III. The moments are in the (111) sheets and directed towards one of the three nearest neighbors in the sheet.

Crystal structure factors have been calculated for these various cases using the magnetic scattering amplitude for Fe^{+++} given by Eq. (6) with $S=5/2$, there being 5 electrons in the $3d$-shell which contribute to the magnetic moment just as in the Mn^{++} ion. Table III summarizes these calculations for the (111) and (100) magnetic reflections for comparison with the observed values. All the values are given as differential scattering cross sections per Fe_2O_3 molecule, and both calculated and observed values are on an absolute scale. It is seen that the room temperature data suggest Model (a) with orientation III as being correct, while at low temperatures the suggested structure is that of Model (a) with orientation II. Thus, the low temperature data could be accounted for as simply a reorientation of the magnetic alignment from within the (111) sheets to one perpendicular to these sheets when the temperature is lowered.

The orientation results for the room temperature lattice fit in rather well with Néel's picture of the weak, parasitic ferromagnetism which is always observed. In his picture there exist small, distorted crystallites of magnetite intimately mixed with normal α-Fe_2O_3 layers in the layer structure built up along the trigonal axis perpendicular to the (111) sheets. In order to account for the directional properties of the weak ferromagnetism in single crystals of α-Fe_2O_3 observed by Smith[30] many years ago, Néel envisages the magnetic moment direction in the magnetite inclusions and in the α-Fe_2O_3 layers to be within the (111) sheets of the lattice. This is just the conclusion drawn from the neutron scattering observations.

The magnetic lattice for α-Fe_2O_3, shown in Fig. 16, exhibits characteristics similar to those of the magnetic lattice for the simple cubic oxides shown in Fig. 5. When additional unit cells to those shown in Fig. 16 are visualized, it is seen that the structure consists of a series of (111) sheets, within which all moments are arrayed ferromagnetically but with antiferromagnetic coupling between neighboring sheets. Interestingly, there are sheets of oxygen ions between each of the antiferromagnetically coupled sheets of iron ions. The alternating ferromagnetic sheet structure with intermediate oxygen planes was just that found in the cubic oxide magnetic structure.

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Properties of (γ, n) Cross Sections*

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The mean energies of photons producing the reactions $Cu^{63}(\gamma, n)Cu^{62}$, $Zn^{64}(\gamma, n)Zn^{63}$, and $C^{12}(\gamma, n)C^{11}$ have been found by measuring their absorption coefficients for many values of Z. Monitor and detector were made of the element investigated. The absorbers were Be, C, Al, Ti, Fe, Ni, Cu, Zn, Se, Mo, and Sn. Less than 1 percent of the radiation striking the detector originated in the absorber. In this geometry, $(1/Z)$ $\times$absorption cross section was a linear function of Z. The Compton cross section was separated from the pair cross section by considering its different Z-dependence. The mean energy was evaluated in two ways: (1) from the observed pair cross section and the Bethe-Heitler formula, and (2) from the observed Compton cross section and the Klein-Nishina formula. A correction was applied for the deviation of pair cross section from the value given by the Born approximation. With this correction, the values of the mean energy were found to be as follows:

	from Compton cross section	from pair production
Zn^{64}	16.6 Mev	20.0 Mev
Cu^{63}	17.3	21.0
C^{12}	23	32

The integrated (γ, n) cross sections for C^{12} and Zn^{64} have been found to be 0.086×10^{-24} Mev-cm^2 and 0.77×10^{-24} Mev-cm^2, respectively.

PART I

WHEN high energy gamma-rays fall on a nucleus, a reaction is usually observed that corresponds to absorption of the gamma-ray with emission of one or more neutrons, protons, heavier charged particles, gamma-rays. In all nuclear species which have been examined so far the nuclear absorption seems to rise to a maximum and then fall off again with increasing energy of the photon. As yet none of the nuclear species examined up to 100 Mev shows a second region in which

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TABLE I. Typical data, and $1/z\times$cross section.

		No absorber	Background (10-cm Pb absorber)	3-cm nickel absorber	$1/z\times$cross section
Copper	Monitor	4434 cpm	4589 cpm	4768	0.138×10^{-24} cm^2
	detector	6480	85	2483	
Carbon	Monitor	7597	7929	7668	0.134×10^{-24}
	detector	1285	41	491	
Zinc	Monitor	12678	9969	12135	0.117×10^{-24}
	detector	4586	57	1845	

gamma-rays are absorbed in an amount comparable to the absorption in the 15–30 Mev region.[1]

This resonance aspect of the photon absorption in nuclei has been interpreted by Goldhaber and Teller[1a] as an electric dipole absorption due to a "dipole" vibration of the neutrons against the protons of a nucleus, and consequently to a single energy level. The width of the level is ascribed to dissipation of the dipole vibration energy into other modes of vibration, after which the nucleus breaks up in various ways or re-emits the photon. These authors find for the integral of the total nuclear gamma-ray absorption

$$\int \sigma_{\gamma,n}(\omega)d\omega=\pi^2Ae^2/2mc, \qquad (1)$$

where A is the mass number of the nucleus. This formula, however, is independent of the detailed Goldhaber-Teller assumption of a single nuclear level, and is in fact a consequence of the sum rule as was pointed out by Levinger and Bethe.[2]

At the present time not much is known experimentally of the nuclear absorptions, since most of the existing information applies only to that part of the nuclear absorption which gives rise to the (γ, n) process. The (γ, n) cross section of Cu^{63} for the 17.5-Mev gamma-ray produced by protons on lithium was estimated by Bothe and Gentner[3] to be roughly 0.05×10^{-24} cm^2, and was later measured as 0.16×10^{-24} cm^2 by Wäffler and Hirzel.[4,4a] Considerable work has been done on the measurement of (γ, n) cross sections relative to that of Cu^{63} for the 17.5-Mev γ-ray.[5,6]

TABLE II. Absorption cross section for photons which activate Cu^{63}, Zn^{64}, and C^{12}. $\sigma/Z\equiv$barns per electron of absorber.

Absorber	Z	Detectors: $Cu^{63}(\gamma,n)Cu^{62}$ (10.1 min)	$Zn^{64}(\gamma,n)Zn^{63}$ (38 min)	$C^{12}(\gamma,n)C^{11}$ (20.5 min)
			σ/Z	
Sn	50	0.185	0.184	0.200
Mo	42	0.167	0.153	0.191
Se	34	0.133	0.133	0.158
Zn	30	0.120	0.127±0.006	0.133
Cu	29	0.122±0.006	0.123	0.131
Ni	28	0.122	0.131	0.143
Fe	26	0.113	0.122	0.134
Ti	22	0.116	0.104	0.0979
Al	13	0.0795	0.0788	0.0849
C	6	0.0550	0.0506	0.0531±0.008
Be	4	0.0465	0.0582	0.0467

Since monochromatic gamma-rays of higher energy are not available, one uses the bremsstrahlung from high energy electron accelerators, e.g., betatrons. This radiation contains photons of all energies up to the maximum energy of the electrons producing it. The first paper on the shape of the (γ, n) absorption curve of Cu^{63} and C^{12} for bremsstrahlung was published by Baldwin and Klaiber.[7] They measure the curve of activity *versus* maximum betatron energy and calculate the response of the monitor ion chamber to the bremsstrahlung spectrum. They find a resonance energy of 30 Mev for C^{12} and 22 Mev for Cu^{63}.

The integrated cross section for the $C^{12}(\gamma, n)C^{11}$ reaction was measured by Lawson and Perlman[8] as $\int\sigma_{\gamma,n}(E)dE=0.148\times10^{-24}$ Mev$\times$cm^2.

In addition, Perlman and Friedlander obtain $\int\sigma_{\gamma,n}(E)dE=1.5\times10^{-24}$ Mev$\times$cm^2 for Cu^{63}. This was determined from the cross section, the relative yields of the two reactions, and the relative quantum intensities at the two resonance energies.

A third determination of $\int\sigma_{\gamma,n}(E)dE$ for Cu^{63} has been made by Diven and Almy[9] likewise from a yield curve of Cu^{62} activity together with an assumed shape of the bremsstrahlung spectrum and a computed ion chamber sensitivity curve. They find $\int\sigma_{\gamma,n}(E)dE=0.6$ Mev barn and $E_{Res}=17.5$ Mev. By the same type of measurement, Katz and co-workers[9a] find the values 0.7 Mev barns, and 17.5 Mev, respectively, for these quantities.

Measurement of the (γ, n) cross section by direct absorption measurements is made difficult by the small size of the nuclear absorption cross section compared with the total electromagnetic absorption cross section (pair formation+Compton scattering). For example, in the case of copper at 17.5 Mev, the electromagnetic cross section is $\sim$3.6 barns, whereas the nuclear cross section is $\sim$0.1 barn.[4,4a]

In the present work the mean energy E_R of the nuclear absorption of Cu^{63}, C^{12}, and Zn^{64} has been measured by a method somewhat analogous to the method of beam calibration of the Berkeley synchrotron used by Blocker, Kenney, and Panofsky.[10]

In principle, the mean energy of nuclear absorption of a given element could be obtained from the absorption coefficient in an absorber of arbitrary Z for photons

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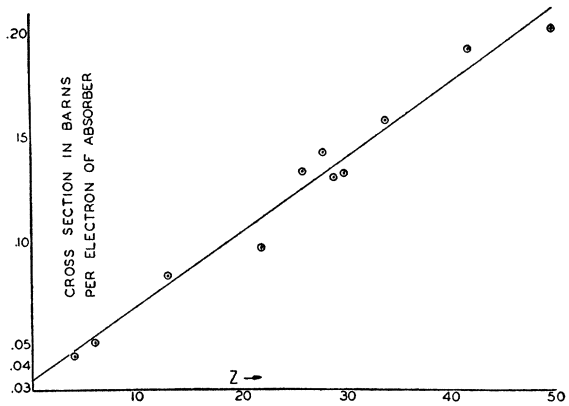

FIG. 1. Absorption cross section for photons which produce the reaction $C^{12}(\gamma, n)C^{11}$.

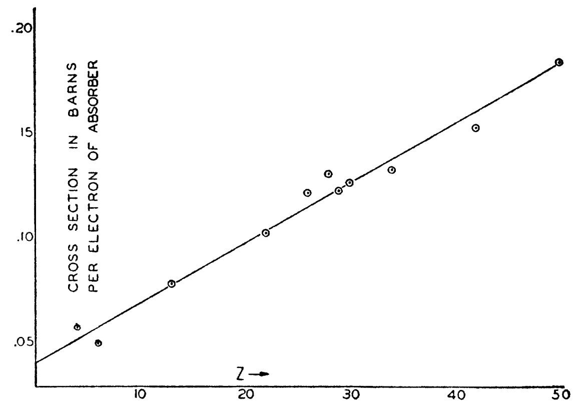

FIG. 3. Absorption cross section for photons which produce the reaction $Zn^{64}(\gamma, n)Zn^{63}$.

which activate the given element. In practice, however, this method is inaccurate for absorbers of low and intermediate Z because the total electromagnetic cross section is not a sensitive function of energy, since it has a broad minimum in the relevant interval. This method is poor for absorbers of high Z, because for these the Born approximation becomes inaccurate, and consequently the electromagnetic cross sections cannot be calculated with sufficient accuracy.

The difficulty is resolved by combining the data on absorption cross section for several elements in order to separate the Compton effect, which is a decreasing function of the energy, from the pair production, which is an increasing function of the energy. Since the Compton effect per atom is proportional to Z and the pair production is proportional to $Z^2+\alpha Z$, the separation is possible. One obtains in this way two independent measurements of the resonance energy from the separate values of the Compton and pair cross sections.

These measurements were made for Cu^{63}, Zn^{64}, and C^{12}. In addition, the relative values of the integrated cross sections were obtained for the last two elements using 50-Mev bremsstrahlung. Absolute values for these quantities have been obtained by using the absolute integrated cross section of copper.[11]

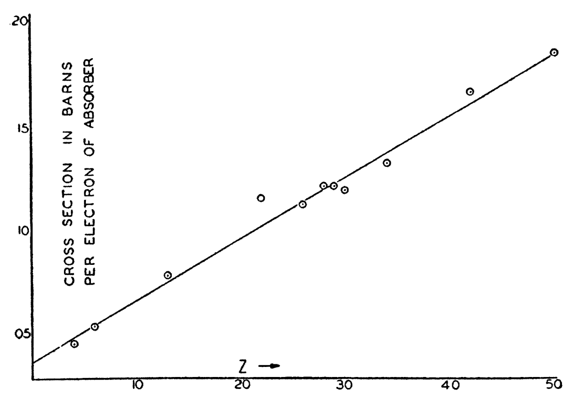

FIG. 2. Absorption cross section for photons which produce the reaction $Cu^{63}(\gamma, n)Cu^{62}$.

PART II

In this experiment a good geometry for the measurement of absorption cross sections was used in order to eliminate effects due to secondary production of bremsstrahlung. The γ-ray beam of the Chicago betatron passed through a monitor foil, a set of absorbers, and a detector foil. Less than 1 percent of the photons activating the detector were of secondary origin, even when the original beam had passed through as much as 6 cm of Pb absorber.

The detectors used were $Cu^{63}(\gamma, n)Cu^{62}$ (10.1 min); $Zn^{64}(\gamma, n)Zn^{63}$ (38 min); and $C^{12}(\gamma, n)C^{11}$ (20.5 min). The data from a typical measurement are given in Table I.

The data are summarized in Table II and Figs. 1, 2, and 3. In Fig. 2, for example, the experimental cross section as measured by a copper detector has been divided by Z of the absorber and plotted *versus* Z of the absorber.

In evaluating these data, the nuclear absorption cross section has been assumed small. The total cross section of absorber for photons activating the detector then may be written

$$\sigma(E_R)=\sigma_{\text{pair}}(E_R)+\sigma_{\text{Compton}}(E_R).$$

TABLE III. Values of E_R. The quantities a and b are the experimental least squares coefficients in the equation $\sigma/Z=aZ+b$.

	a	b	E_R from a	E_R from b
Cu^{63}	0.00296±0.00011	0.0380±0.0031	17.4±1.1 Mev	16.6±2.2 Mev
Zn^{64}	0.00285±0.00012	0.0409±0.0034	16.7±1.4	14.5±2.2
C^{12}	0.00350±0.00017	0.0345±0.0051	25.5±2.3	19.5±4.7
Mean energies after correction for deviation from Born approximation				
		E_R from a		E_R from b
Cu^{63}		21.0 Mev		17.3 Mev
Zn^{64}		20.0		16.6
C^{12}		32.0		23.0

[11] Rosenfeld, Marshall, and Wright, Phys. Rev. **82**, 301(A) (1951).

TABLE IV. Integrated cross sections.

		Zn^{64}	C^{12}
$\left\{\frac{\text{Saturated counts/roentgen/atom element}}{\text{Saturated counts/roentgen/atom Cu}^{63}}\right\}$ 50 Mev		1.05	0.0605
$\int \sigma_{\gamma n}(E)dE$	experimental	0.77×10^{-24} Mev cm^2 [b]	0.086×10^{-24} Mev cm^2
	theoretical (sum rule)[a]	0.96×10^{-24} Mev cm^2	0.18×10^{-24} Mev cm^2

[a] See reference 1.
[b] This value differs form that reported in reference 11 (0.71 Mev barns) by the ratio of the average value of E_k found in the present work, $\frac{1}{2}(21.0+17.3)$ Mev, to the assumed value of 17.6 Mev.

The pair production cross section is the sum of the pair formation in the field of the screened nucleus and the pair formation by photons which ionize orbital electrons. The nuclear part may be represented for light elements by $Z^2\varphi_{\text{pair}}{}^{\text{nuclear}}$, where $\varphi_{\text{pair}}{}^{\text{nuclear}}$ is independent of Z, and is calculated from the Bethe-Heitler formula with screening which assumes the Born approximation. For heavy elements the Born approximation is no longer allowable, and $\varphi_{\text{pair}}{}^{\text{nuclear}}$ becomes Z-dependent. The electron contribution to pair formation may be written $Z\varphi_{\text{pair}}{}^{\text{electrons}}$.

The Compton cross section may be written as $Z\varphi_c(E_R)$, where $\varphi_c(E_R)$ is independent of Z and is calculated with the Klein-Nishina formula. The foregoing equation now becomes

$$(1/Z)\sigma(E_R)=Z\varphi_{\text{pair}}{}^{\text{nuclear}}(E_R)+[\varphi_{\text{pair}}{}^{\text{electrons}}(E_R)+\varphi_c(E_R)].$$

The left-hand side of this equation is the absorption coefficient per electron of absorber for photons which activate the detector. The right-hand side has the form $aZ+b$. The experimental results show a linear dependence on Z (see Figs. 1, 2, and 3) over a large range in Z. In addition, there is no indication for any of the detectors of an increased cross section due to self-absorption. It appears, therefore, that no large error is introduced by neglecting the nuclear cross section compared with the pair and Compton cross sections. No attempt has been made to correct for this omission.

The equations of the best straight lines to fit the data for each detector have been found by least squares analyses. In each case two independent values of the mean energy of the nuclear absorption have been evaluated, one from the slope and the Bethe-Heitler pair formula, and the other from the intercept together with the Klein-Nishina Compton formula and the electron pair cross section. The last quantity is a small correction and has been taken as equal to the pair cross section for $Z=1$. The experimental least squares coefficients a and b in the linear relation $aZ+b$ are given in Table III, as are also the values of E_R found independently from slope and intercept. The data have been corrected for the failure of the Born approximation as found by Walker[12] for 17.5 Mev. The corrected values of E_R are given in Table III.

The difference in the mean values of E_R as measured by pair cross section and by Compton cross section may be taken as indication of a relatively large energy width for the nuclear absorption. The lack of evidence of self absorption is in agreement.

Consider the case of Cu^{63} for example. Assume that the points for high Z are shifted up more than the points for low Z. This will be true if the nuclear absorption of copper is large in the region where Sn, Mo, Se, etc., also absorb, but falls off rapidly to higher energies where C, Be, etc., absorb. In this case the slope gives too high a value for E_R, and the intercept gives a correct or a too low value for E_R depending on whether there is negligible or non-negligible absorption by Be, C, etc., for photons which activate Cu^{63}.

If the nuclear absorption of copper is so wide that it extends through the region where C, Be, etc., also absorb, then the curves of Figs. 1, 2, and 3 in each case will be shifted upward an almost constant amount for all values of Z. In this case the slopes will give correct values for E_R but the intercepts will give values for E_R which are too low. At present perhaps, the best that can be done is to use an average of the values of E_R.

The integrated cross sections of C^{12} and Zn^{64} have been determined, with the aid of the resonance energies found above, assuming[11] the integrated cross section of Cu^{63} to be 0.77×10^{-24} Mev cm^2. Thin foils of zinc, polyethylene, and copper were irradiated together in the 50-Mev bremsstrahlung beam, and the activities relative to copper were measured. The results are given in Table IV.

During the progress of this work, activation curves have been determined for Cu^{63}, C^{12}, Cl^{35}, F^{19}, K^{39}, Br^{79}, and Zn^{64} for bremsstrahlung of maximum energy from 10 to 50 Mev. Relative activity was plotted *versus* $(E_{\text{max}}-E_{\text{threshold}})$. It was found that these curves when normalized to a maximum height of 1.00 were of identical shape, with one exception: in the case of fluorine, the activation curve was slightly wider.

The author is grateful for discussion with Professor Fermi and is indebted to Charles McKinney and his betatron crew, Konrad Benford, Watts Humphreys, and Frank Sammons.

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