qualitative experimental agreement is obtained with the level order predicted by the central force for the states of the $(h_{9/2}g_{9/2})$ configuration.

VII. ACKNOWLEDGMENTS

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Note added in proof.—Recently Blomqvist and Wahlborn, Arkiv Fysik (in print), have calculated energy levels in the lead region using a diffuse potential of the Woods-Saxon type. They obtain the same single-particle level order as is suggested in the present work.

It has been suggested by Golenetskii et al., Z. Eksp. Teor. Fiz. S.S.S.R. **37**, 560 (1959), that no α-decaying state exists close to the ground state. Instead, a 9− state at about 0.22 Mev excitation is proposed, in good agreement with the present suggestion of a 9− state at about 0.28 Mev.

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Total Gamma Absorption in C^{12}, N^{14}, O^{16}, and Al^{27} at 20 Mev*

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Total gamma absorption cross sections were measured of C^{12} from 20.0 to 21.2 Mev, and of N^{14}, O^{16}, and Al^{27} from 20.0 to 20.5 Mev using monochromatic gamma rays. A direct absorption technique was used, utilizing $T^3(p,\gamma)He^4$ photons, varied in energy by changing the energy of the incident protons. The C^{12} cross section showed structure with possible resonances at 20.15 Mev, 20.46 Mev, and 20.92 Mev, with integrated cross sections of 1.1, 1.0, and 6.6 Mev millibarns, respectively. O^{16} showed a sharply rising cross section suggesting a strong resonance above about 20.3 Mev. The cross sections of N^{14} and Al^{27} were smooth over the energy interval investigated.

INTRODUCTION

ONE of the most striking features of photonuclear reactions is the "giant-resonance" region of photon absorption. This resonance is ascribed principally to electric-dipole absorption. Experiments in this energy region have usually measured the various partial cross sections, principally the (γ,p) and the (γ,n) reactions, using heterogeneous bremmstrahlung photons. Several of these experiments have indicated fine structure in the "giant resonance" absorption by light elements.[1] Attempts to investigate such structure[2] using monochromatic gamma rays have not been generally successful. The present experiment is a further attempt to measure the detailed total photon absorption in the giant resonance region using monochromatic gamma rays.

EXPERIMENT

Figure 1 shows a simplified schematic diagram of target, absorbers, detectors, and associated electronic circuitry. An electrostatic accelerator provided protons

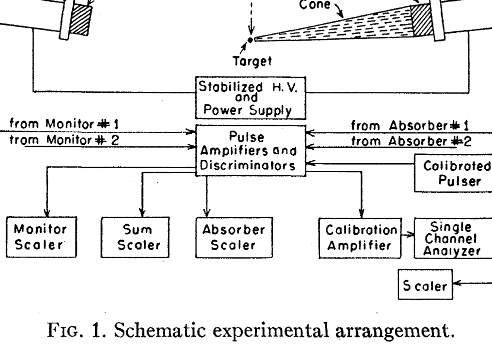

FIG. 1. Schematic experimental arrangement.

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† Now with the Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania.

1 L. Katz, R. N. H. Haslam, A. G. W. Cameron, and R. Montalbetti, Phys. Rev. **95**, 464 (1954); A. S. Penfold, and B. M. Spicer, Phys. Rev. **100**, 1377 (1955); L. Katz, Conference on Photonuclear Reactions, National Bureau of Standards, 1958 (unpublished); F. K. Goward and J. J. Wilkins, Proc. Roy. Soc. (London) **A217**, 357 (1953); L. Cohen, A. K. Mann, B. J. Patton, K. Reibel, W. E. Stephens, and E. J. Winhold, Phys. Rev. **104**, 108 (1956); S. A. E. Johansson and B. Forkman, Arkiv Fysik **12**, 359 (1957).

2 D. St. P. Bunbury, Proc. Phys. Soc. (London) **A67**, 1106 (1954); J. G. Campbell, Australian J. Phys. **8**, 449 (1955); D. C. Foster, doctoral thesis, Cornell University, 1956 (unpublished); M. M. Wolff and W. E. Stephens, Phys. Rev. **112**, 890 (1958); L. D. Cohen and W. E. Stephens, Phys. Rev. Letters **2**, 263 (1959); T. Nakamura, K. Fukunaga, T. Takamatsu, M. Yata, and S. Yasumi, J. Phys. Soc. Japan **14**, 1117 (1959).

of energies from 340 kev to about 2 Mev, at currents of up to 50 microamperes. The protons were incident on a thin target of tritium gas adsorbed in a thin layer of zirconium deposited on a water-cooled platinum disk. Four NaI(Tl) crystals were placed symmetrically around the target, about 63 cm distant, and at an angle of $97\frac{1}{2}$ degrees to the proton beam. Conical absorbers about two feet in length were suspended by wires between the target and two of the crystals, while the other two crystals served to monitor the photon intensity.

The detected gamma-ray pulses were amplified and fed through a discriminator window which selected those pulses whose height fell between 12 and 21.5 Mev. Gains of the photomultipliers and amplifier were maintained constant to within $\pm 0.2\%$ by measuring the steeply rising leading edge of the 1.28-Mev gamma radiation from a Na^{22} source for each counter between each 20 minute run.

The thickness of the target for 1.1-Mev protons was determined by measuring the $T(p,n)He^3$ neutron yield in the forward direction with a "long counter" as the proton energy was varied through the neutron threshold. The observed yield was compared with curves obtained by numerical integration of the thin target results of Jarvis et al.[3] for various assumed target thicknesses. The thickness so determined was 58 ± 8 kev. The variation of target thickness with proton energy was obtained from Madsen's curves[4] by interpolation.

The energy of the gamma ray was determined from the proton energy using the good approximation:

$$h\nu=\left[Q+E_p\left(1-\frac{M_p}{M_\alpha}\right)\right]\times\left[1+\frac{M_p}{M_\alpha}\left(\frac{2E_p}{M_pc^2}\right)^{\frac{1}{2}}\cos\theta\right]\left[1-\frac{Q}{8M_pc^2}\right],$$

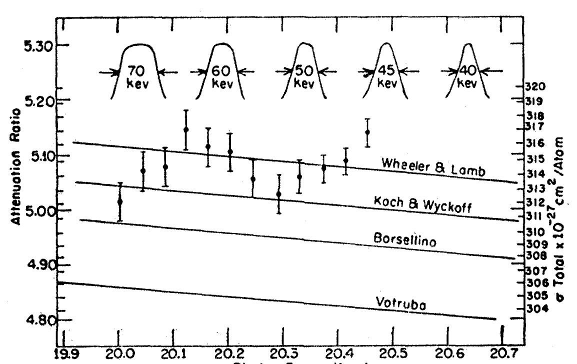

FIG. 2. Total absorption in C^{12}. The points indicate the experimental results. The lines show the total atomic cross sections calculated as described in the text using the indicated triplet calculations. The curve marked Koch and Wyckoff includes a 2.25% addition to the pair production and the Borsellino triplet cross section.

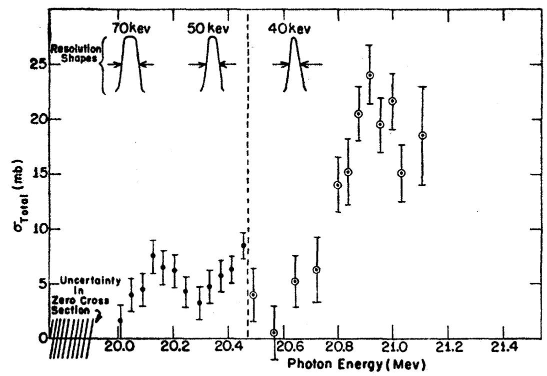

FIG. 3. Total nuclear absorption in carbon-12. The cross section in millibarns is plotted as a function of photon energy.

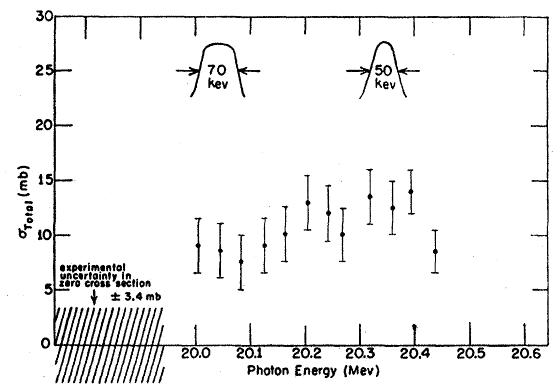

FIG. 4. Total nuclear absorption in nitrogen-14.

where E_p is proton energy in Mev, θ is laboratory angle from the proton beam, and the Q value is 19.812 ± 0.011 Mev. The crystals subtended an angle of 0.12 radians at the target, introducing a Doppler spread in photon energy of 43 ± 6 kev at 20.52 Mev. The resolution of the apparatus was determined from the target thickness, Doppler energy spread, and the accelerator energy wander of ± 2.3 kev, to yield a trapezoidal line shape as indicated on Figs. 2, 3, 4, and 5.

The carbon and aluminum absorbers were in the form of machined, truncated cones, two feet and one foot long, respectively. The absorbers used for N^{14} and O^{16} were hydrazine (93% N_2H_4, 7% H_2O) and distilled water, respectively; both liquids were held in truncated pyramidal Plexiglas boxes with $\frac{1}{16}$-inch thick walls, and two feet in length.

CORRECTIONS

Corrections were made to the data to account for (1) air absorption, (2) absorption in the Plexiglas when using liquids and (3) cosmic-ray backgrounds ($\sim 10\%$ of total counts). Corrections necessitated by the "bad" geometry were calculated to account for (1) unscattered Compton photons, (2) Compton electrons formed in the end of the absorbers which entered the crystals to cause spurious counts, and (3) electrons and positrons

[3] G. A. Jarvis et al., Phys. Rev. **79**, 932 (1950).
[4] C. B. Madsen, Kgl. Danske. Videnskab Selskab, Mat.-fys. Medd. **27**, No. 13 (1953).

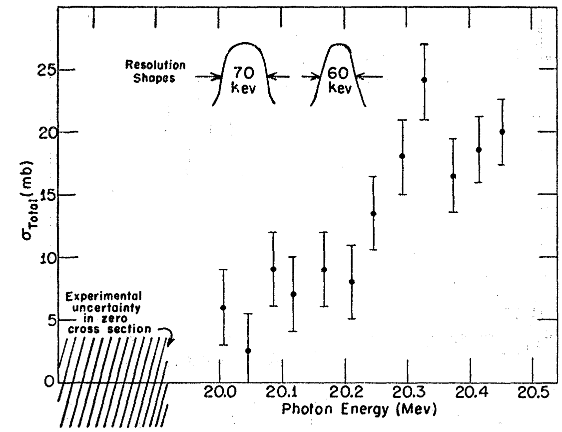

FIG. 5. Total nuclear absorption in oxygen-16.

formed in the pair-production and triplet processes which entered the crystals from the absorber ends also to cause spurious counts. The higher energy data on carbon were taken above the $T^3(p,n)He^3$ threshold, and additional corrections were necessitated by the pileup of 7-Mev gamma pulses from neutron capture in the I^{127} of the crystals. The "bad" geometry corrections varied from 2.5% for the aluminum absorber to 7.0% for the water. After these corrections had been applied to the measured ratios of monitor to detector counts, the total absorption cross sections were deduced. Table I shows the estimated uncertainties to be associated with the measured cross sections. Within these uncertainties, there is reasonable agreement between these results and the total absorption measurements of Ziegler, Kockum, and Starfelt.[5]

ATOMIC CROSS SECTIONS

Calculated atomic cross sections were subtracted from the corrected experimental data to yield the total

TABLE I. Table of estimated uncertainties to the measured cross sections.

Absorber	Carbon (20.1–20.5 Mev)	Carbon (20.5–21.2 Mev)	N_2H_4	H_2O	Al
Statistics of attenuation ratio	0.40%	0.91%	0.54%	0.52%	0.55%
Statistics of zero ratio	0.21%	0.25%	0.37%	0.31%	0.22%
Density	0.15%	0.15%	0.15%	0.15%	0.15%
Impurities	0.1%	0.1%	0.5%	···	···
Corrections made	0.54%	0.4%	0.56%	0.6%	0.3%
Neutron pile-up	···	0.1%	···	···	···
Totals					
Relative uncertainty between points	0.4%	0.95%	0.54%	0.52%	0.55%
Absolute uncertainty for *each* point	0.7%	1.1%	1.0%	0.9%	0.7%

[5] B. Ziegler, Z. Physik **152**, 566 (1958); J. Kockum and N. Starfelt, Nuclear Instr. and Meth. **5**, 37 (1959).

nuclear absorption. The atomic cross sections were calculated at 20 Mev as follows: (1) the Compton scattering cross section was taken from the Klein-Nishina formula for free electrons as tabulated by White.[6] (2) The pair-production cross sections were calculated using the Bethe-Heitler unscreened formula[7] and subtracting (a) the screening corrections calculated with Hartree-Fock form factors,[8] and (b) Coulomb corrections.[9] (3) The triplet cross sections of Borsellino[10] were used. The cross sections so calculated are shown in Table II.

The triplet cross sections of Wheeler and Lamb[11] and Votruba[12] seemed too high and too low, respectively, for a reasonable interpretation of this experiment in light of the known average nuclear cross sections in this energy region. The 2.25% increase in pair production cross sections used by Koch and Wyckoff[8] seems unnecessary at this energy. This is shown graphically in Fig. 2 for carbon as representative of the results. The points are the observed values of total cross section while the

TABLE II. Table of atomic cross sections (in millibarns) at 20 Mev.

	Hydrogen	Carbon	Nitrogen	Oxygen	Aluminum	Water	Hydrazine
Compton	30.2	181.4	212.0	242.0	393.0	302.2	544.8
Pair prod.	3.2	115.5	156.97	205.1	536.8	211.62	326.98
Koch's pair prod.	3.2	118.1	···	209.7	548.9	216.1	···
Triplet							
Borsellino	2.3	14.0	16.0	18.0	30.0	22.6	41.2
Votruba	1.5	9.2	11	12	20	15	28
Wheeler and Lamb	3.1	19.5	22.8	26	42.2	32.1	58.0
Totals							
Koch	35.7	313.5	···	469.7	971.9	540.9	···
Borsellino	35.76	310.9	384.97	465.1	959.8	536.42	912.98
Votruba	34.96	306.1	379.97	459.1	949.8	528.82	899.78
Wheeler and Lamb	36.56	316.4	391.77	473.1	972.0	545.92	929.78

lines are the total atomic cross sections calculated as described.

RESULTS

The experimental data, after subtraction of the atomic cross sections, are shown in Figs. 3, 4, 5, and 6. The uncertainties shown for each point are only the relative statistical uncertainties. The root mean square value of all other uncertainties applies equally to all points in each set, and is indicated as an uncertainty in the zero cross section.

[6] G. White, National Bureau of Standards Report No. 1003, 1952 (unpublished).

[7] *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley & Sons, Inc., New York, 1953), Vol. 1, first ed.

[8] H. W. Koch and J. M. Wyckoff, National Bureau of Standards Report No. 6313 (U. S. Government Printing Office, 1959).

[9] H. Davies, H. A. Bethe, and L. C. Maximon, Phys. Rev. **93**, 788 (1954).

[10] A. Borsellino, Helv. Phys. Acta. **20**, 136 (1947); Nuovo cimento **4**, 1112 (1947).

[11] J. A. Wheeler and W. E. Lamb, Jr., Phys. Rev. **55**, 858 (1939).

[12] V. Votruba, Phys. Rev. **73**, 1468 (1948).

The measurements on carbon were made in two parts, divided at the $T^3(p,n)He^3$ threshold. The pileup of $I^{127}(n,\gamma)I^{128}$ pulses in the crystals necessitated lower counting rates and higher discriminator settings in the upper-energy region. Due to a different zero-reading there is a relative uncertainty between the two sets of data of ± 1.3 millibarns in addition to that shown in Fig. 3.

Carbon

The total nuclear absorption cross section for carbon shows possible structure. One resonance seems resolved at 20.15 Mev, with a peak cross section of 6.5 ± 2 millibarns, and width at half-height of 165 ± 30 kev. The integrated cross section is 1.1 ± 0.6 Mev-mb.

At 20.46 Mev, straddling the two sets of data, there seems to be another resonance. If it exists, the height is 7 ± 3 millibarns, and width at half-height is 145 ± 30 kev. Note that if the two sets of data are moved relative to one another as far as the statistical uncertainties permit, the shape of the cross-section curve in the vicinity of 20.53 Mev still indicates a partially resolved resonance. The integrated cross section is 1.0 ± 0.75 Mev-mb.

A stronger resonance is observed rising steeply to a peak of 22 millibarns at 20.92 ± 0.025 Mev. The measurements do not extend high enough in energy to determine the width, but it appears to be from 225 to 350 kev wide. Assuming a width of 300 kev, this gives an integrated cross section of about 6.6 ± 1.2 Mev-mb. The sum of the three resonances yields the total integrated cross section from 20.00 to 21.20 Mev as 8.7 ± 2.6 Mev-mb.

Nitrogen

The nitrogen results are shown in Fig. 4. There is no resolved structure, and the best straight line through the data has a small positive slope of 6 millibarns/Mev. The average total cross section over the energy range measured is 10.5 ± 4 millibarns.

Oxygen

The total cross section for O^{16} is shown in Fig. 5. The cross section is smooth and steeply rising, with some suggestion of peaking at or above 20.33 Mev. The peak cross section attained is 22.5 ± 4 mb, while the average cross section is 13.5 ± 4 mb. The size of the peak cross section measured indicates that a decrease must take place at slightly higher energies in order to maintain a reasonable integrated cross section. The position of this steeply rising cross section is apparently associated with the (γ,p) peak observed in this region.[13]

[13] L. Cohen, A. K. Mann, B. J. Patton, K. Reibel, W. E. Stephens and E. J. Winhold, Phys. Rev. **104**, 108 (1956); S. A. E. Johansson and B. Forkman, Arkiv. Fysik **12**, 359 (1957); D. L. Livesey, Can. J. Phys. **34**, 1022 (1956).

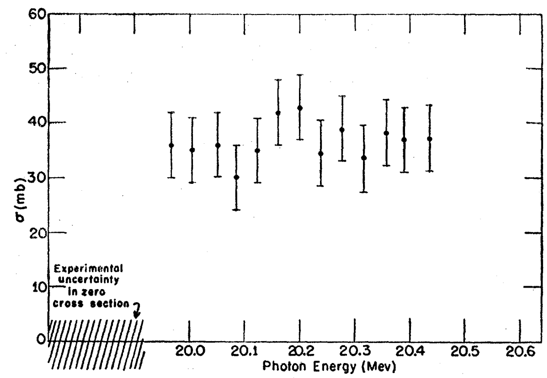

FIG. 6. Total nuclear absorption in aluminum-27.

Aluminum

The total cross section for Al^{27} is shown in Fig. 6. All the points are consistent with a smooth, slowly rising line and an average cross section of 37 ± 4.5 mb.

DISCUSSION

The sensitivity ($\sim 0.5\%$ relative uncertainty between points) and resolution (40 to 70 kev) of this experiment enable structure to be resolved in the total nuclear absorption cross section of C^{12}. The resolved resonances, presumable 1^- levels in C^{12}, have widths of several hundred kev, of the same order as the level spacing. Strong indications are present of structure in the O^{16} cross-section curve. The results for N^{14} and Al^{27} showed smooth behavior over the energy range measured.

Reasonable agreement exists between the levels as deduced from the results of this experiment and some energy levels in this energy region indicated by other recently tabulated[14] evidence. Levels are listed in C^{12} at 20.27,[15] 20.49,[16] and 20.65 [16] Mev with widths of 180 kev. A $C^{12}(\gamma,p)B^{11}$ experiment[17] shows a level at about 20.8 Mev with a width of about 300 kev. Recent $C^{12}(\gamma,n)C^{11}$ experiments at this laboratory[18] show levels at 20.25, and ~ 20.9 Mev, of widths of about 100 kev. Other $C^{12}(\gamma,n)C^{11}$ work[19] has reported abrupt changes of slope in the neutron yield curve at 20.13, 20.29, 20.62, 20.90, and 21.08 Mev.

In the case of O^{16}, the (γ,n) studies[20] show energy levels at 20.33, 20.58, 20.79, and 20.93 Mev (all ± 0.2 Mev), of widths <60 kev. The $O^{16}(\gamma,p)N^{15}$ experiments[13] show a level at about 20.6 Mev.

Using the Breit-Wigner formula as derived by

[14] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[15] Not seen in $B^{11}(p,\gamma_0)C^{12}$.
[16] Nonresonant for $B^{11}(p,\gamma_0)C^{12}$.
[17] L. Cohen, A. K. Mann, B. J. Patton, K. Reibel, W. E. Stephens, and E. J. Winhold, Phys. Rev. **104**, 108 (1956).
[18] K. Geller, E. Muirhead, and J. Halpern (private communication).
[19] L. Katz, Conference on Photonuclear Reactions, National Bureau of Standards, 1958 (unpublished).
[20] A. S. Penfold and B. M. Spicer, Phys. Rev. **100**, 1377 (1955).

Peaslee,[21] the gamma-ray widths of the resonances indicated in the carbon absorption curve can be determined. The peak cross section for total gamma-ray nuclear absorption is (neglecting branching)

$$_{\text{total}}\sigma_{\text{peak}}=4\pi\lambda\!\!\!^{-2}S_0\Gamma_\gamma/\Gamma,$$

where $\lambda\!\!\!^{-}=\hbar c/E_\gamma$ is the gamma-ray wave length, $S_0=(2J+1)/2(2I+1)$, I is the initial spin, and J the final spin. Thus $\Gamma_\gamma=\Gamma_t\sigma_p/4\pi\lambda\!\!\!^{-2}S_0$ can be determined from the observed width and peak cross sections of Fig. 3. The gamma-ray widths are then 70 ± 10, 70 ± 10, and 450 ± 70 ev for the 20.15, 20.46, and 20.92-Mev levels, respectively. These are smaller than the single particle Weisskopf widths for $E1$ transitions,[22]

$$\Gamma_{\gamma w}=0.11A^{\frac{2}{3}}E_\gamma^{3}\text{ ev},$$

which gives 4700, 4900, and 5300 ev for these levels, but not surprisingly smaller considering the possible number of such states which may make up the giant resonance.

The oxygen peak at 20.6 Mev is not completely determined, but the peak cross section and width can be estimated as about 20 mb and 450 kev. This suggests a gamma-ray width of 500 ± 100 ev compared to a Weisskopf width of 6000 ev.

In those cases where resonances are not resolved, and if the observed cross section may be considered to be made up of isolated resonances, the average photon absorption cross section may be expressed as

$$_{\text{total}}\bar{\sigma}=2\pi^2\lambda\!\!\!^{-2}S_0\Gamma_\gamma/D,$$

where D is the level spacing. Mutual interference of levels, or the presence of a continuum contribution, or very wide levels would of course complicate the averaging. However, neglecting such complications,

$$\Gamma_\gamma/D={}_t\bar{\sigma}/2\pi^2\lambda\!\!\!^{-2}S_0=3.6\times10^{-4},\ 1.3\times10^{-3},$$

for N^{14} and Al^{27}, respectively. These values are consistent with the values deduced from the observed spacing in carbon and the calculated gamma-ray widths. Peaslee[21] finds such values for this ratio in these light elements to indicate a high degree of coherence in the motion of the many particle compound state. Thus our results are consistent with an appreciable contribution of the "Goldhaber-Teller"[23] concept to the absorption of photons in these elements.

On the other hand, Wilkinson[22] estimates the radiation width from shell model theory to be a fraction $0.05D$ to $0.5D$ of the Weisskopf unit. Since D here is observed to be about 0.3 Mev we should then expect radiation widths of less than 0.15 to 0.015 of the Weisskopf unit. We observe 0.1 to 0.01 in agreement.

If we apply our observed values of $\Gamma_\gamma/D\sim10^{-3}$ to the formula 7.21 in Blatt and Weisskopf[24] for electric dipole radiation,

$$\frac{\bar{\Gamma}_{E1}}{D_1}\sim\frac{3}{4}\frac{e^2}{\hbar c}\frac{\hbar\omega}{D_0}\left(\frac{\omega R}{c}\right)^2,$$

we can determine the "single particle level spacing" D_0 to be about 7 Mev in contrast to the large values reported from neutron capture work[25] but consistent with the value deduced from elastic scattering of fluorine gamma rays.[26] Although the approximations involved in these calculations are very crude, they serve to remove some irrelevant factors and to allow comparisons with other work.

ACKNOWLEDGMENTS

We wish to thank Professor Ralph Amado and Dr. W. Koch for discussions of these matters.

[21] D. C. Peaslee, Phys. Rev. **88**, 812 (1952).
[22] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956).
[23] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).
[24] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 648.
[25] J. S. Levin and D. J. Hughes, Phys. Rev. **101**, 1328 (1956).
[26] K. Reibel and A. K. Mann (private communication).