.78±0.04 Mev. A check with a polystyrene target showed the γ ray to be in O^{16*}, while a two-crystal pair spectrometer spectrum showed the above interpretation of the peaks to be correct.

IV. PROTON-GAMMA RAY COINCIDENCES

Experiments to study p-γ coincidences between the various inelastic proton groups and possible subsequent γ radiation were made with a 30-mμsec resolving time coincidence apparatus. The scintillation detectors were NaI(Tl), used as previously to obtain pulse-height information.

The Princeton FM cyclotron has an effective duty cycle of 2 to 3% with, however, a superimposed fine structure of 10^{-8} sec repeated every 5×10^{-8} sec due to the beam bunching on acceleration. The existence of this fine structure was successfully demonstrated with the coincidence circuit used (with the resolving time reduced to 15 mμsec).

The combination of a comparatively poor duty cycle, the slow scintillation phosphor decay time, and the desire to obtain constant coincidence efficiency over a substantial range of pulse heights required the design of a special coincidence circuit. The basic circuit arrangement follows that outlined by Bell, Graham, and Petch.[9] The main coincidence tubes, however, were *EFP* 60 secondary emission types operated as trigger tubes, continuously passing an anode current of 15 ma in the quiescent state to achieve high sensitivity.[10] The

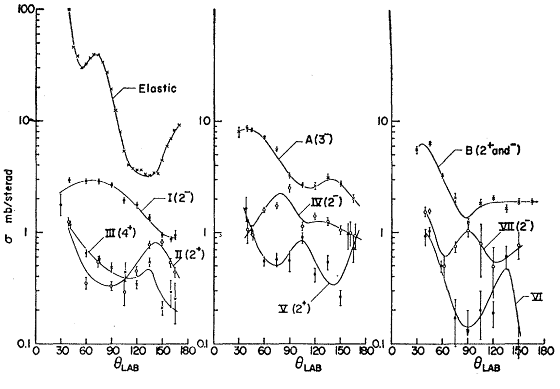

FIG. 5. Differential cross sections as a function of laboratory angle for $O^{16}(p,p')$ at 19 Mev. The spin and parity of the levels in O^{16} are given in parentheses where known. The smooth curves are drawn primarily to connect points; the estimated probable errors are shown.

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[9] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

[10] Moody, McLusky, and Deighton, Electronic Eng. **24**, 214 (1952). Also I. A. D. Lewis and F. H. Wells, *Millimicrosecond Pulse Techniques* (Pergamon Press, London, 1954).

TABLE I. Total integrated cross sections: $O^{16}(p,p')$ at 19 Mev.

Group	E_L(Mev)	σ_T(mb)
A	6.14	59 ±7
B	7.02	34 ±4
I	8.87	28 ±3
II	9.85	8 ±2
III	10.34	8 ±2
IV	11.08	19 ±3
V	11.51	11 ±2
VI	12.02	6 ±2
VII	12.53	11 ±2
VIII	13.06	~10
IX	13.39	

trigger sensitivity obtained was approximately 0.1 volt with a triggered anode current pulse of 0.3 amp having a 5-mμsec rise time. The terminated *RG* 114 *U* shorted-line pulse shaper thus presented 30-volt singles pulses to the coincidence diode rather than the usual fraction of a volt.

Because of the fine structure of the cyclotron beam, a reduction of the coincidence resolving time below 30 to 50 mμsec does not reduce the accidental coincidence rate significantly, unless the resolving time is made short compared to 10 mμsec. A resolving time of 30 mμsec gave substantially constant coincidence efficiency over a range of a factor of 5 in pulse height on either input, with no readjustment of the length of the signal cables, when the photomultiplier tubes gave average pulses of 30 volts. By way of calibration and control for the carbon present in the cellulose acetate targets used to study the $O^{16}(p,p')O^{16*}(\gamma)$ reaction, the coincidence spectrum was run on $C^{12}(p,p')C^{12*}(\gamma)$ with a polystrene target. The proton detector was at 150° and the γ-ray detector at 90°, relative to the incident beam direction. Accepting all γ scintillation events of more than 1 Mev gave the coincidence proton spectrum shown in Fig. 7.

Only the proton group leading to the first excited state in C^{12} at 4.43 Mev shows conspicuous *p*-γ coincidences. The accidental rate was determined from the number of coincidence events falling in the *elastic* line. It should be noted that cable length displacement methods usually used for determining the accidental rate could not be used here because of the beam fine structure and its possible modulation envelope.

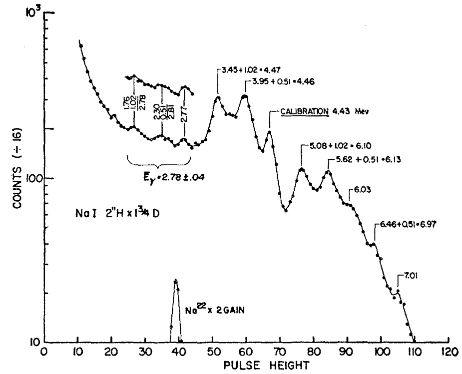

FIG. 6. The γ-ray spectrum in a NaI(Tl) crystal 2 in. high and 1¾ in. in diameter, using a cellulose acetate target and 19-Mev protons. The γ rays are from C^{12*} and O^{16*}.

A similar run with a cellulose acetate target gave the coincidence proton spectrum shown in Fig. 8. In addition to the groups corresponding to the C^{12} 4.43-Mev and the O^{16} 6- and 7-Mev states, conspicuous *p*-γ coincidences appear for groups I, IV, and VII in O^{16}.

The γ-ray spectra corresponding to these proton groups was investigated with the results shown in Fig. 9. The 20-channel discriminator recorded the coincident gamma-ray spectrum when gated by a single channel discriminator used to select different groups of protons. When the inelastic proton groups leading to the 4.43-Mev state in C^{12} and the 7-Mev states in O^{16} were used as gate signals, the γ spectra appeared as expected to consist of single 4.4- and 7.0-Mev lines, within the resolution of the apparatus (Fig. 9). For counting rate reasons the resolution was unavoidably set low so as to encompass as much of the γ-ray spectrum as possible with the available 20 channels.

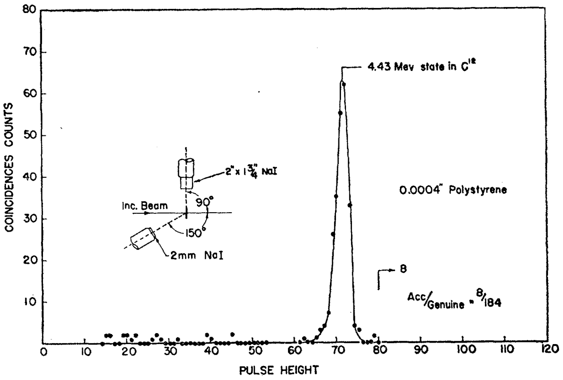

FIG. 7. The coincidence spectrum of protons from $C^{12}(p,p')C^{12*}$-$(\gamma)C^{12}$, using a polystyrene target and accepting all γ-scintillation events ≥1 Mev.

The γ-ray spectra accompanying the proton groups I and IV are seen to be complex and to consist of energies below about 7 Mev. The group VII protons have coincidence γ rays of energy approximately that of the 4.43-Mev γ ray from C^{12*}.

V. DISCUSSION OF RESULTS

The highest energy inelastic group observed for O^{16} (group *A* of Figs. 3 and 4 and Table I) yields an excitation energy of 6.14±0.02 Mev averaged over all scattering angles and suggests that the excitation of the 0^+ level at 6.06 Mev is no more than 10% as probable as the excitation of the 3^- level at 6.14 Mev. On the other hand group *B* corresponds to a level energy of 7.02±0.02 Mev and is presumably an unresolved mixture of the 2^+ level at 6.91 Mev and the 1^- level at 7.12 Mev with approximately equal intensities.

Groups II, III, V, and VII correspond to level energies that are within 20 kev of those previously

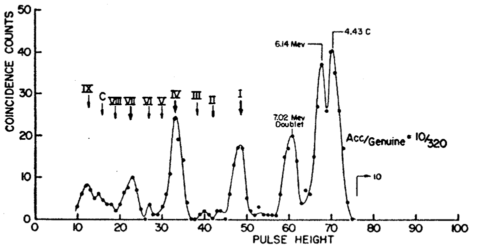

FIG. 8. The coincidence spectrum of protons from a 0.01-inch cellulose acetate target, accepting all γ-scintillation events $\geqslant 1$ Mev. The arrows indicate the proper location of the various O^{16} inelastic groups leading to level excitations greater than 7 Mev. Only groups I, IV, and VII show prominent p-γ coincidences.

reported in the literature.[2] Within this energy range all but two of the reported narrow levels (which would appear as groups with well defined energies in a scintillation spectrum) have been seen in this experiment. The exceptions are the levels at 6.06 and 12.43 Mev. These could, of course, not be resolved from their close neighbors, but the observed energies suggest that they are at best only weakly excited. Except for group VII none of these groups gave conspicuous p-γ coincidences. The γ-ray spectrum associated with group VII is consistent with the assumption that this γ ray is the 4.43-Mev γ-ray from C^{12*}, and would thus agree with the observation in the $N^{15}(p,\alpha)$ reaction involving the same level in O^{16} that the α-particle emission goes mostly to the first excited state in C^{12}. Groups IV, VI, and the possibly spurious group IX, do not correspond to previously reported levels.[2] The elastic protons of group I were previously observed in this laboratory by Fulbright and Bush[11] who placed the corresponding level at 8.6±0.4 Mev. Toppel, *et al.*[12] have recently reported γ rays in the reaction $F^{19}(p,\alpha)O^{16}$ which they attribute to a level in O^{16} at 8.87 Mev.

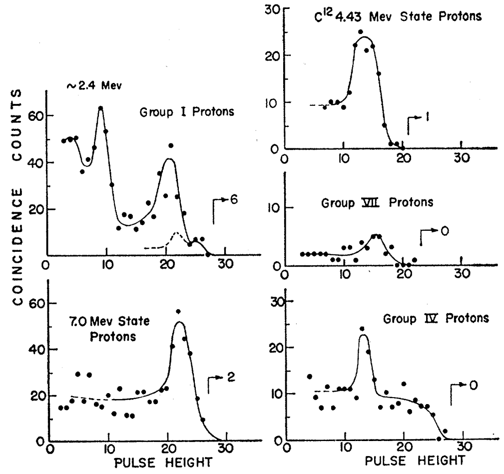

FIG. 9. The coincidence spectrum of γ rays, gated by the various proton groups showing strong p-γ coincidences in Fig. 8.

Group I gives a level excitation of 8.87±0.03 Mev and shows conspicuous p-γ coincidences. The coincidence γ ray spectrum (Fig. 9) shows γ rays of approximately 2.4- and 6-Mev energy and a less intense 7-Mev γ-ray (intensity $\approx 20\%$). The lack of any higher energy gamma-ray indicates the absence of any direct transition to the ground state. The γ-ray de-excitation of the 8.87-Mev level is therefore about 80% cascade through the 3^- level at 6.14 Mev and 20% cascade through either or both levels at 7 Mev. The 2.78-Mev γ ray observed in the spectrum of Fig. 6 is in all likelihood the cascade γ ray to the 3^- state.

The strength of the p-γ coincidences for group I is comparable to the strength of the p-γ coincidences for the pure γ-emitting states at 4.43 Mev in C^{12} and at 6 and 7 Mev in O^{16}, thus suggesting of the order of one γ-ray cascade per inelastic proton. If the level at 8.87 Mev is to decay by α-particle emission to C^{12} as well as by the observed γ-ray cascading, the α-particle partial width can be no more than approximately equal to the γ-ray partial width. In addition the spin and parity would have to be 1^-, 2^+, 3^-, 4^+, 5^-, etc. In the most favorable case of 3^-, the γ ray to the 3^- level at 6.1 Mev would be $M1$ with a width $\Gamma_\gamma \approx 0.1$ ev, giving a reduced α-particle width of 0.01% of the Wigner sum rule limit. The other spin assignments all involve considerably narrower γ-ray widths with only a comparatively slight gain from the barrier penetration factor for the 4^+ and high spin states, thus leading to even lower reduced widths. While a reduced width of 0.01% of the sum rule limit is not impossible, it is rather improbable.

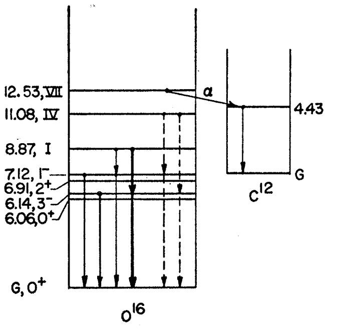

FIG. 10. The decay scheme for the levels in O^{16} giving strong p-γ coincidences in inelastic excitation. (The 6.91 and 7.12 Mev levels are unresolved in the present experiment).

Of the pure γ-ray emitting assignments 1^+, 2^-, 3^+, 4^-, etc., the 2^- assignment is most consistent with the observed γ-ray cascade branching ratios, with 3^+ not entirely ruled out. Thus, from this experiment, the most probable spin and parity assignment for the 8.87 Mev level is 2^-, although this assignment is not unique leaving $3^\pm$ as remote but possible assignments.

Group IV leads to a level energy of 11.08 Mev, and shows strong p-γ coincidences involving the 6- and 7-Mev states in a cascade decay sequence. Although Bittner and Moffat report a possible resonance in $C^{12}(\alpha,\alpha)$ scattering giving 11.10 Mev as the O^{16} level energy with a width of 10 kev, the present level is unrelated to it; a 10 kev width would lead to a p-γ coin-

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[11] H. Fulbright and R. Bush, Phys. Rev. **74**, 1323 (1948).

[12] Toppel, Wilkinson, and Alburger, Phys. Rev. **99**, 632(A) (1955).

cidence rate about 10^4 times smaller than the observed rate. Among the pure γ-ray emitting level assignments again 2^- is most consistent with the observed results, although 3^+ cannot be ruled out.

In summary, the decay schemes for the levels fed by the inelastic proton groups giving strong p-γ coincidences are indicated in Fig. 10.

There is some indication that the comparatively weak group VI leading to a level in O^{16} at 12.02±0.03 Mev, is probably accompanied by γ-ray emission (refer to Fig. 8 and refer to Fig. 5 for the relative yield at $\theta_{\text{lab}}=150°$, the angle of observation in the coincidence runs).

VI. CONCLUSION

Three levels in O^{16} which have not been observed in the α-C^{12} scattering experiments appear in the inelastic scattering of 19-Mev protons by O^{16}. The levels at 8.87- and 11.08-Mev decay by γ emission; the characteristics of the decay suggest that these levels are 2^- states. The decay of the level at 12.02 Mev is probably accompanied by γ emission.

The present investigation was undertaken in order to locate the negative-parity members of the $2^\pm$ doublets predicted by the α-particle model of Dennison.[3] The energy splitting is expected to be small with the 2^- level shifted, if at all, to higher energies.[3,13] Under scheme (a) of Dennison[3] we might have expected to find γ-emitting levels close to 9.83, 11.51 and 12.95 Mev; while under scheme (b) the 2^- members are at 6.9, 9.83, 11.51 and 12.51 Mev. With the obvious exception of the 6.9-Mev level, there is no correspondence in either case with our observed γ-emitting states. Thus the present results do not lend support to this α-particle model. It should be noted that this model does not predict isolated 2^- states. If our present assignments to the levels at 8.87 and 11.08 Mev are correct and further measurements do not uncover 2^+ states close to these (there is the uncertain level at 11.10 Mev[1]), one must view these levels from the standpoint of other nuclear models (see reference 13).

The authors wish to express their thanks to S. Berko of the University of Virginia for his assistance in the development of the coincidence circuit used in this experiment, to G. Likely and G. Schrank for the use of some of their experimental equipment and to W. Stone for his able assistance. This research was stimulated by conversations with H. T. Richards and W. A. Fowler on the level structure of O^{16}.

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[13] D. R. Inglis, Revs. Modern Phys. 25, 390 (1953).

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Radiation Widths in Slow Neutron Resonances*

H. H. Landon†
Brookhaven National Laboratory, Upton, New York

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A summary of current measurements of total radiation widths as observed in slow neutron resonance capture is presented together with the most recent data for a number of resonances in iridium, lutetium, and tungsten.

The general features of the dependence of radiation width upon atomic weight is discussed in terms of a model proposed by Blatt and Weisskopf.

INTRODUCTION

It is possible to study the virtual excited states of heavy nuclei near the neutron binding energy by means of the measurements of total and scattering neutron resonance cross sections. For slow neutrons the predominate mode of decay of these virtual states is by gamma-ray emission. Analysis of the cross sections for the Breit-Wigner resonance parameters yields directly a measure of the radiation width or lifetime of the excited states for de-excitation by gamma emission, a parameter which depends sensitively on the wavefunctions of these states. Because of this dependence, significant information regarding nuclear wave functions should be obtained from a comparison of experimental gamma-decay transition probabilities with theoretical values calculated on the basis of specific models of the nucleus.

The development and success of the nuclear shell model led Weisskopf[1] to estimate the matrix elements for electric and magnetic multipole transitions of a single nucleon which moves independently within the nucleus. Goldhaber and Sunyar[2] have examined the isomeric transitions for low-lying states in medium and heavy nuclides in terms of these estimates. In light nuclei Wilkinson[3] has made comparison with these estimates for highly excited states. They have found that

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* Research performed under contract with U. S. Atomic Energy Commission.

† Present address: Centre D'Étude Nucléaires de Saclay, France.

[1] V. F. Weisskopf, Phys. Rev. 83, 1073 (1951).

[2] M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 906 (1951).

[3] D. H. Wilkinson, Phil. Mag. 44, 450 (1953).