annihilation of both the metastable molecules and the metastable atoms. The diffusion coefficient of the metastable atom is in good agreement with the results of other work. The three-body collision frequencies are comparable with those obtained for similar reactions in other gases.

VI. ACKNOWLEDGMENT

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Dipole and Quadrupole Transition Probabilities in Neutron-Capture Gamma Radiation

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An analysis of the intensities of neutron-capture γ rays in even-charge nuclei shows that at high energies the emission probability of $E1$ radiation is greater than that of any other multipole order. This conclusion is supported by additional evidence from odd-charge nuclei. In three nuclei (Mg^{25}, Si^{29}, and S^{33}) a direct comparison shows that (at the same energy) the emission probability of $E1$ is 200 times greater than that of $M1$ radiation. The rate of emission of $E2$ radiation has been compared directly with $E1$ radiation in only one instance, *viz.*, Mg^{25}, where (at 7 Mev) it was found to be lower by a factor of 2000. Further evidence is adduced to show that this ratio is not exceptional and that the rate of emission of $E2$ radiation (at 7 Mev) is less than that of $M1$ radiation. The absolute rates of emission for $E1$ and $M1$ γ rays are evaluated in those instances where the radiation width of the capturing state is known. When corrected for the level spacing near the initial state (and for the nuclear radius, in the case of $E1$ radiation), the rates of emission are remarkably constant; they are independent of the nuclear charge and mass over a range where the level spacing may vary by a factor of 10^4 or more. The emission rates of $E1$ and $M1$ radiation are generally ten times lower than those predicted by the formula of Weisskopf, which is based on the independent-particle model. The emission rates do not exceed those expected from that formula in the case of the exceptionally strong $M1$ ground-state γ rays from F^{20} and Al^{28}. It is shown that the identification of the spins and parities of excited states in many nuclei can be made on the basis of intensity measurements. Finally, the influence of closed shells on the γ-ray spectra is discussed.

INTRODUCTION

A DETERMINATION of the relative emission probabilities of different multipole orders of γ radiation is of considerable interest for it throws a direct light on the mechanism responsible for the emission of radiation. In the absence of selection rules or other limitations, one would expect that the probability of detection of low-energy electric dipole ($E1$) radiation,[1] would far exceed that of higher multipole orders, for, theoretically, the relative probabilities of emission of the various multipoles should decrease by successive factors of the order of $(R/\lambda)^2$, where R is a quantity of the order of the nuclear radius and $2\pi\lambda$ is the wavelength of the radiation. For 1-Mev radiation and for a nucleus of mass 100, this factor is about 0.1 percent.

Now the greater part of the experimental data on the relative rates of emission of the various multipoles has been derived from the study of the γ rays following β decay. It became increasingly apparent that, among the observed γ rays, far more are of $M1$ and $E2$ types than $E1$. Until recently, this fact has not been fully appreciated because of the tendency of early experimenters working with the heavy elements to obtain internal photoelectric conversion coefficients which were too low. Since the coefficients increase with increasing multipole order, and since they are generally greater for magnetic than for electric radiations, $E2$ radiations were mistaken for $E1$, and $M1$ radiations for $E2$. That these radiations are actually $E2$ and $M1$ is confirmed by more exact calculations[2] of internal conversion coefficients which have given results which are lower than early estimates.[3] Consequently, the few examples of $E1$ radiations following β decay have become fewer still, and, although some well-authenticated

[1] We follow here the notation for electric and magnetic multipole radiation introduced by M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 906 (1951).

[2] Rose, Goertzel, and Spinrad, Phys. Rev. 83, 79 (1951).

[3] H. R. Hulme, Proc. Roy. Soc. (London) A138, 643 (1932); H. M. Taylor and N. F. Mott, Proc. Roy. Soc. (London) A138, 665 (1932); J. B. Fisk and H. M. Taylor, Proc. Roy. Soc. (London) A143, 274 (1933); A146, 178 (1934); H. M. Taylor, Proc. Cambridge Phil. Soc. 32, 291 (1936).

examples remain,[4] the occurrence of $E1$ radiations at low energies is exceptional. As a result, the rather widespread belief has arisen that some mechanism inhibits the emission of $E1$ radiation.

The emission of $E1$ radiation from a given state may be forbidden by selection rules, e.g., if all states of lower energy have the same parity, or it may be suppressed because of peculiarities of nuclear structure. Delbrück and Gamow[5] were the first to point out that if all the nuclear constituents have the same specific charge, no relative displacement of the centroids of mass and charge can occur and no $E1$ radiation will be emitted. For example, no $E1$ radiation can be emitted as a result of the relative motion of the constituents of a nucleus consisting entirely of α particles. A similar inhibition of $E1$ radiation must hold for the radiations emitted by the oscillations of a liquid-drop nucleus in which strong correlations exist between the motions of protons and neutrons. Therefore, if it were found that the ratio of the transition probabilities of $E2$ to $E1$ radiation were much greater than $(R/\lambda\!\!\!^{-})^2$, or if the ratio of $M1$ to $E1$ were unexpectedly large, it might be concluded that the emission of $E1$ radiation was being suppressed by some such correlated motion. Conversely, if the relative emission probabilities of $E2$ to $E1$ radiations were of the order of $(R/\lambda\!\!\!^{-})^2$ or less, at least part of the energy emitted as $E1$ radiation would have to be attributed to a single particle moving in an orbit with a size comparable to that of the nucleus, or to groups of particles with a specific charge very different from that of the rest of the nucleus. If the emission is due entirely to the displacement of a neutron, it can be shown[1] that the ratio of $E2$ to $E1$, or the relative emission probabilities of any two successive electric multipoles, is less than $(R/\lambda\!\!\!^{-})^2$ by a factor of the order of the square of the atomic weight. This, in effect, would make undetectable all electric multipoles above the first.

The rates of emission of multipoles of orders higher than $E1$ have been examined by Goldhaber and Sunyar.[1] In some instances, e.g., $M4$ radiations, these authors show that the emission probability is in good agreement with the estimates of Weisskopf.[6] In others, e.g., $E3$ radiations (and more recently, $M1$ radiations[7]), the emission probability is consistently less than that given by Weisskopf's formula, while for $E2$ radiation there are wide variations in emission probability, some $E2$ γ rays being faster and some slower than is expected from that formula. Although some examples of very slow $E1$ radiations of low energy are known, it is probably unsafe as yet to conclude that the rate of emission of low-energy $E1$ radiation is always much lower than that expected theoretically. The infrequent detection of $E1$ radiation following β decay is probably better ascribed to the absence of low-lying excited states which have the proper spin and which differ in parity from the ground state, rather than to an inhibition of the emission of $E1$ radiation.

In the study of neutron-capture gamma rays, we observe transitions between a state near the neutron binding energy (corresponding to an excitation usually near 7 Mev) and the ground state or excited states. The range of energy covered by these γ rays is much higher than that produced in β decay and also much higher than that covered by Goldhaber and Sunyar's analysis of isomeric transitions, and quite new phenomena, therefore, may be expected.

In an earlier paper[8] we have described very briefly certain regularities occurring in the emission of neutron-capture γ rays, which suggest that, in even-charge nuclei at excitations of several Mev, the predominant feature is the emission of $E1$ radiation. These data are discussed in greater detail in the present paper (Sec. 2).

Since the earlier paper[8] was written, the angular distributions of the protons in the (d,p) reaction have been measured in some nuclei of special interest. These results give the orbital angular momentum carried by the neutron in the formation of the ground state and some excited states of the product nucleus and thus provide the means for identifying the multipole type of the γ rays producing these states in the (n,γ) reaction. This additional evidence confirms our conclusions about the strength of $E1$ radiation. In particular, three examples were found where the emission probability of $E1$ and $M1$ γ rays emitted by the same state could be directly compared. The results show that the transition probability for $E1$ radiation is 200 times greater than that for $M1$ radiation. In one instance, where $E1$ and $E2$ γ rays could be directly compared, the transition probability for $E1$ radiation was found to be 2000 times greater than that for $E2$ radiation at 7 Mev. These results are discussed in detail in Sec. 3.

In certain cases the absolute value of the transition probability for $E1$ and $M1$ γ rays can be compared with the theoretical predictions of Weisskopf. It is found that the theoretical predictions give values which are too high by an order of magnitude for both types of radiation. These results also confirm the conclusion, obtained from the direct comparison, that the transition probability for $E1$ radiation is about 200 times greater than that for $M1$ radiation. A detailed discussion is given in Sec. 4.

2. THE INTENSITY OF GROUND-STATE GAMMA RAYS

The multipole order of high-energy γ rays can be directly determined from measurements of the internal conversion coefficient for the production of pairs or from angular or polarization correlations of successive γ rays. For neutron-capture γ rays such measurements are difficult and none have yet been reported. In the

[4] Beling, Newton, and Rose, Phys. Rev. **87**, 670 (1952); A. W. Sunyar, Phys. Rev. **90**, 387 (1953).
[5] M. Delbrück and G. Gamow, Z. Physik **72**, 492 (1931).
[6] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[7] R. L. Graham and R. E. Bell, Can. J. Phys. **31**, 377 (1953).
[8] B. B. Kinsey and G. A. Bartholomew, Physica **18**, 1112 (1952).

absence of such information, we know the multipole orders of only those γ rays for which the spins and parities of the initial and final states are known. Except for a very few excited states, this information is available only for the ground states of nuclei and consequently, the nature of only those γ rays which are emitted in direct transitions from the initial state of the compound nucleus to the ground state can generally be determined. For want of a better name we shall call these γ rays the "ground-state" γ rays, a term which we have used consistently in other communications. Now, the present results have been obtained under conditions where the capture of thermal neutrons predominates. Since the capture of thermal neutrons occurs only for s waves, the parities of the ground-state γ rays are determined uniquely by the parities of the ground states of the target and of the product nucleus. The angular momentum radiated is determined by a combination of the spins of these states and the spin of the neutron.

In general, two alternative ways of emitting the ground-state γ ray will exist in all cases where a neutron is captured by an even-odd[9] or by an odd-charge nucleus, corresponding to the neutron spin being added parallel or antiparallel to the spin of the target nucleus. Except for a very few instances (e.g., the gamma rays produced by capture in Cd) in which thermal neutron capture is of a specifically resonant type, the extent to which the compound nucleus is formed with the one spin or the other is unknown, and with certain exceptions (which we shall discuss later) the resulting ground-state radiation consists of an undetermined mixture of γ rays of two multipole orders. We shall refer to this mixture as "composite" radiation. The intensity of this composite radiation is not characteristic of a γ ray of any particular multipole order. When thermal capture is not resonant, it is perhaps not strictly correct to refer to the "state" of the compound nucleus. However, hereafter we shall call this level of excitation the "capturing state," whether the capture is resonant or not.

TABLE I. Spins and parities of states which combine with emission of $E1$ radiation.

Type of product nucleus	Configuration or spin and parity: Target nucleus	Capturing state	Ground-state product nucleus	Possible types or multipole radiation
Even-odd	$0(+)$	$1/2(+)$	$p_{1/2}(-)$	$E1$ only
	$0(+)$	$1/2(+)$	$p_{3/2}(-)$	$E1, M2$
Even-even	$p_{1/2}(-)$	$0(-)$	$0(+)$	Forbidden
		$1(-)$	$0(+)$	$E1$ only
	$p_{3/2}(-)$	$1(-)$	$0(+)$	$E1$ only
		$2(-)$	$0(+)$	$M2$ only
		$J+1/2(\pm)$	$J\pm1/2(\mp)$	$E1, M2, E3, \cdots$
		$J-1/2(\pm)$	$J\pm1/2(\mp)$	$E1, M2, E3, \cdots$
Odd-odd	$J(\pm)$	$J+1/2(\pm)$	$J+3/2(\mp)$	$E1, M2, E3, \cdots$
		$J-1/2(\pm)$	$J+3/2(\mp)$	$M2, E3, \cdots$
		$J+1/2(\pm)$	$J-3/2(\mp)$	$M2, E3, \cdots$
		$J-1/2(\pm)$	$J-3/2(\mp)$	$E1, M2, E3, \cdots$

Theoretically, the probability of emission of radiation increases rapidly with the energy, and, therefore, the occurrence of relatively strong ground-state γ rays is to be expected in nuclei which radiate exclusively γ rays of the same multipole order. Such nuclei, of course, are exceptional. In general, the neutron-capture γ-ray spectra contain radiations of many different multipole orders which, presumably, have very different emission probabilities. Consequently, relatively strong ground-state γ rays should occur, in general, only when the multipole emitted is the one with the highest transition probability.

Prominent ground-state γ rays are the exception rather than the rule. We find, in fact, that the only even-charge nuclei which produce a ground-state γ ray of exceptional strength are those which, according to the shell model,[10] have an odd neutron in a p state in the ground state of either the target or product nucleus. In the even-odd product nuclei up to zinc which we have so far examined, we have found no exception to this rule.

In the upper part of Table I the possible multipole types of ground-state γ rays are given for even-charge nuclei where the odd neutron (in the target or product nucleus) is in a p state. Assuming that all even-even nuclei have zero spin and even parity, it is clear that for even-odd product nuclei the capturing state must have a spin of 1/2 and even parity. For $p_{1/2}$ states the ground-state γ ray will be of $E1$ type. This is also true for $p_{3/2}$ states, for, although the radiation may have an $M2$ component, it is to be expected theoretically that the rate of emission of $M2$ radiation is much lower than that of $E1$ radiation. The association of strong ground-state γ rays with p states in even-odd nuclei, therefore, suggests that this strength is due to their $E1$ character.

Three even-even product nuclei have been studied which have been produced by neutron capture by nuclei in $p_{3/2}$ states. In these nuclei, which form a special class, the ground-state γ rays are usually weaker than those producing the first-excited state. This is to be expected if the emission of $E1$ radiation is the most probable process, as the even-odd product nuclei appear to show. For even-even product nuclei, the capturing state can have one of two possible spins. As Table I shows, the resulting composite radiation always has an $E1$ component, the other component being $M2$ or entirely absent; and the observed intensity, in photons per capture, will depend on the proportion in which the two spin states are formed. However, the parity of the first-excited state is probably even and its spin is 2 units. For a $p_{3/2}$ target nucleus, then, both components

[9] In this adjective and in similar adjectives mentioned hereinafter, we describe the proton number (Z) first, and the neutron number (N) second.

[10] We use the strong-coupling model of M. G. Mayer, Phys. Rev. **78**, 16 (1950), and Haxel, Jensen, and Suess, Z. Physik **128**, 301 (1950).

of the composite radiation emitted to this state will be $E1$. Disregarding the energy dependence of emission probability, it follows that, if the matrix elements of the two transitions are equal, the intensity of the ground-state γ ray will be the weaker (for it will consist, in part, of $M2$ radiation).

In odd-odd product nuclei the relationship between the multipolarity of the ground-state γ ray and the configuration of the product nucleus is less simple, for now both target and product nuclei have spins greater than zero. In Table I are listed all possible combinations of spin and parity of the target and product nuclei for which the emission of an $E1$ component in the ground-state radiation is possible. As in the case of even-even product nuclei, composite ground-state γ rays are emitted. If the spin of the ground state of the product nucleus is $J\pm 1/2$, where J is the spin of the target nucleus, both components of the composite ground-state γ ray will contain $E1$ radiation. If the spin of the ground state is $J\pm 3/2$, $E1$ radiation will be emitted from only one of the two possible capturing states.

The experimental results will now be considered in detail. Since the γ rays emitted by odd-charge nuclei are weaker and more numerous than those emitted by even-charge nuclei, and since also they are more difficult to interpret, we shall deal separately with even- and odd-charge nuclei. We shall consider the light even-charge elements first, because for these nuclei there is usually sufficient data from other sources to determine the neutron binding energies or the positions of excited states. The "light" elements will be defined as those with atomic numbers equal to or less than that of zinc. The remainder will be called "heavy" elements.

2.1. Intensities of Ground-State γ Rays of Even-Charge Light Elements

The experimental results for the ground-state γ rays of all even-charge nuclei up to zinc are listed in Table II.[11] The first column gives the category under which it will be convenient to discuss these results in some detail, the second, the neutron number (N), and the third, the configuration of the ground state of the even-odd nucleus according to the shell structure theories,[10] regardless of whether this nucleus happens to be the target or the product nucleus. The product nucleus responsible for the emission of the γ ray observed is listed in columns four and five, the designation of the γ ray used in previous publications in the sixth, and its intensity in the seventh. The last two mentioned were taken from the published tables[12–14] of the intensities of the ground-state γ rays from the natural element, corrected for the contribution to the thermal neutron capture caused by the isotope in question.[15]

TABLE II. Intensities of ground-state γ rays of even-charge nuclei up to zinc. In those marked with an asterisk, it is not yet certain whether the γ ray listed is correctly identified.

Group	Neutron number N	Ground state of even-odd nucleus	Product Nucleus odd N	Product Nucleus even N	γ ray	Intensity in photons per 100 captures	Reference
1	6	$p_{3/2}$		Be^{10}	A	75	a
	7	$p_{1/2}$	C^{13}		A	70	a
2	13	$d_{5/2}$	Mg^{25}		C	0.4	b
	14	$d_{5/2}$		Mg^{26}		<0.2	b
	15	$s_{1/2}$	Mg^{27}		F_1	~ 13	c
	15	$s_{1/2}$	Si^{29}		B	2	b
	16	$s_{1/2}$		Si^{30}	A	3	b
	17	$d_{3/2}$	Si^{31}			<15	b
	17	$d_{3/2}$	S^{33}		A	1	d
3	21	$f_{7/2}$	Ca^{41}			<0.2	d
	23	$f_{7/2}$	Ca^{43}			<1	d
	26	$f_{7/2}$		Ti^{48}		<1	e
	27	$f_{7/2}$	Ti^{49}			<0.2	e
	27	$f_{7/2}$	Cr^{51}			<1	e
	28	$f_{7/2}$		Ti^{50}		<1	e
4	29	$p_{3/2}$	Cr^{53}		D	40	e
	29	$p_{3/2}$	Fe^{55}		B	~ 50	e
	30	$p_{3/2}$		Cr^{54}	A	13	e
	31	$p_{3/2}$	Fe^{57}		E	40	e
	31	$p_{3/2}$	Ni^{59}		A	50	e
	32	$p_{3/2}$		Fe^{58}	A	~ 5	e
	33	$f_{5/2}$	$*Ni^{61}$		B	80	e
	35	$f_{5/2}$	$*Zn^{65}$		E	40	e
	38	$f_{5/2}$		Zn^{68}	A	0.3	e

[a] See reference 16.
[b] See reference 12.
[c] See reference 25.
[d] See reference 13.
[e] See reference 14.

A casual inspection of Table II clearly shows that strong ground-state γ rays are associated for the most part with those nuclei which, according to the shell model, are in p states, while weak ground-state γ rays are associated with nuclei in d states, s states, or $f_{7/2}$ states. The table suggests, therefore, that the strength of the ground-state γ rays in Groups 1 and 4 is due to the greater emission probability of $E1$ radiation and that the weakness of the ground-state γ rays in Groups 2 and 3 is caused, respectively, by the relative weakness of $M1$, or $E2$, and of $E3$ radiation.

While the absolute intensity of a γ ray is not in itself a criterion of emission probability, the above interpretations would appear to be correct, for, in the even-odd nuclei in Groups 2 and 3, very strong γ rays are found which lead to excited states, and which will be shown, on the basis of independent evidence, to be of the $E1$ type. We shall now discuss the experimental evidence in more detail and we shall commence with a consideration of the nuclei-producing strong ground-state γ rays, *viz.*, those contained in Groups 1 and 4.

[11] This table contains all those nuclei up to zinc which we have so far been able to investigate with existing apparatus. The γ rays of some nuclei, such as C^{14} or Si^{31}, have still to be determined, while for others, e.g., O^{17} and S^{35}, the cross sections are so low that the capture γ rays have not been detected.

[12] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951).

[13] Kinsey, Bartholomew, and Walker, Phys. Rev. **85**, 1012 (1952).

[14] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

[15] H. Pomerance, Phys. Rev. **88**, 412 (1952).

2.1.1. *Group 1*

In Group 1 there is only one even-odd nucleus, C^{13}. In this nucleus only three states are known to exist which can be excited by transitions from the neutron binding energy at 4.95 Mev. It is significant, as has been shown elsewhere,[16] that only those transitions have been detected which can take place with the emission of $E1$ radiation.

2.1.2. *Group 4*

In Group 4 the identification of the strong γ rays with the direct transition to the ground state in even-odd nuclei is certain only in Cr^{53}, Fe^{55}, and Ni^{59}, and probable in Fe^{57}. In Ni^{61} and Zn^{65} strong ground-state γ rays appear to be associated with $f_{5/2}$ states. Such γ rays, if indeed they are ground-state γ rays,[17] are of $M2$ type. However, in the absence of information on the positions of the excited states in these nuclei, it is quite possible that the γ rays observed are not, in fact, ground-state γ rays but are emitted in $E1$ transitions to low-lying excited states. [This explanation accounts for the strength of the strong γ ray originally ascribed to the ground-state transition of K^{40} (see Sec. 2.3.3).]

It is interesting to note that the decay of Fe^{55} and Ni^{59} is consistent[18] with the assignment of a $p_{3/2}$ configuration to the ground states of these nuclei and with the known spins of Mn^{55} (5/2) and Co^{59} (7/2). The spin of the stable isotope, Cr^{53} which has been found[19] to be 3/2, also indicates a $p_{3/2}$ state. That the ground states of Cr^{53} and Fe^{57} are, in fact, p states has recently been demonstrated by studies of the (d,p) reaction.[20] Also, existing data on the decay of Co^{57} show that both the ground state and the 14-kev state[21,22] of Fe^{57} should be p states. Both, therefore, should be produced by the emission of $E1$ radiation from the capturing state. It has already been shown[14] that the strong γ ray at 7.639 ± 0.004 Mev can be identified with either transition. Further analysis of the shape and width[23] of the coincidence peak suggests that this γ ray is indeed the ground-state γ ray (see Appendix A).

The γ rays produced in the ground-state transitions in the even-even nuclei Cr^{54} and Fe^{58} are relatively weak. While the γ ray producing the first-excited state in Fe^{58} has not been detected separately from the ground-state γ ray of Fe^{55}, the γ ray leading to the first-excited state of Cr^{54} is stronger than the ground-state γ ray in that nucleus. (This is also true of Be^{10} if the intensities of the γ rays are corrected by the cubes of the energies.) For these nuclei it is very probable that the spin of the first-excited state is 2 units;[24] and the γ ray producing this state, therefore, is $E1$, regardless of the spin of the capturing state, whence it follows that the ground-state γ rays can be relatively weak as explained in a previous section.

2.1.3. *Group 2*

The weak ground-state γ rays in this group have intensities of the order of a few photons per 100 captures. The isotopic neutron capture cross sections of Mg^{26}, Si^{29}, and Si^{30} are low.[15] Consequently, only the ground-state γ ray has been identified in[25] Mg^{27} and in Si^{30}, while no γ rays have been detected in Si^{31} for which the intensity of the ground-state γ ray given in Table II is an upper limit. The remaining even-odd nuclei, Mg^{25}, Si^{29}, and S^{33}, all have one striking characteristic, *viz.*, in the spectrum of each there is one γ ray of exceptional strength produced in a transition from the capturing level to a highly excited state. Since the ground-state γ rays of the nuclei of Group 2 produce no change in parity (they are $E2$ or $M1$ or mixtures of both), it is probable that the outstanding γ ray must be a multipole of a much higher emission probability, i.e., it must be $E1$. Recently this conclusion has been confirmed in measurements by Holt and Marsham[26,27] on the angular distribution of the protons in the (d,p) reaction in these three even-odd nuclei. From these measurements it appears that the state excited by the strong γ ray in the neutron capture process is the lowest state for which the neutron is absorbed in the (d,p) process with unit orbital angular momentum. Since the target nucleus, in each instance, has zero spin and even parity, it is clear that this state is a p state. The strong γ rays, therefore, are indeed $E1$, while the relatively weaker γ rays, producing directly the ground state or other even states, are $M1$ or $E2$. The latter are also emitted from the capturing state and, therefore, compete with the $E1$ γ ray. A study of the intensities of the even- and odd-parity γ rays, therefore, gives directly the ratio of the emission probabilities of $E2$ or $M1$ relative to $E1$ radiations. A detailed account of the γ rays emitted by these three nuclei is given in Appendixes B, C, and D.

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[16] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 49 (1953).

[17] Ni^{61}: It is not yet established (reference 14) whether the strong γ ray in question (8.532 Mev) is the ground-state γ ray of Ni^{61} or whether it represents a transition to an excited state of Ni^{59}. Zn^{65}: The strong γ ray E (7.876 Mev) has an energy close (100 kev) to the estimated neutron binding energy of Zn^{65}. The positron decay of Zn^{65}, suggests that the spin of Zn^{65} is very different from that of Cu^{65}, which is 3/2 ($p_{3/2}$ proton).

[18] The decay of both nuclei takes place by electron capture between ground states. The β decay of Fe^{55} is presumably allowed ($\log ft = 5.9$), while that of Ni^{59} is clearly forbidden ($\log ft = 11$). This is to be expected, for the spin of Co^{59} is greater than that of Mn^{55} by one unit.

[19] B. Bleaney and K. D. Bowers, Proc. Phys. Soc. (London) **A64**, 1035 (1951).

[20] C. F. Black, Phys. Rev. **90**, 381 (1953).

[21] E. H. Plesset, Phys. Rev. **62**, 181 (1942).

[22] M. Deutsch and W. E. Wright, Phys. Rev. **77**, 139 (1950).

[23] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 537 (1953).

[24] This is certainly true of Be^{10} [see E. Bedewi, Proc. Phys. Soc. (London) **A65**, 64 (1952); see also reference 16] and also of Fe^{58} [see Bishop, Daniels, Goldschmidt, Halban, Kurti, and Robinson, Phys. Rev. **88**, 1432 (1952)].

[25] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 901 (1953).

[26] J. R. Holt and T. N. Marsham, Phys. Rev. **89**, 665 (1953).

[27] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 258 (1953).

No strong γ rays leading to excited states have been detected in the spectrum of the even-even nucleus Mg^{26}. No odd states were found by Holt and Marsham in Mg^{26} below an excitation of 6 Mev. This explains the absence of unusually strong γ rays in that nucleus: all those detected with the pair spectrometer which can be identified with this nucleus are $M1$ radiations.

2.1.4. Group 3

The ground-state γ rays have not been detected from any of the nuclei in this group. In all cases, the intensity is less than 1 percent per capture. Now, the unpaired neutron in the ground state of an even-odd nucleus in this group is in an $f_{7/2}$ state. The ground state, therefore, has odd parity and its spin is probably either 7/2 or 5/2.[28] The weakness of the ground-state γ ray in these nuclei, therefore, demonstrates the relatively low probability of emission of $E3$ or $M2$ radiation in comparison with γ rays of lower multipole order.

It has been possible to attempt an analysis of the capture radiations from only two nuclei in this group, *viz.*, Ca^{41} and Ti^{49}. In both, an exceptionally strong γ ray is emitted leading to the first-excited state, and a somewhat weaker γ ray to the second-excited state. Holt and Marsham[29] have shown that in Ca^{41} both excited states are p states. In Ca^{41}, therefore, it is certain, and in Ti^{49} it is very probable, that the strong γ ray is $E1$. The level systems of both nuclei are probably very similar, for in Ca^{41} the unpaired neutron is the only occupant of the $f_{7/2}$ shell, and in Ti^{49} there is one neutron less than that required to fill the shell. Therefore, the ground states of both nuclei almost certainly have spin 7/2 and the ground-state γ rays must be $E3$. The ratio of the measured upper limit of the intensity of this γ ray to the intensity of the $E1$ γ ray gives an upper limit for the emission probability of $E3$ radiation relative to $E1$. A detailed account of the γ rays emitted by these nuclei is given in Appendixes E and F.

2.2. Intensities of Ground-State γ Rays in Heavy Even-Charge Nuclei

The investigation of these nuclei is still incomplete.[30] Those even-charge nuclei which have already been studied are listed in Table III according to the multipole order of the ground-state γ ray expected from shell structure.[31]

An inspection of Table III shows that the ground-state γ rays, like those in the lighter elements, are relatively strong when the shell model predicts that they are of $E1$ type and relatively weak when they are of $M1$ type or of higher order, in agreement with the conclusions of the previous section. This is confirmed by a few examples, such as Sr^{87}, where a very strong γ ray[30] is observed producing an excited state which is known to be a p state from the evidence of isomeric transitions.

TABLE III. Lowest multipole orders and intensities (reference 30) of ground-state γ rays in heavy even-charge nuclei in photons per 100 captures in the separated isotope.

$E1$		$M1$		Higher orders		
Se^{77}	4	Cd^{114}	0.14	Sr^{87}	($E4$)	<1[a]
Se^{78}	0.3	Sn^{118}	0.3[c,b]	Sr^{88}	($E4$)	<0.05[a]
W^{183}	10[c]	Ba^{138}	0.3	Zr^{92}	($E2$)	1
W^{184}	3			Mo^{96}	($E2$)	0.05
W^{187}	4[c]			Sm^{150}	($E3$ or $M4$)	<0.05[a]
Pt^{196}	0.3[b]			Gd^{156}	($E3$)	<0.03[a]
Hg^{200}	<0.1[a]					
Pb^{207}	100					
Pb^{208}	100					

[a] γ ray not detected.
[b] Minimum value; contribution of isotope to total capture cross section unknown.
[c] Identification of γ ray not certain.

There are two exceptions: Se^{78}, where the ground-state γ ray (10.6 Mev) is some fifteen times weaker than that producing a low-energy excited state, and Hg^{200}, where the ground-state γ ray apparently is not detected, for the highest-energy γ ray observed has an energy much less than that expected of the neutron binding energy in that nucleus. Both nuclei are even-even, and, according to the shell model, the ground states of the even-odd target nuclei are $p_{1/2}$ states. It can be seen from Table I that a weak ground-state γ ray would indicate that the thermal capture occurs predominantly in a state with zero spin. In mercury, the greater part of the thermal neutron capture cross section appears to be caused by a negative energy resonance[32] in Hg^{200}. The above evidence that the spin of this resonance is zero is not consistent with the interpretation of measurements of the scattering of neutrons at thermal energies[33] which indicate spin 1.

The outstanding intensities of the lead γ rays will be discussed in a later section.

2.3. The Intensity of Ground-State γ Rays in Odd-Charge Nuclei

The products of neutron capture in odd-charge nuclei are mainly nuclei of the odd-odd type. (The only odd-even nucleus which has been examined in detail is N^{15}; to a lesser extent the γ rays of K^{41} and V^{51} have been studied.) The identification of the capture γ rays produced by odd-odd nuclei is more difficult than the identification of those of even-charge nuclei, for the density of levels and, therefore, the total number of γ rays emitted, is much greater. In many heavy odd-odd nuclei, the highest energy γ rays have not been resolved. Furthermore, the ground-state radiation is generally

[28] This is true if the nucleus contains three or five $f_{7/2}$ neutrons. For example, it would appear that the spin of 5/2 for Mn^{55} is caused by the coupling of five $f_{7/2}$ protons. See Mayer, reference 10.
[29] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 565 (1953). We are indebted to Dr. Holt for the privilege of seeing these results before publication.
[30] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).
[31] See P. F. A. Klinkenburg, Revs. Modern Phys. **24**, 63 (1952).
[32] W. W. Havens and J. Rainwater, Phys. Rev. **70**, 154 (1946).
[33] Hibdon, Muehlhause, Ringo, and Robillard, Phys. Rev. **82**, 560 (1951).

TABLE IV. Intensities of the ground-state γ rays in odd-charge nuclei in photons per 100 captures in the separated isotope. For those γ rays marked with an asterisk the multipolarity is the same regardless of the spin of the capturing state. For the others, the lowest multipole order of the "composite" radiation is given.

$E1$		$M1$		Higher orders		
*N^{15}	20[a]	*F^{20}	20[b]	Na^{24}	$(E2)$	<1[b]
*K^{42}	30[c]	*Al^{28}	35[b]	K^{40}	$(M2)$	<0.3[c]
Sc^{46}(?)	0.3[d]	P^{32}	0.5[b]	Nb^{94}	$(E2)$(?)	0.4[e]
*V^{52}	7[f]	*Cl^{36}	3[b]	In^{114}	$(E4)$	<0.05[e]
*Mn^{56}	12[d]	Sb^{122}	1[e]	Au^{198}	$(M2)$	<0.3(?)[e]
*Co^{60}	3[d]					
*Cu^{64}	24[d]					
*Cu^{66}	50[d]					
*Rh^{104}	0.2[e]					
*Ag^{108}	1.2[e]					
*Pr^{142}	2[e]					
Ta^{182}	0.7[e]					
*Tl^{204}	5[e]					

[a] See reference 34.
[b] See reference 12.
[c] See reference 48.
[d] See reference 36.
[e] See reference 46.
[f] The intensities for vanadium in reference 12 are too large by a factor of 1.6.

composite. This last difficulty is removed when thermal capture is dominated by one resonance or, for dipole radiation, when the spin of the final state in the product nucleus is equal to $J\pm 1/2$ (see Table I). In such cases, the multipole order of the ground-state γ rays or those leading to some low-lying states may be determined when the relevant spins and parities are known. The ground-state spin has been directly measured for only a very few odd-odd nuclei, but in many cases it can be inferred from the β activity. In others, recent measurements of the angular distribution of the protons in the (d,p) reaction are of assistance.

The intensities and multipolarities of the ground-state γ rays from odd-charge nuclei are listed in Table IV. A casual inspection of this table will show that there is no obvious regularity of the kind shown in the even-charge nuclei (Table II).

2.3.1. The $E1$ γ Rays

In the lighter elements, the $E1$ ground-state γ rays are generally strong, although that of Sc^{46} is an exception. For the remaining nuclei, excepting Cu^{64} and Cu^{66}, the $E1$ ground-state γ rays do not dominate the spectrum as they do in the even-charge nuclei. We shall now consider some of the salient features of these spectra.

The γ rays produced by N^{15} have been described elsewhere.[34] An unexplained feature is the relative weakness of the $E1$ ground-state γ ray: it is weaker than the γ ray of half the energy emitted in the transition to the first excited state. Moreover, it is not much stronger than the γ rays producing highly excited states, some of which, according to the results of Gibson and Thomas,[35] must be $M1$.

[34] Kinsey, Bartholomew, and Walker, Can. J. Phys. **29**, 1 (1951).
[35] W. M. Gibson and E. E. Thomas, Proc. Roy. Soc. (London) **A210**, 543 (1952).

feature of N^{15} is the relative weakness of the ground-state γ ray: it is weaker than the γ ray of half the energy emitted in the transition to the first excited state.

If correctly identified as an $E1$ γ ray, the weakness of the ground-state γ ray in Sc^{46} is unusual. This weakness might result from the high density of excited states in this nucleus.[36] It is, however, much weaker than other γ rays leading to excited states. It is quite possible that its multipole order has not been correctly identified,[37] for the assumption that this γ ray is $E1$ is based on the spin of Sc^{46} being 4 units.[38]

The three nuclei V^{52}, Mn^{56}, and Co^{60} produce rather similar γ-ray spectra.[36] In each case the thermal neutron capture cross section appears to be derived mainly from the lowest resonance, and in each case the ground-state γ ray, or the γ ray with the highest energy, is almost certainly of $E1$ type (see Appendix G). An interesting feature common to these three nuclei is that many other γ rays are produced with very similar intensities; presumably, they also are $E1$.

The nuclei Cu^{64} and Cu^{66} differ from all other odd-charge nuclei in that the $E1$ ground-state γ rays (see Appendix G) like those of the even-charge nuclei in Group 4, are by far the strongest in the spectra. Moreover, the spectra appear simpler than those of neighboring odd-odd nuclei. This simplicity, together with the great strength of these ground-state γ rays, may be caused by a wider spacing of the levels near the ground-state.

2.3.2. The $M1$ γ Rays

The $M1$ γ rays emitted by the odd-charge nuclei show some wide variations in intensity and some interesting anomalies.

In the two nuclei P^{32} and Cl^{36} the $M1$ ground-state γ rays are of relatively low intensity. In P^{32} the ground-state γ ray is much weaker than a number of other high-energy $M1$ γ rays which are also emitted by the capturing state (see Appendix G). The fact that neutron capture in P^{31} is nonresonant might account for the weakness of the ground-state γ ray and for the lack of uniformity in the intensities of other high-energy $M1$ γ rays in P^{32}. In Cl^{36}, where the thermal neutron capture

[36] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).
[37] The spin of Sc^{45} being 7/2, this γ ray will be $E1$ regardless of the spin of the capturing state, provided that the spin of the ground state of Sc^{46} is 4 units. The assignment of 4 units for the spin rests on the assumption that the spin of the isomeric state is 7 units, for the isomeric transition is $E3$ or $M3$. If the spin of the ground state were 5, which would be consistent with its β decay, the spin of the isomeric state would have to be 8 or 2, of which the former is inconsistent with any simple interpretation of the shell model. Such evidence as exists on the decay of the isomeric state, however, does not exclude the possibility that its spin is 2. In that event, it is quite possible that the ground state (with spin 5) is produced by neutron capture more often from a compound state of spin 3 than from spin 4. This could account for the observed weakness of the ground-state γ ray.
[38] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

is resonant,[39] the intensities of the high-energy γ rays are much more uniform.

The $M1$ ground-state γ rays in F^{20} and in Al^{28} are exceptionally strong[12] and dominate the spectrum of these nuclei. This is peculiar in that the level systems of both nuclei are more complicated than in even-charge nuclei of similar atomic weight.

The spin[40] of the ground state of F^{20} is probably 1, and therefore the ground-state γ ray is $M1$. It is possible that the anomalous strength of this γ ray is connected in some way with the unusual configuration of the ground state, which does not decay to the ground state of Ne^{20} except by a forbidden transition. Such a conclusion, however, is purely speculative, for no similar explanation is appropriate to Al^{28}.

In Al^{28}, the strength of the ground-state γ ray is especially striking, for this nucleus possesses the most complicated level system of any light nucleus yet examined.[41] Recent measurements show that the energy of this γ ray is indeed that of the neutron binding energy of Al^{28}, and is not to be confused with the transition to the low-lying excited state at 31 kev.[42] The ground-state γ ray is probably (but not certainly) $M1$, for measurements on the angular distribution of the (d,p) reaction (which do not resolve the ground-state doublet) show that the configuration of the unpaired neutron in the ground-state, in the 31-kev state, or in both, is that of an s state.[43] However, it is not clear from the measurements that, if the unpaired neutron in the 31-kev state is in an s state, the ground-state could not be a p state; but in view of the even parities of the ground-states and of low-lying states in this region of the periodic table, this possibility seems most unlikely.[44] It is most probable that both the ground-state and the 31-kev state are s states for the unpaired neutrons. The great strength of the ground-state γ ray and the relative weakness of the remaining γ rays is difficult to explain. The latter cannot all be $E2$ radiations, for at least one component of the doublet at 1.0 Mev appears to have a spin of either 2 or 3 units.[43] We conclude that most of these γ rays also must be $M1$ radiations and that the remarkable prominence of the ground-state γ ray is due to some peculiar property of the ground state possibly associated with the presence of the unpaired proton.[45]

2.3.3. *E2, M2, and Higher-Order γ Rays*

No γ rays which are known to be of the $E2$ or $M2$ type or of higher orders have been observed in studying the light odd-charge nuclei. Among the heavy elements, the identification of the highest energy γ ray with the ground-state transition is usually uncertain, because the higher-energy γ rays detected are seldom completely resolved, even when the line width of the instrument is 100 kev, and the errors in the neutron binding energies (obtained from other sources) are usually less than the mean spacing of the levels near the ground state. In gold,[46] where the highest-energy γ ray, A, has an energy close to the known neutron binding energy, we do not know for certain whether this γ ray is the $M2$ ground-state γ ray or whether it is emitted in a transition to a low-lying excited state. From a consideration of the absolute intensities of the gold γ rays it seems much more probable that the observed high-energy gold radiations are all $E1$, and that the $M2$ ground-state γ ray was not detected.

Until recently, the ground-state γ ray in the nucleus K^{40} seemed anomalous. The existence of a strong γ ray with an energy near the known neutron binding energy of K^{40} has been pointed out in a previous communication.[13] Since the spin of K^{40} is known to be 4 units[47] and that of K^{39} is 3/2, it follows that the ground-state γ ray is composite with $M2$ and $E3$ components. It is now known that a low-lying state exists in K^{40} near 30 kev, and that the energy of the strong γ ray is in good agreement with the energy expected for a direct transition to this state.[48] If, as seems probable, the spin of this state were 2 units, the γ ray would be $E1$ regardless of the spin of the capturing state. The coincidence peak produced by this γ ray is very well defined and there is no evidence of a peak lying just above it which could be due to the $M2$ γ ray.

3. RELATIVE EMISSION PROBABILITIES

It is impossible to obtain reliable information on the relative emission probabilities of different multipoles

[39] C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **79**, 44 (1950).

[40] Bromley, Bruner, and Fulbright, Phys. Rev. **89**, 396 (1953).

[41] Enge, Buechner, and Sperduto, Phys. Rev. **88**, 963 (1952).

[42] The energy corresponding to the end point of the coincidence peak is in good agreement with that corresponding to the neutron binding energy of Al^{28} (see reference 23). The equivalent energy displacement between the peak of the coincidence curve and the observed end point is normal. If the greater part of the peak coincidence counting rate were due to a transition to the 31-kev state, this displacement would be greater than the normal value by 31 kev, and such a difference would be easily detected (see Appendix A).

[43] H. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A65**, 763 (1952); Proc. Phys. Soc. (London) **A66**, 249 (1953).

[44] An indication that the ground-state γ ray must have a lower rate of emission than that expected of $E1$ radiation is afforded by the existence of a γ ray with an energy of 7.34 Mev and an intensity fifty times lower. As pointed out in a previous communication (see reference 12), this γ ray must arise from a transition from a highly excited state, which, in turn, is excited in a transition of 0.38 Mev. If the 0.38-Mev transition and the ground-state transition were of the same multipole order, the intensity of the former should be lower by a factor of 10^4. The fact that it is only 50 times lower suggests very strongly that it is $E1$, while the ground-state γ ray is $M1$.

[45] It has been pointed out by M. Vosko [thesis, McGill University, 1952 (unpublished)] that the relative strengths of the Al^{28} $M1$ γ rays might be explained on the basis of an extension of the single particle selection rules to take account of the odd neutron and odd proton. For an allowed transition, then, $\Delta J = \pm 1$ and for a forbidden transition, $\Delta J = 0$. There is as yet little evidence to show whether these selection rules apply.

[46] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 1025 (1953).

[47] Z. A. Zacharias, Phys. Rev. **61**, 270 (1942).

[48] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 927 (1953); Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).

TABLE V. Ratios of emission probabilities of pure $M1$ and $E1$ radiation.

Nucleus	$E1$ γ Ray	$E1$ Energy	$E1$ Intensity	$M1$ γ Ray	$M1$ Energy	$M1$ Intensity	Ratios of corrected intensities
Mg^{25}	J	3.92 Mev	0.90	E	6.75 Mev	0.020	0.5 percent
Si^{29}	M	3.54 Mev	0.60	B	8.47 Mev	0.022	0.3 percent
S^{33}	G	5.43 Mev	0.60	B	7.78 Mev	0.016	0.9 percent
						Mean	0.6 percent

except in even-odd nuclei or such odd-odd or even-even nuclei for which the thermal neutron energy lies close to that of a resonance. There are as yet very few data on the parities and spins of the excited states of odd-charge nuclei which exhibit resonant capture, and consequently it is not yet possible to compare the emission probabilities for γ rays emitted by elements in this group. Among the few even-even nuclei which are known to capture thermal neutrons in one spin state only, there is only one, Cd^{114}, for which something is known about the character of the low-lying states.

3.1. Relative Emission Probabilities of $E1$ and $M1$ Radiation

In the even-odd nuclei we have found three examples of $E1$ radiation in competition with pure $M1$ radiation. We list these examples in Table V. In the last column of this table we give the ratios ($M1$ to $E1$) of the emission probabilities; these quantities are equal to the ratios of the intensities divided by the ratios of the cubes of the respective energies.

The mean ratio of the emission probabilities is of the order of magnitude expected theoretically[6,49] on the single-particle model, *viz.*, $10(\hbar/McR)^2$, which, for a nucleus of mass 30, is about 2 percent.

It is important to note that all three $M1$ γ rays given in Table V violate the orbital angular momentum selection rules for single-particle transitions. In each case, the transition is $s_{1/2}\rightarrow s_{1/2}$ for the odd neutron.[50] Among the even-even and odd-odd product nuclei we have found, unfortunately, no examples in which an $E1$ and a competing allowed $M1$ γ ray can be compared.

3.2. Relative Emission Probabilities of $E2$ and $E1$ Radiation

Only one nucleus, Mg^{25}, has been found[12] in which a pure $E2$ γ ray (the γ ray C) is in competition with an $E1$ γ ray (J). (The γ ray C is 7.32 Mev and the γ ray J, 3.92 Mev.) Since the emission probability of $E2$ radiation increases as the fifth power of the energy, while that of $E1$ radiation increases as the cube, such a comparison has meaning only at one energy. If we choose 7 Mev, we find that the ratio of emission probabilities of $E2$ to $E1$ radiation is 0.05 percent.

It would appear from this result that, at 7 Mev, the emission probability of $E2$ is an order of magnitude less than that of $M1$ radiation and of the same order as that given by Weisskopf's formula.[6] Although this instance is the only one in which such a direct measurement can be made, there is additional evidence which shows that the emission probability of $E2$ is not greater than that of $M1$ radiation. For example, near 7 Mev, if the emission probability of $E2$ radiation were greater than that of $M1$ radiation, the intensities of those γ rays which could, theoretically, consist of mixtures of $M1$ and $E2$ components, would be greater than that of pure $M1$ γ rays. In Cd^{114}, the γ ray B (8.48 Mev)[30] could contain both $E2$ and $M1$ components arising from a transition from an initial state of spin 1 and a final state of spin 2. This γ ray is only a little stronger than the pure $M1$ γ ray leading to the ground state (9.046 Mev). Similar instances occur in Si^{29} and S^{33}. In Si^{29}, the mixed γ ray, E (7.19 Mev), has an intensity only four times that of the pure $M1$ ground-state γ ray (8.47 Mev). In S^{33}, the mixed ground-state γ ray is nearly equal in intensity to that of the pure $M1$ γ ray producing the first-excited state. However, the mixed transitions in Si^{29} and S^{33} involve a change in the orbital angular momentum of 2 units (they are transitions of the type $s_{1/2}\rightarrow d_{3/2}$), which on the single-particle model are forbidden for $M1$ radiation. It would be possible to argue, therefore, that the mixed transitions emit exclusively $E2$ radiation, and that the relative intensities observed are the relative intensities of $E2$ to $M1$ radiation. However, the apparent absence of suppression of $M1$ radiation in the $s_{1/2}\rightarrow s_{1/2}$ transition in Si^{29} and Mg^{27}, and the strength of $E2$ γ rays corresponding to single-neutron transitions both suggest that the single-particle selection rules do not hold.

3.3. Relative Emission Probabilities of $E3$ (or $M2$) and $E1$ Radiation

In the few nuclei in which $E3$ radiations might be detected (e.g., those of Group 3 of Table II), these γ rays are in some instances in competition with $E1$ radiations of comparable energy. The emission probability at 7 Mev is certainly less than 0.1 percent of that of $E1$ radiation. This upper limit, however, is of the same order of magnitude as the relative emission probability of $E2$ to $E1$ radiation. To improve upon the measured upper limit for the intensity of $E3$ radiation emitted in competition with $E1$ radiation is extremely difficult, even in the most favorable case, *viz.*, Ca^{41}. A reliable estimate of the emission probability of $E3$ radiation can be made best by comparison with $M1$ or $E2$ radiation in a nucleus in which $E1$ radiation does not contribute appreciably to the total radiation width. No suitable nucleus has yet been found.

[49] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[50] All $M1$ γ rays emitted by the capturing states formed by the capture of thermal neutrons in even-even nuclei must violate such selection rules. The only other single-particle transition which can give rise to $M1$ radiation from the capturing state is $s_{1/2}\rightarrow d_{3/2}$, which is also forbidden.

It is not possible, from the existing data, to compare directly the strength of $M2$ radiation with that of $E1$ or any higher multipole. Only two even-odd nuclei, Ni^{61} and Zn^{65}, have been examined in which $M2$ ground-state γ rays are expected to occur. It has already been shown (Sec. 2.1.1) that there is some doubt that the γ rays observed are actually ground-state γ rays. Resonant capture occurs in the odd-odd nucleus, Au^{198}, and the ground-state γ ray emitted must be of the $M2$ type.[46] However, in this instance also, there is no direct proof that the γ ray detected is the ground-state γ ray (see Sec. 2.3.3).

4. ABSOLUTE EMISSION PROBABILITIES

It is of interest to examine the nuclear properties which determine the absolute emission probability or, in other words, the experimental radiation width Γ_r for a γ ray r. The widths of transitions of the same type in different nuclei may be compared among themselves and with theoretical predictions. If radiation is assumed to be emitted through the motion of a single proton or a neutron in the nucleus, the theoretical widths $\Gamma_{th}(E1)$ and $\Gamma_{th}(M1)$, for electric and magnetic dipole radiation, according to Weisskopf,[6] may be expressed in terms of the energy E and the radius of the nucleus R, as follows:

$$\Gamma_{th}(E1)=0.047E^3R^2,$$
$$\Gamma_{th}(M1)=0.021E^3,$$

where the units are so chosen that E must be expressed in Mev, R in units of 10^{-13} cm, and Γ_{th} in ev. The complete expressions for the widths include statistical factors which depend on the quantum numbers of the initial and final single particle states. These quantities are not included in the above expressions.

For purposes of comparison it is convenient to use the quantity $(2J_i+1)|M|^2$, where J_i is the spin of the initial state,[51] and $|M|^2$ is the ratio of the observed radiation width to Γ_{th}, the width predicted by the individual particle formula, and is a measure of the matrix element of the transition.

For emission by highly excited states, where the single-particle approximation is not expected to hold, Blatt and Weisskopf[49] have predicted that the radiation width will also be proportional to D, the average level spacing near the initial state between levels which combine with the lower state with the emission of radiation of the same multipole order. An order of magnitude estimate for the proportionality constant, as shown by Blatt and Weisskopf, is 2 Mev^{-1}. Therefore, for high-energy neutron capture γ rays, the quantity $(2J_i+1)(|M|^2/2D)$ is a better measure of the matrix element.

If the total radiation width of a nuclear state is Γ_γ, then $\Gamma_r=I_r\Gamma_\gamma$, where I_r is the intensity of the γ ray in photons per disintegration. Thus, the partial width of any γ ray emitted by the capturing state may be obtained if the radiation width of a low-lying s-wave resonance is known, and if it can be assumed that the observed absolute intensity of the γ ray produced by thermal-neutron capture is identical with that which would be observed for neutron capture at exact resonance. Such an assumption is probably justified in relation to s-wave resonances in even-odd product nuclei, for, in these nuclei, the spin of all s-wave resonances is 1/2. In even-even or odd-odd product nuclei, we can assume that the observed γ-ray intensities are those which apply at exact resonance only when it is known that the thermal neutron capture cross section is determined entirely by the nearest resonance. Unfortunately, a calculation of the radiation width can be made for only a few nuclei, and, even in these, the validity of the calculation is difficult to estimate. However, in odd-odd nuclei if the spin of the final state differs from that of the ground state of the target nucleus by 1/2, both components of the composite radiation will be of the dipole type. In such a case it is probably sufficient (though not strictly correct) to take the radiative width of any s resonance as the appropriate width for the calculation of the partial width of the ground-state γ ray even though thermal capture is not resonant. The error committed will certainly be small in heavy nuclei where the radiation widths for the two types of s resonance should be almost identical.

In the heavy elements, there is no difficulty in estimating the radiation width, for the greater part of the total width is due to radiation and the low-lying resonances can all be taken as s resonances. The total widths are remarkably constant and for the present purposes no serious error is committed if we assume that $\Gamma_\gamma \simeq 0.1$ ev. However, such an assumption is probably incorrect for lead and bismuth, which have abnormally simple capture γ-ray spectra. In the lighter elements, from atomic weight 80 downwards, the radiation width usually contributes only a small fraction to the total widths of low-lying resonances. The radiation width can be determined by measurement of the absorption cross section by activation methods at the resonance energy, from a measurement of the resonance absorption integral, or by a direct measurement of the resonance yield of capture γ rays. The last method is very difficult and has not yet been accomplished. The activation methods are usually applicable to the odd-charge nuclei but are not suitable to the even-charge nuclei of interest here, for these are either stable, or have activities which are unsuitable for measurement. In these cases, the only available quantity is the thermal neutron capture cross section, and the radiation width may be calculated from this only if a nearby resonance is assumed to be responsible for it. This restriction reduces the number of nuclei which can be examined and eliminates all of the interesting nuclei in Group 4 of Table II.

[51] We adopt here the procedure used by Goldhaber and Sunyar (see reference 1) and others. Although $(2J_i+1)$ is not the correct statistical factor (see references 49 and 62) we include it for convenience in comparing the present results with other data (see reference 56).

TABLE VI. Emission probabilities of $E1$ radiation. Where relevant, the energy of the resonance presumed responsible for the thermal neutron capture is given in the second column and its parameters in the third and fourth. D is the estimated mean level spacing at the neutron binding energy. The γ ray is designated according to the system used in previous communications and its intensity is given in photons per capture in the separate isotope.

Nucleus	Resonance energy	Γ_n	Γ_γ ev	D Mev	γ ray	E Mev	I_r photons per capture	$(2J_i+1)\lvert M\rvert^2$	$(2J_i+1)\lvert M\rvert^2/2D$
Even-charge nuclei:									
Si^{29}	170 kev[a]	37 kev[a]	14	0.5	M	3.54	0.6	0.4	0.4
S^{33}	108 kev[b]	18 kev[b]	26	0.3	G	5.43	0.6	0.2	0.3
W^{183}			0.07[d]	1×10^{-5} [d]	D	6.18	0.13	2.3×10^{-5}	1.2
W^{184}			0.1[c]	4×10^{-5} [d]	A	7.42	0.036	$\geq5\times10^{-6}$	0.06
W^{187}			0.15[d]	1×10^{-4} [d]	F	5.24	0.06	4×10^{-5}	0.2
Odd-charge nuclei:									
V^{52}	2700 ev[e]	780 ev[e]	1.0	2×10^{-2}	A	7.31	0.07	1×10^{-3}	0.02
Mn^{56}	345	22[f]	0.6[f]	2×10^{-3}	A	7.26	0.12	8×10^{-4}	0.2
Co^{60}	120	4[g]	0.27[g]	1×10^{-3}	A	7.48	0.03	1×10^{-4}	0.05
Cu^{64}			0.2[g]	1×10^{-3} [c]	A	7.91	0.25	2×10^{-4}	0.1
Cu^{66}			0.2[g]	1×10^{-3} [c]	B	7.63	0.5	5×10^{-4}	0.3
Rh^{104}	1.3		0.16[h]	1×10^{-4} [c]	A	6.79	0.002	1×10^{-6}	0.006
Ag^{108}			0.1[c]	5×10^{-5}	A	7.27	0.01	3×10^{-6}	0.03
Ag^{110}	5.2		0.17[d]	5×10^{-5}	D	6.67	≤0.004	$\leq2\times10^{-6}$	≤0.02
								Mean	0.26

[a] See U.S. Atomic Energy Commission Report AECU-2040, 1952 (unpublished).
[b] See reference 57.
[c] Assumed value.
[d] Calculated from results obtained by W. Selove, Phys. Rev. **84**, 869 (1951).
[e] See reference 83.
[f] See reference 84.
[g] See Appendix G.
[h] V. L. Sailor, Phys. Rev. **91**, 53 (1953).

Now, D is the average spacing near the neutron binding energy between states which have the same spin and parity as the initial state.[52] In the heavy elements such spacings are not difficult to estimate, for only s resonances are detected in neutron transmission measurements. In the light elements, however, where the spacing of resonances may be 50 kev apart, p-wave and higher-wave resonances are detected, and D must be estimated from those resonances which show the characteristic s-wave interference with the potential scattering. Since only a few of these are usually recognizable, estimates of their spacing are less reliable than those obtained from the heavy elements.

It is well known that a quantity depending on the ratio of the radiation width to the spacing can be obtained from the capture cross sections of medium-fast neutrons. For s-wave neutrons, this capture cross section is related to Γ_γ/D through the equation $\bar{\sigma}=2\pi^2\lambda\!\!\!^{-2}\Gamma_\gamma/D$, where D is a mean level spacing for s resonances. The observed values of $\bar{\sigma}$, however, for neutrons of 200 kev and 1 Mev,[53] give values for Γ_γ/D which are too high by factors between 2 and 10. This discrepancy is due mainly to the contributions of higher orbital angular momenta, which, in elements such as nickel, are large even for neutrons with energies as low as a few tens of kilovolts.[54] It is not possible, however, to estimate the contributions to $\bar{\sigma}$ made by the different angular momenta, and for this reason we have found it necessary here to reject all data based on fast neutron capture cross sections and to use only those results which give separately the two quantities required. Even if this method were free from objection, it would not, in general, yield the information required for the capture cross sections for fast neutrons have been determined by activation measurements which exclude most even-charge nuclei.[55]

4.1. $E1$ Radiation

The results of the comparison of $E1$ radiations are listed in Table VI. It will be seen that the quantities $(2J_i+1)|M|^2$ (column 9) vary over a range of 10^5 while division by $2D$ (column 10) eliminates the greater part of this variation. The matrix elements for the odd-charge nuclei tend to be rather lower than those for even-charge nuclei, but, as will be shown below, none of these entries is completely reliable for one reason or another, and, therefore, this apparent dependence on Z may be spurious. A similar constancy in the rate of emission of $E1$ radiations produced by proton capture in the lightest elements has been reported by Wilkin-

[52] To calculate D, we assume that the spacing between states with spins $J+1/2$ is identical with that between states with spin $J-1/2$, where J is the spin of the target nucleus. Then D is equal to the spacing of s-wave resonances when $J=0$ and twice this spacing when $J\neq0$.

[53] H. Halban and L. Kowarski, Nature **142**, 393 (1938); J. H. E. Griffiths, Proc. Roy. Soc. (London) **A170**, 513 (1939); Hughes, Spatz, and Goldstein, Phys. Rev. **75**, 1781 (1949); L. E. Beghian and H. Halban, Nature **163**, 366 (1949).

[54] A detailed and consistent analysis of some fast-neutron capture cross-section measurements has been given by B. Margolis, Phys. Rev. **88**, 327 (1952).

[55] An exceptionally large value for the radiation width of Ni^{59} has been obtained by E. P. Wigner [Am. J. Phys. **17**, 99 (1949)]. However, it is now known that the activity observed was almost certainly not that of Ni^{59}, which has a very long period; see H. W. Wilson, Phys. Rev. **82**, 548 (1951).

son,[56] although no variation with even or odd Z was noted. The agreement of the theoretical predictions with experiment is perhaps surprising in view of the approximate nature of the theory.

Only those nuclei have been included in Table VI for which the radiation widths or the level spacings near the binding energy can be estimated with some assurance. Probably for neither quantity can such estimates be made to better than a factor of two. As already pointed out, no data are available suitable for the calculation of radiation widths of those nuclei in Group 4 of Table II and the same difficulty is encountered for the two nuclei Be^{10} and C^{13} in Group 1 of that table. Of the heavier nuclei in Table III, the isotopes of lead also are unsuitable, since the radiation widths are not available. The isotope Se^{77} cannot be used because nothing is known about the level spacing D. In Se^{78} the degree to which capture occurs in a state of spin zero is not known. The nucleus Pt^{196} is not included because the capture cross section of Pt^{195} has not been measured, because the radiation width in Pt^{196} is unknown, and because the radiation is composite.

Both silicon and sulfur show a marked resonance at low energies which is responsible for their low scattering cross sections at thermal energies. In S^{33} the shape and energy dependence of the scattering cross section at low energies has been studied by Adair, Bockelman, and Peterson,[57] who showed that the 108-kev resonance was responsible for it; the scattering length at thermal energies can also be accounted for by this resonance.[58] Silicon is similar but no detailed analysis has yet been made. For both nuclei we assume that the thermal neutron capture is due to the lowest resonance and we have calculated the value of the radiation width from the thermal capture cross section and the measured neutron width. There is, as yet, no quantitative check on the validity of this procedure and the results obtained, therefore, must be taken as a rough indication only of the required width. For W^{183} and W^{187} we have assumed without any direct confirmatory evidence that the γ rays listed are the ground-state γ rays. The identification of the ground-state γ ray in W^{184} is certain, but it appears that thermal capture cannot be accounted for entirely by the parameters of the resonance at 4 ev, and, therefore, the value of $|M|^2$ is a lower limit.

Among the odd-charge elements, thermal neutron capture in vanadium, manganese, and cobalt appears to be caused in the main by a low-lying resonance in each case (see Appendix G). The spacings assumed for these nuclei, however, are very rough, and may well be overestimated. For the copper isotopes, the radiation width (0.2 ev) is a very rough value consistent with slow-neutron measurements (see Appendix G). The spacings assumed for the copper nuclei are mere estimates. In the silver isotopes, the identification of the ground-state γ ray is not absolutely certain. The same is true of rhodium. In this element the spacing is uncertain, for only one resonance (at 1.3 ev) has been detected in a range of 100 ev.

Other nuclei which are expected to emit $E1$ ground-state γ rays but which have not been examined are those of Br, Y, Tm, Hf, and Ir. The two nuclei Pr^{142} and Tl^{204} emit $E1$ ground-state γ rays which have been studied, but these nuclei are excluded from the table because they both lie near closed shells and may, therefore, have somewhat larger level spacings than neighboring nuclei and may possess radiation widths which differ considerably from 0.1 ev. Both quantities are unknown for both nuclei. The nucleus Ta^{182} is excluded because it seems probable that the ground-state γ ray was not resolved.

4.2. $M1$ Radiation

The matrix elements for $M1$ radiations and the data from which they were calculated are listed in Table VII. It will be seen that, except for the F^{20} and Al^{28} ground-state γ rays, the correction for the level spacing yields remarkably constant values while the spacing varies over a factor of nearly 10^4. The matrix elements agree with the predictions of Blatt and Weisskopf[49] for F^{20} and Al^{28} but are lower by an order of magnitude for most of the other nuclei shown.

The cadmium data are unsatisfactory in that only one resonance has been detected; the values for D in Table VII were obtained on the assumption that the spacing of all s resonances is 50 ev, a value consistent with that deduced from the neutron width[49] of the 0.17-ev resonance.

The radiation widths of the F^{20} and Al^{28} nuclei have been obtained by direct methods. Rough (and possibly too high) values have been given by Henkel and Barschall.[59] For Al, these authors give $\Gamma_\gamma = 5$ to 15 ev; their results were obtained from the ratio of peak absorption to peak scattering cross sections and are rather smaller than those which can be derived from slow-neutron measurements.[60] We adopt the low value $\Gamma_\gamma = 5$ ev.

5. MECHANISM OF THE RADIATIVE PROCESS

The ratio of the rates of emission of $M1$ and $E1$ radiation, in the few cases where they have been directly compared (Sec. 3. 1), are in agreement with Weisskopf's formula. The absolute values of the emission rates of $M1$ and $E1$ radiation tend to be lower than (but within an order of magnitude of) the values given by the single-particle formula when that formula is modified to take into account the complexity of the initial state. This agreement is remarkable in view of the very large corrections which have been made.

It is clear that the complexity of the initial state must

[56] D. H. Wilkinson, Phil. Mag. **44**, 450 (1953).
[57] Adair, Bockelman, and Peterson, Phys. Rev. **76**, 308 (1949).
[58] D. C. Peaslee, Phys. Rev. **85**, 555 (1952).
[59] R. K. Henkel and H. H. Barschall, Phys. Rev. **80**, 145 (1950).
[60] Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950).

TABLE VII. Emission probability of $M1$ radiation. For explanation of headings, see caption of Table VI.

Nucleus	Resonance energy	Γ_n	Γ_γ ev	D Mev	γ ray	E Mev	I_r photons per capture	$(2J_i+1)\|M\|^2$	$(2J_i+1)\|M\|^2/2D$
Even charge									
Si^{29}	170 kev[a]	37 kev[a]	14	0.5	B	8.47	0.02	0.04	0.04
Si^{29}	170 kev	37 kev	14	0.5	E	7.19	0.08	0.3	0.3
S^{33}	108 kev[b]	18 kev[b]	26	0.3	A	8.65	0.012	0.05	0.08
S^{33}	108 kev	18 kev	26	0.3	B	7.78	0.016	0.08	0.14
Cd^{114}	0.17 ev		0.11[c]	$\sim 10^{-4}$	A	9.05	0.0014	3×10^{-5}	0.15
Cd^{114}	0.17 ev		0.11	$\sim 10^{-4}$	B	8.48	0.0023	6×10^{-5}	0.3
Odd charge									
F^{20}			15[d]	0.4	A	6.63	0.2	1.0	1.2
Al^{28}			5[e]	0.3	A	7.72	0.35	1.1	1.8
Al^{28}			5[e]	0.3	C	6.77	0.014	0.06	0.1
Cl^{36}			0.3[f]	0.04[g]	A	8.56	0.03	2.7×10^{-3}	0.03
								Mean	0.4

[a] See U.S. Atomic Energy Commission Report AECU-2040, 1952 (unpublished).
[b] See reference 57.
[c] B. V. Brockhouse, Can. J. Phys. 31, 432 (1953).
[d] See reference 60.
[e] See text.
[f] See reference 39.
[g] See Kiehn, Goodman, and Hansen, Phys. Rev. 91, 66 (1953).

obliterate to a large extent any simple picture of the radiative process in terms of the motion of a single particle. It is not surprising, therefore, that no major reduction of the rate of emission is apparent in cases where such might be expected on the basis of a strict single-particle model. For example, the matrix elements of the $E1$ ground-state γ rays in Rh^{104}, Ag^{108}, and Ag^{110} (Table VI) are rather small though perhaps not significantly smaller than those of the other γ rays listed. For these three nuclei, the transition must involve a shift in the configuration of both the unpaired neutron and the unpaired proton.[61] Such a simultaneous displacement of two particles should, in the single-particle model, reduce the transition probability. (This hypothesis has been invoked by Moszkowski[62] to account for the weakness of isomeric $E3$ transitions and by Trocheris[63] to account for the absence of β decay in the isomeric state of Y^{87}.) Furthermore, the $M1$ γ rays observed in Mg^{25}, Si^{29}, and S^{33} violate the single-particle selection rule for change of orbital angular momentum. The matrix elements for such transitions (Table VII) are an order of magnitude smaller than those of the F^{20} and Al^{28} ground-state γ rays. However, as yet there is insufficient evidence to show that this difference is derived from single-particle selection rules. Finally, the ratio of the rates of emission of $E2$ to $E1$ radiation in the odd-neutron nucleus Mg^{25} indicates that the radiative mechanism cannot be identified with the simple displacement of a neutron in that nucleus, for in that event the intensity of the $E2$ radiation would be so low that it would be undetectable.

For heavy elements, the initial highly excited state must contain many different configurations, and presumably some always exist which make possible a radiative transition of any given type. The interpretation of the relative emission probabilities of different multipoles would require a detailed knowledge of the density and the distribution in energy of the levels with the appropriate spin and parity; in the absence of such information it is perhaps surprising that the ratio of the transition probabilities of $M1$ and $E1$ radiations follows so closely that predicted by Weisskopf's formula. An understanding of such details requires a complex model of the nucleus; a start in this direction has been made by Bohr and Mottelson.[64]

6. DISCUSSION

It has been shown in Tables VI and VII that the values for the matrix elements for $E1$ and $M1$ radiation tend to be lower than the estimates of Blatt and Weisskopf by about the same amount (an order of magnitude). It follows, therefore, that the ratio of the matrix element for $M1$ radiation to that for $E1$ radiation agrees with the predicted value, *viz.*, $10(\hbar/McR)^2$, which for medium weight nuclei is about 1 percent. (The same result was obtained directly in Table V.)

The difference between the emission probability of $E1$ and $M1$ radiation is sufficiently great and the variations of emission probability in each group are sufficiently low by comparison to make possible a guess of the multipolarity of other high-energy capture γ rays

[61] From shell structure it would appear that the ground state of the odd proton in the odd-even target nucleus is a $p_{1/2}$ state. From β-decay evidence the ground state of the product nucleus has a spin of 1 and even parity. From the shell model the only way such a state could be produced for these three nuclei is by the combination of a $g_{9/2}$ proton with a $g_{7/2}$ neutron. Therefore, in the $E1$ transition the odd proton must change configuration. It should be pointed out again that there is no conclusive evidence in any of these cases that the ground-state γ ray was observed; it is still possible that weak γ rays with higher energies remain to be detected.

[62] S. A. Moszkowski, Phys. Rev. 89, 474 (1953).

[63] M. Trocheris, Physica 18, 1094 (1952).

[64] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 26, No. 14 (1952); A. Bohr and B. Mottleson, Physica 18, 1066 (1952).

in certain cases. The data required are the absolute intensity of the γ ray, the density of states near the initial state, and the total radiation width. Alternatively, if the multipole order of one γ ray in the spectrum is known, that of the others may be deduced with some certainty. In the spectra of nuclei such as V^{52}, Fe^{57}, Co^{60}, where the ground-state γ ray is $E1$, all competing γ rays with comparable intensities and lower energy are probably of the same type. Thus, the capture γ-ray spectrum should reveal the sequence of levels which differ in parity and by one unit in spin from that of the capturing state; in even-odd nuclei such as Fe^{57} the spectrum reveals the sequence of p states. In nuclei such as Mg^{25} or S^{33}, where the ground-state γ ray has even parity, a similar argument applies to those γ rays emitted by the capturing state with energies less than that of the $E1$ γ ray with the highest energy. As pointed out in Appendix C, this conclusion is verified in the case of S^{33}. We cannot conclude, however, that all low-energy γ rays are $E1$, for many of these must be emitted by states other than the capturing state, and their intensity may depend on factors other than multipole order, e.g., the extent to which the initial state is excited.

The weakness of second-order radiation and the fail ure to detect any γ rays of higher order shows that the greater part of the energy emitted in neutron-capture radiation is carried by $E1$ and $M1$ γ rays, for which the emission probability varies as the cube of the energy. Blatt and Weisskopf[49] have attempted to calculate the total radiation width to be expected from Al, Ag, and W, on the assumption that the radiation emitted is entirely of one multipole order. Except for W, the results obtained even for $M1$ radiation are all too high. If the radiation is predominantly $E1$, as our measurements appear to show, their results are about 100 times too high. We have seen that the partial radiation widths predicted by the single-particle model are too high by about an order of magnitude. If allowance is made for this fact, the theoretical result might be reduced by a factor of 10. However, we have seen that the parities of the low-lying levels tend to be the same as those of the ground state, at least for the lighter elements, and in one nucleus (S^{33}) there is evidence that they are distributed in bands. The effect of such an uneven distribution on the calculation of the total width is difficult to estimate and a large measure of disagreement is not surprising.

While the finer details of the distribution of energy levels cannot easily be deduced from the observed spectra of neutron-capture radiation mainly because the experimental resolution has been insufficient, some general effects have been observed. The gross shape of the spectrum expected theoretically has been calculated by Margolis.[65] The net result is a peaked distribution, the peak being at a relatively lower energy when the density of the levels is high. Owing to the insensitivity of the pair spectrometer to low-energy γ rays, the spectrum is difficult to trace reliably near 3 Mev, and in only a few instances is there evidence of the peak in the distribution. In most cases the number of γ rays emitted per unit energy range appears to increase continuously as the energy is reduced to 2.5 Mev, the lowest energy at which it is possible to make measurements with a pair spectrometer. An attempt has been made to determine the variation of level density with energy from the observed shape of the spectrum, but the results are probably unreliable.[66]

There is some evidence for a general reduction in the level density near the closed neutron shells. In the spectra of Zr (50 neutrons) and Ba and Pr (82 neutrons), a decrease in the relative number of high-energy γ rays and an increase in their intensity is indicative of a decrease in level density. A more obvious effect is shown in the γ ray spectra of Au, Hg, and Tl, in which the maximum in the γ ray spectrum is clearly shifted to high energies. However, the level densities near the ground states of Au^{198} and Hg^{200} are very different, and the observed effect could be produced by a concentration of $E1$ radiation in γ rays leading to low-lying excited states with appropriate spin and parity. The effect is most striking in the γ-ray spectrum produced by the two isotopes of lead, Pb^{207} and Pb^{208}, for which the intensities of the ground-state γ rays appear to be near 100 percent. It is well known that the spacing of the levels in Pb^{208} is exceptionally wide. It is noticeable that tin[30] shows no peculiar characteristics, although at this element the 50-proton shell is closed; however, it is doubtful whether any conclusion can be drawn from this observation, for it is not yet known whether the capture spectrum is derived from essentially one isotope or whether all the numerous isotopes of tin make their contribution.

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APPENDIX A. Fe^{57}

It seems certain[20] that the ground state of Fe^{57} is odd and must have a spin of 1/2 or 3/2. If the energy difference of 14 kev between the energies of the two principal γ rays emitted in the decay of Co^{57} is really due to the excitation of a state only 14 kev above the ground state of Fe^{57} (and this is probable, although published evidence[21,22] does not prove it), the $M1$ character of the 14-kev transition shows that the spin of that state must be 1/2, 3/2, or 5/2. The last alternative can be ruled

[65] B. Margolis (private communication).

[66] J. D. Jackson (private communication); J. D. Jackson and B. B. Kinsey, Phys. Rev. 82, 345 (1951).

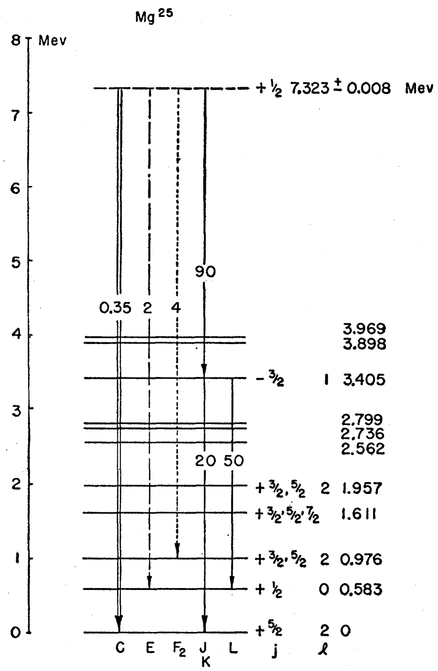

FIG. 1. Decay scheme for the capture γ rays of Mg^{25}. For explanation, see reference 70, Appendix B.

out, for this state is not excited directly in the decay of Co^{57}, for which the spin[67] is 7/2.

That the spin of the ground state is 1/2 and that of the 14-kev state is 3/2 can be shown from a consideration of the internal conversion of the two principal γ rays (133 kev and 119 kev) emitted in the decay of Co^{57}. The number of conversion electrons produced by these γ rays are about equal, although the ratio of the intensities of the 133-kev to the 119-kev γ ray is roughly[68] 1 to 3. If the lifetime of the 133-kev state is short (as would appear from reference 22) neither γ ray can be $E3$ as has been claimed.[69] In iron, at this energy, the conversion coefficients of electric and magnetic radiations of the same multipole order are approximately the same. It follows that the two γ rays are of different multipole orders, one being electric and the other magnetic, for they have the same parity. The 119-kev γ ray has the highest intensity and is, therefore, of the lowest multipole order; and since this γ ray must excite the 14-kev state, it follows that the spin of the 14-kev state must be greater than that of the ground state, which, therefore, must be 1/2. It then also follows that the 133-kev state has spin 5/2.

Since both the ground state and the 14-kev state are p states, both should be produced by emission of $E1$ radiation. The 7.6-Mev peak, however, appears to be normal in all respects:[14] the energy equivalent of its width and the displacement between the peak and its end point are just those expected of a homogeneous γ ray (100 ± 5 kev and 60 ± 5 kev, respectively). One of the two γ rays, therefore, must be weaker than the other. If the weaker γ ray is the ground-state γ ray, it must be at least 20 times weaker than the other because otherwise its existence would have been detected in the latter of the two parameters just mentioned. It seems much more likely, therefore, that the ground-state γ ray is the stronger of the two, for in that case the presence of a weaker γ ray (with lower energy) would not be revealed as an increase in the width of the peak, if its intensity were less than one third of the other.

APPENDIX B. Mg^{25}

The decay scheme for this nucleus is shown in Fig. 1, which has been constructed[70] from the positions of the energy levels found by Endt and co-workers.[71] The parities and spins of some of these levels are shown on the right, together with the orbital angular momentum found by Holt and Marsham.[27] The 1.611-Mev state was not examined by Holt and Marsham. It is excited in the decay[72] of Na^{25}, from which it may be deduced that its spin is 3/2, 5/2, or 7/2.

Recent measurements on the energy of the strong γ ray J gives the value[25] 3.918 ± 0.004 Mev and identify it with the transition from the capturing state at 7.323 Mev to the state at 3.405 Mev. A recalculation of the intensity of the γ ray J, based on a more reliable estimate of the energy dependence of the coincidence counting rate of the spectrometer,[23] gives 0.7 photon per capture in natural magnesium. This is equivalent to 1.4 photons per capture in Mg^{24}, which is obviously too high.[73] We adopt the more realistic figure 0.9.

The 3.405-Mev state is the lowest p state found by Holt and Marsham; its spin must be 1/2 or 3/2. There exist two strong γ rays K and L which have energies which correspond to transitions from this state to the ground state and to the first excited state, respectively. The sum of their intensities is roughly equal to that of the γ ray J. Since both of these γ rays must also be of odd parity, and since the ground state of Mg^{25} has a spin of 5/2, it follows that the spin of the 3.405-Mev state is 3/2, for otherwise the transition from it to the ground state (the γ ray K) would be $M2$ and would not be expected to compete with the γ ray L. The existence

[67] Baker, Bleaney, Bowers, Shaw, and Trenam, Proc. Phys. Soc. (London) A66, 305 (1953).
[68] L. G. Elliott (private communication).
[69] Cheng, Dick, and Kurbatov, Phys. Rev. 88, 887 (1952).

[70] In this and subsequent decay schemes, electric and magnetic radiations are represented by full and by broken lines, respectively, dipoles by single lines, quadrupoles by double lines, etc. Unidentified γ rays are shown by dotted lines. The figures in the middle of the lines give the intensities in photons per 100 captures; vertical figures are those obtained with the pair spectrometer and slanting figures are those obtained by Braid (reference 74).
[71] Endt, Enge, Haffner, and Buechner, Phys. Rev. 87, 27 (1952).
[72] E. Bleuler and W. Zünti, Helv. Phys. Acta 20, 195 (1947).
[73] This result is incompatible with the equality of the contributions made by Mg^{24} and Mg^{25} to the total magnesium thermal-capture cross section, as found by Pomerance (reference 15); the errors in that determination were large (about 30 percent) and may account for the discrepancy.

of the γ ray L has been confirmed by Braid[74] and its intensity measured by him with results in rough agreement with our own. Braid has also found weaker γ rays (at 1.9 and at 1.1 Mev) which can probably be assigned to Mg^{26}. One might expect to observe the γ ray produced in the transition from the 3.405-Mev state to that at 1.611 Mev. Part of the 1.9-Mev γ ray might be emitted in this transition.

The γ rays ascribed to Mg^{25} account for the greater part of the de-excitation of this nucleus. It will be seen from Fig. 1 that the sequence of events is determined very largely by the emission of $E1$ radiation.

APPENDIX C. Si^{29}

The decay scheme of this nucleus is shown in Fig. 2, which is constructed from the positions of the energy levels determined by Endt *et al.*[75] The main feature of the γ-ray spectrum is a cascade of two very strong γ rays (K and M) of nearly equal intensity. Recent measurements[23] of the energies of these γ rays give the values (K) 4.933±0.005 Mev and (M) 3.540±0.006 Mev. Added together, these energies are in agreement with that of the ground-state γ ray B, which is 8.468 ±0.008 Mev. The accuracy of these measurements is sufficient to identify the intermediate level as that at 4.934 Mev.[75] As in Mg^{25}, the strong γ ray M excites the lowest p state found by Holt and Marsham.[26] In Si^{29}, this p state is the highest member of a close triplet. While it is not clear from the work of Holt and Marsham whether or not the other two states of the triplet also have odd parity, the energy measurements make it certain that the strong γ ray M excites only the highest component, and that the transitions to the others are much less frequent.

A recalculation of the intensities of these γ rays, based on the original data[12] and on the new counting efficiency curve,[23] shows that the intensity of the γ ray M is a little less than that of K. Roughly the intensity of both is about 0.7 photon per capture in Si^{28}. The equality of the intensities of the γ rays K and M shows that the transition from the 4.934-Mev state to lower intermediate states are relatively infrequent. Transitions from this state to the first and second excited states would produce γ rays with the energies 3.656 and 2.907 Mev. Neither has been detected although the detection of a weak γ ray with the latter energy is difficult experimentally. The 3.656-Mev γ ray, however, would produce a peak in the coincidence spectrum partly resolved from that of M but lying just above it. Such a peak has not been found; its intensity is less than one-tenth of that of M (or K). It seems certain that the 3.656-Mev transition must also be $E1$, for of the two possibilities for the spin of the first excited state obtained from the results of Holt and Marsham, only a spin of 3/2 is consistent with an allowed decay of P^{29} to this state.[76] It is not surprising that the 3.656-Mev γ ray is not observed, for it is only necessary that the matrix element of this transition be less than one-third of that for the γ ray K.

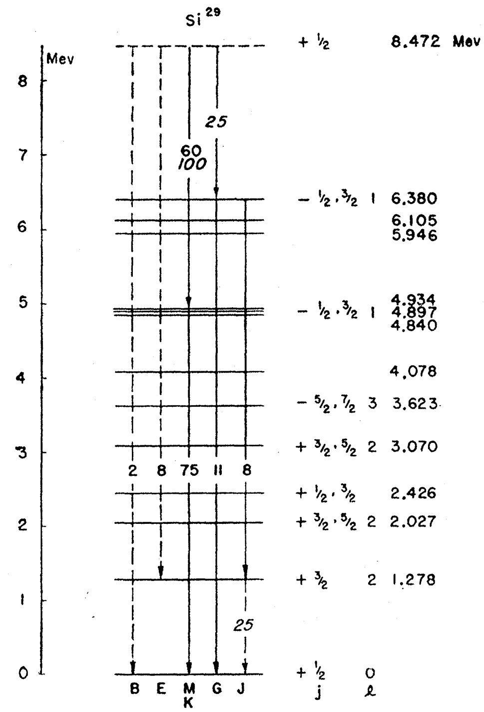

FIG. 2. Decay scheme for the capture γ rays of Si^{28}. For explanation, see reference 70, Appendix B.

Few of the other intermediate states appear to be excited to an appreciable extent by transitions from that at 4.934 Mev, for of the three low-energy γ rays found by Braid,[74] one corresponds to a transition from the first excited state to the ground state, another to a transition from the capturing state to the p state at 6.38 Mev, and the third cannot as yet be fitted into this decay scheme. The intensity of the former (25 percent per capture in Si^{28}) is somewhat greater than the intensities of the two γ rays known to be feeding this level. The intensity of the latter is somewhat greater than that of the γ rays produced by the 6.38-Mev level, which, as is to be expected, produces transitions to the ground state and to the first-excited state.

APPENDIX D. S^{33}

Most of the numerous γ rays emitted by sulfur can be accounted for by the excitation of the nucleus S^{33}. The contribution of S^{33} to the thermal capture cross section is unknown; presumably it is small like that of S^{34} and S^{36}. A tentative decay scheme is shown in Fig. 3, in which the positions of the excited states found by

[74] T. H. Braid (private communication).

[75] Endt, Van Patter, Buechner, and Sperduto, Phys. Rev. **83**, 491 (1951).

[76] Roderick, Lönsjö, and Meyerhof, Phys. Rev. **90**, 371 (1953). The spin of P^{29} must be 1/2, for the β decay to the ground state of Si^{29} is of the super-allowed type.

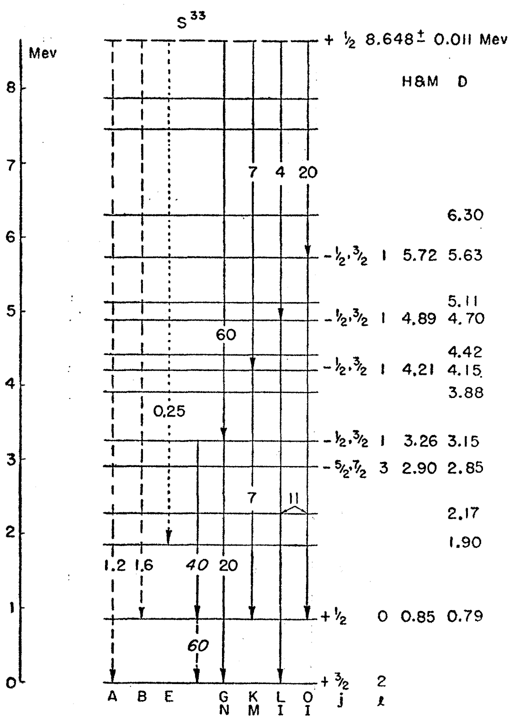

FIG. 3. Decay scheme for the capture γ rays of S^{33}. For explanation, see reference 70, Appendix B.

Holt and Marsham[26] and by Davison[77] are shown on the right. The energies of these states are not known with the precision of those of the nuclei discussed above and for this reason the identification of the sulfur γ rays is less certain.

Excepting the two weak $M1$ transitions, A, producing directly the ground state, and B, the first-excited state, and another of unknown multipolarity producing the second excited state, the remainder of the γ-ray spectrum is obviously derived from transitions to a succession of p states found by Holt and Marsham.

The strongest γ ray is the γ ray G, which excites the lowest of these p states (at 3.2 Mev). The γ ray G is followed by the emission to the ground state of the γ ray N, which is noticeably weaker than G. It is clear from this that some of the excitation of the 3.2-Mev state is relieved by the emission of γ rays in transitions to intermediate states. These γ rays have energies too low for detection by the pair spectrometer, but a 2.3-Mev γ ray has been detected by Braid[74] which may be identified as the transition between the 3.2-Mev level and the first excited state at 0.8 Mev. The intensity of this γ ray, when added to that of N, is roughly equal to the intensity of G.

Similar transitions to the ground state and to the first excited state are to be expected from the higher p states, for they will all be of $E1$ type, and some of these can be identified. (Those which have not been recorded are such that the coincidence peaks which they would produce are masked by the tails of much stronger γ rays.) It follows that the first level is excited very frequently in the neutron capture process. The γ ray emitted by this state (0.8 Mev) has been detected and measured by Braid;[74,78] its intensity (0.6 photon per capture)[74] is in agreement with the sum of the intensities of the γ rays known to be feeding this level.

APPENDIX E. Ca^{41}

A decay scheme for this nucleus is shown in Fig. 4, in which the positions of the energy levels are those obtained by Sailor,[79] and the spins and parities of the levels are those obtained by Holt and Marsham.[29] It is clear that the two strong γ rays C and D are of $E1$ type, and account for the greater part of the neutron captures producing Ca^{41}. A recalculated value for the intensity of the γ ray C is 40 photons per 100 captures in natural calcium; this value corresponds roughly to 80 photons per 100 captures in Ca^{40}, for about half[15] of the natural capture cross section of this element is derived from Ca^{42}. None of the remaining calcium γ rays can be identified with certainty, for the positions of the excited states of Ca^{43} are mostly unknown.

A strong γ ray with an energy of 1.9 Mev has been detected by Braid.[74] This γ ray clearly represents the decay of the first excited state. No γ ray was found by Braid at 2.4 Mev, which would correspond to the

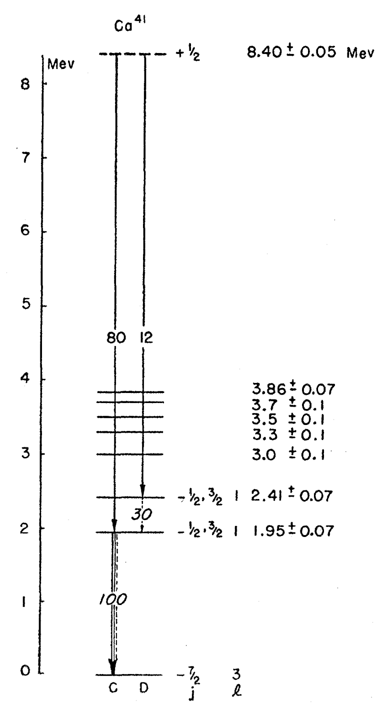

FIG. 4. Decay scheme for the capture γ rays of Ca^{41}. For explanation, see reference 70, Appendix B. The transition from the first excited state to the ground state is shown as either $E2$ or $M3$.

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[77] P. W. Davison, Phys. Rev. **75**, 757 (1949).

[78] T. H. Braid, Phys. Rev. **90**, 355 (1953).

[79] V. L. Sailor, Phys. Rev. **75**, 1836 (1949).

transition between the second excited state and the ground state. This transition is evidently forbidden (as in Ti^{49}, discussed below) and the excitation of the second state is relieved by a transition to the first, for a γ ray of 0.48 Mev has been measured by Braid. The spins of the first two states could be both 1/2, both 3/2, or one 1/2 and the other 3/2. The transition from the first excited state to the ground state, therefore, is $E2$ or $M3$.

APPENDIX F. Ti^{49}

The decay scheme for this nucleus is shown in Fig. 5, in which the energies of the levels shown on the right are those obtained by Pieper.[80] This nucleus has not been examined by Holt and Marsham; the γ-ray spectrum, however, is very similar to that of Ca^{41}, and since the nucleus Ti^{48} contributes the greater part of the capture cross section of natural titanium, the γ rays have been measured with some precision and their identification is not in doubt.

As in Ca^{41}, Braid[78] has measured two strong γ rays with energies equal to that of the first excited state (1.4 Mev) and to the difference (0.3 Mev) in the energies between that state and the second excited state. In addition, he has found some evidence[74] for the existence of a 1.7-Mev γ ray, corresponding to a direct transition from the second state to the ground state. The intensity of this γ ray, if it exists, is 0.1 photon per capture or less. If this is indeed its origin, then the spins of the first and second excited states must be 1/2 and 3/2, respectively, and the competing γ rays are $M1$ and $E2$, contradicting a suggestion made by Breit[80] that the spins of these states are in the reverse order.

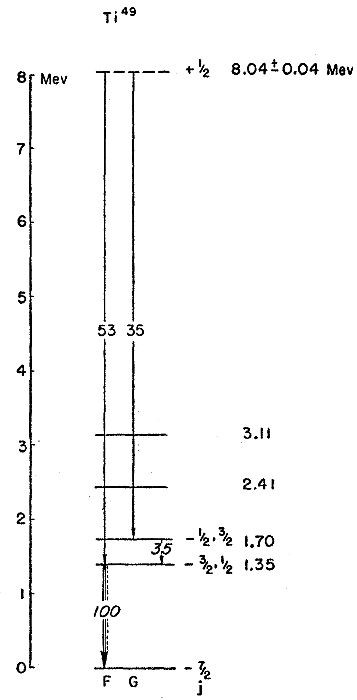

FIG. 5. Decay scheme for the capture γ rays of Ti^{49}. For explanation, see reference 70, Appendix B. The transition from the first excited state to the ground state is shown as either $E2$ or $M3$.

APPENDIX G. NOTES ON SOME ODD-CHARGE NUCLEI

V^{52}

The parity of the ground state of V^{52} is certainly even, for it decays by an allowed transition to the first excited state of Cr^{52}, which, presumably, is even and has a spin of 2 units. This conclusion has been verified by recent measurements on the (d,p) reaction.[81] The spin of V^{52} is probably 3 units. If this is true, the ground-state γ ray is $E1$ whatever the spin of the capturing state. The scattering of thermal neutrons seems to be determined largely by the resonance at 2700 ev,[82] and we assume that the thermal absorption cross section is likewise derived from this resonance.

Mn^{56}

In manganese the thermal-neutron scattering and absorption cross sections seem to be derived mainly[83] from the 345-ev resonance, for which the spin is 3 units. The spin of Mn^{56} is 5/2. While the classification of the β decay of Mn^{56} is uncertain ($\log ft \simeq 7$), the spin of the ground state is probably 3 units and at most does not differ from this by more than 1 unit. Provided that the spin of Mn^{56} is not more than 3 units, the ground-state γ ray must be $E1$ regardless of the spins of the resonances which contribute to the thermal neutron capture cross section.

Co^{60}

The neutron scattering in cobalt at low energies seems to be derived[58] from the 120-ev resonance and is consistent with a spin of 4 units. The total cross section at exact resonance has been measured by Seidl[84] and is consistent only with a spin of 4 units. However, the value of the neutron width obtained from the strength of the resonance $(\sigma_0\Gamma^2)$[85] is about 4 ev, which suggests that the spin is 3 units. The actual value of the spin, therefore, is still uncertain. The radiation width is obtained from this value of Γ after multiplication by the ratio of the resonance absorption and scattering integrals.[60] It is 0.27 ev and accounts for about one-half of the thermal absorption cross section. The remainder must be due to the tails of other resonances.

Assuming that the spin of the ground state of Co^{60} is 5 units and that that of the isomeric state at 59 kev is

[80] G. Pieper, Phys. Rev. **88**, 1299 (1952).
[81] J. S. King and E. H. Beach, Phys. Rev. **90**, 381 (1953).
[82] M. Hamermesh and C. O. Muehlhause, Phys. Rev. **78**, 175 (1950).
[83] Harris, Hibdon, and Muehlhause, Phys. Rev. **80**, 1014 (1950).
[84] F. G. P. Seidl, Phys. Rev. **75**, 1508 (1949).
[85] W. W. Havens and L. J. Rainwater, Phys. Rev. **83**, 1123 (1951); A. W. Merrison and E. R. Wiblin, Proc. Roy. Soc. (London) **A215**, 278 (1952).

2 units, it follows that the ground-state γ ray is $E1$, if the spin of the 120-ev resonance is 4 units, while that leading to the isomeric state is $M2$, and, presumably, forbidden. If the spin of the resonance is 3 units, these multipole orders are interchanged. It is clear, therefore, that the highest energy γ ray observed must be $E1$ although energy measurements do not determine whether this γ ray is the ground-state γ ray or that leading to the isomeric state.

Cu

There is no evidence that the thermal capture of neutrons in copper is due predominantly to any particular resonance. Since the spins of both copper isotopes are 3/2 and since it is very probable that the spins of both Cu^{64} and Cu^{66} are unity (both decay by allowed β transitions to the ground states of the product nuclei), the ground-state γ rays of both must be $E1$ regardless of the spins of the capturing states. The positions of the resonances have not been accurately determined, but it is clear from slow neutron measurements and from the detection of the Doppler-effect[86] that their widths cannot be more than a few ev. We adopt 5 ev for the total width, and, from the ratio of the resonance integrals we find that the radiation widths are of the order of 0.2 ev.

P^{32}

The shape of the angular distribution[81] of the protons in the (d,p) reaction suggests that the spin of the ground state of P^{32} is 1 or 2. If the latter, the weakness of the ground-state γ ray might be explained by its composite character. King and Beach[87] have found that the first excited state is produced by ingoing neutrons with an orbital angular momentum of 2 units, the second, third, and fourth (0.51, 1.15, and 1.32 Mev) by a mixture of $l=0$ and $l=2$. The spins of the last three states, therefore, would appear to be unity, and the γ rays producing them are $M1$, regardless of the spin of the capturing state. Of these γ rays, those producing the second (C) and the third (D) are much stronger than those producing either the ground state or the first excited state; the γ ray D (6.76 Mev) is some fifty times stronger than the ground-state γ ray. The excited states at 2.18 and 2.23 Mev are again mixed s and d states for the odd neutron, and the γ rays producing them are less powerful. The first odd states to appear are at 3.26 and 3.32 Mev and seem to be mixed p and f states for the odd neutron. If these states are indeed of mixed character, their spin is 2, and the γ ray producing them can contain $E1$ radiation. The strong γ ray L (4.68 Mev) can be identified with one of these γ rays. Its intensity is about the same as that of the $M1$ γ ray D; it is, however, very different from the preponderant intensities of the $E1$ γ rays in the even-odd nuclei. As yet, it is not possible to determine whether this weakness is due to the admixture of $M2$ radiation derived from nonresonant capture or whether, like the ground-state γ ray in N^{15}, it is due to some other cause.

[86] Coster, DeVries, and Diemer, Physica **20**, 281 (1943).

[87] J. S. King and E. H. Beach, see reference 81; and E. H. Beach (private communication).