This experiment, the result of which was previously published,[3] does not show any maximum at 15 cm Pb or more, but indicates a small maximum at 7 cm.

I have repeated the experiment as described[3] and have reached the conclusion that this maximum at 7 cm Pb was due to statistical or other fluctuations, and should not be considered. As an effect like the one mentioned by Tsai-Chü could be more or less obliterated by a very important background of oblique rays, I placed another counter tray directly below the absorbent and measured the fivefold coincidences in order to make sure that the radiation really comes from the lead. The results were also negative.

The first curve of Fig. 1 is the same one which we have previously published. It was obtained with two crossed trays of 12 thin glass counters each with fourfold coincidences. The second curve was obtained with two trays of 10 counters instead of 12 (this explains the difference of ordinates). The measurements were carefully checked, and the precision of each point is 1 percent. The 8 percent ratio of fourfold to fivefold coincidences shows that the radiation emerging from the lead is responsible for only 27 percent of the observed counting rate. This explains the small amplitude of the first, well-known maximum.

[1] Tsai-Chü, Phys. Rev. **83**, 867 (1951).
[2] W. Bothe and H. Thurin, Phys. Rev. **79**, 544 (1950).
[3] R. Mazé and Tsai-Chü, Compt. rend. **232**, 224 (1951).

The β-Decay of Radium E and the Pseudoscalar Interaction*

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(Received October 25, 1951)

The selection rules associated with the five forms of β interaction[1] imply that the only type of transition which can reveal the presence of the pseudoscalar (P) interaction is a $0\rightarrow0$ yes transition. The contribution of the P interaction to all other types of transitions will be two orders of "forbiddenness" smaller than the contribution from the tensor (T) or axial vector (A) interaction which must be present. Examination of the list of radioactive nuclei[2] shows that one of the most promising candidates for a $0\rightarrow0$ yes transition is RaE, provided that its β spectrum is simple.[3] If we assume, as in the past, that the β spectrum of RaE is simple, then the forbidden shape which is observed[4] can be explained on the assumption that the spin change is 2 units and that the transition does not involve a parity change. The recent successes of the shell model make it desirable to reexamine this theoretical fit since the RaE nucleus, with its 83 protons and 127 neutrons, is ideally suited for shell model predictions. The shell model predicts[2] that the extra proton is $h_{9/2}$, $f_{7/2}$ or $p_{3/2}$ and that the extra neutron is $i_{11/2}$, $g_{9/2}$ or $d_{5/2}$. The shell model prediction is therefore unequivocal that the parity of RaE is odd although the prediction for the spin is not as clearcut (spin 2 or 0 is favored). Since the parity of the final even-even nucleus must be even, the β-ray transition in RaE must involve a parity change, and the previous fit with no parity change must be regarded as an accident.

We have attempted to fit the RaE β-spectrum by assuming a parity change and considering spin changes from 0 to 2; a spin change larger than 2 is excluded by the lifetime. All possible linear combinations of the five interaction forms (S, V, T, A, P) were examined except those excluded by the Fierz condition,[5] namely (SV) and (TA). The forbidden correction factors were calculated using the formulas of Konopinski and Uhlenbeck[6] and the interference formulas of Smith.[7] The finite radius corrections were taken from the paper by Rose and Holmes.[8] No corrections were applied for screening by the atomic electrons; these are said to be

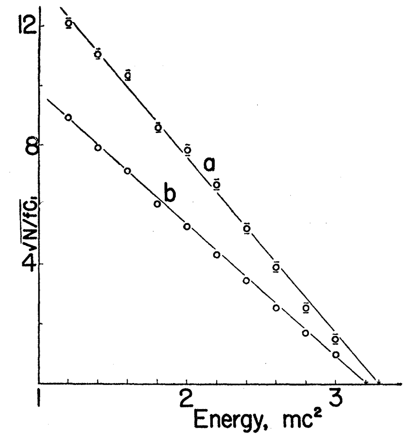

Fig. 1. Kurie plots of the RaE spectrum for (TP) mixture of interactions (a) $W_0=3.29$, $\Gamma=12.8$; (b) $W_0=3.20$, $\Gamma=13.8$.

small.[9] Since the chief feature of the correction factor needed to explain the spectrum of RaE is the large ratio ρ (about 2.6) of its value at low energies ($W=1.2\ mc^2$) to its value at high energies ($W=3.0$), it is possible to eliminate all but one of the linear combinations (TP) either by inspection or by maximizing the theoretical ρ.

The details are as follows: $\Delta J=2$, yes gives rise to a unique correction factor on either the T or A theories, which do not interfere; ρ turns out to be 0.7 which is almost a factor 4 too small. $\Delta J=1$, yes allows the following four linear combinations: (ST), (SA), (VT), (VA). For (ST) and (VA), the maximum value of ρ is less than 1.5 and for the other two combinations less than 1.3. These ratios are still too low by a factor of 2. $\Delta J=0$, yes allows the linear combinations (AP) and (TP); the A interaction alone allows the maximum value 1.2 for ρ whereas T alone allows 0.9. The linear combination (AP) does not fare any better; however, for the linear combination (TP) the maximum value of ρ is 3.6, and hence this theory has been subjected to further scrutiny.

The correction factor for the linear combination (TP) corresponding to $\Delta J=0$ yes is, in the notation of Smith:

$$C_{1(T+P)}=(M_0+\tfrac{2}{3}KN_0+\tfrac{1}{9}K^2L_0)+2\Gamma(N_0+\tfrac{1}{3}KL_0)+\Gamma^2L_0, \quad (1)$$

where $\Gamma=-i\lambda_P\int\beta\gamma_5/\lambda_T(\int\beta\sigma\cdot r)^*$ is taken to be real.[10] The large ratios occur where the nearly constant functions M_0, N_0 and L_0 almost cancel, thereby enhancing the importance of accurate values of these functions. Thus, an error in the finite radius corrections of approximately 0.1 percent leads to an error of up to 25 percent in $C_{1(T+P)}$ and explains the large theoretical errors assigned to the points in the Kurie plot of Fig. 1, corresponding to $\Gamma=12.8$ in the correction factor C_1 of Eq. (1). Figure 1 also contains a Kurie plot drawn for an end point of $W_0=3.2\ mc^2$, instead of the accepted $W_0=3.29$, and $\Gamma=13.8$; the required ρ is now 1.9 and the maximum attainable with other mixtures is 1.55 for (ST) or (VA). The theoretical errors in curve (b) are about half those in curve (a); for both curves, the errors are larger than the experimental errors. Reducing the endpoint to $W_0=3.15\ mc^2$ destroys the (TP) fit completely.

Within the errors noted previously, the linear combination of tensor and pseudoscalar interactions corresponding to $\Gamma=13\pm1$, can be regarded as giving a satisfactory fit of the RaE spectrum. Moreover, it is the only linear combination which can explain the forbidden shape of the RaE spectrum if the spectrum is simple and if the parity prediction of the shell model is accepted. Subject to this qualification, our calculation provides the first clearcut evidence for an admixture of the pseudoscalar interaction to explain all β-ray phenomena. It is evident that the $0\rightarrow0$ yes transition which is indicated for RaE cannot decide whether the S or V interaction must also be added to the (TP) combination.

We are indebted to Mrs. Petschek for assistance with the numerical calculations.

* This work was supported by the AEC.
[1] See E. J. Konopinski, Revs. Modern Phys. **15**, 209 (1943).
[2] Mayer, Moszkowski, and Nordheim, Argonne National Laboratory Report 4626 (1951); see also A. G. Petschek, Rochester Report 3035 (1951).
[3] Zavel'ski, Umarov, and Matushevski [J. Exptl. Theor. Physiks (U.S.S.R.) **19**, 1136 (1949), reported in Brookhaven Guide to Russian Scientific Periodical Literature **3**, 147 (1950)] have claimed that a very weak γ-ray (with an intensity of 0.1 percent) accompanies the β-decay of RaE; this claim, however, has not been substantiated by any of the numerous experimentalists who have studied RaE.
[4] Compare Flammersfeld, Z. Physik **112**, 727 (1939); G. J. Neary, Proc. Roy. Soc. (London) **A175**, 71 (1940) and most recently L. M. Langer and H. C. Price, Jr., Phys. Rev. **76**, 461 (1949) and R. Morrissey and C. S. Wu, Phys. Rev. **75**, 1288 (1949).
[5] Compare M. Fierz, Z. Physik **104**, 553 (1936), and the recent work on the β-decay of H^3 and He^6. We have not applied the de Groot condition [S. R. de Groot and H. A. Tolhoek, Physica **16**, 456 (1950)] because there is no experimental evidence to support it.
[6] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).
[7] A. M. Smith, Phys. Rev. **82**, 955 (1951).
[8] M. E. Rose and D. K. Holmes, Oak Ridge National Laboratory Report 1022 (1951); see also Phys. Rev. **83**, 190 (1951). We are indebted to Dr. Rose for correspondence concerning these calculations.
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Relaxation Effects in Ferromagnetic Resonance*

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(Received November 1, 1951)

By investigating the ferromagnetic resonance effect at high levels of microwave power, the saturation of the electronic spin system has been observed. This experiment, analogous to the saturation effect extensively studied in the nuclear and electronic paramagnetic resonance,[1] provides a means of determining the spin-lattice relaxation time, T_1, which is the characteristic time describing the transfer of energy from the spin system to the crystal lattice. The word "saturation," as used here, denotes a heating-up of the spin system, and so is used in a different way than is customary in connection with ferromagnetism.

Two methods are used for observing saturation. The first is a measurement of the decrease in the imaginary part of the permeability, μ'', as the microwave magnetic field strength, H_1, is increased. There should be a concomitant decrease in M_z, the component of magnetization along the static field, and this is the basis of the second method. The change in M_z is observed by pulsing the microwave field and observing the video voltage induced in a pick-up coil with its axis along the static field. This voltage is proportional to M_0-M_z, where M_0 is the total magnetization, and M_z is the steady-state value of the component of magnetization along the static field when the microwave field is on.

The samples used were single crystals of nickel ferrite,[2] made into spheres of about 0.5-mm diameter. Microwave power was supplied to the rectangular cavity by a magnetron, operating at 9000 Mc/sec. This generated 1-μsec pulses with a repetition rate of 500 pps. The influence of repetition rate was shown to be negligible, indicating that the over-all heating of the sample was negligible.

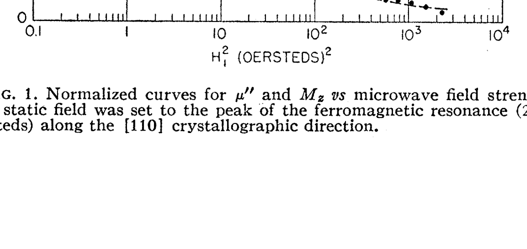

Fig. 1. Normalized curves for μ'' and M_z *vs* microwave field strength. The static field was set to the peak of the ferromagnetic resonance (2800 oersteds) along the [110] crystallographic direction.

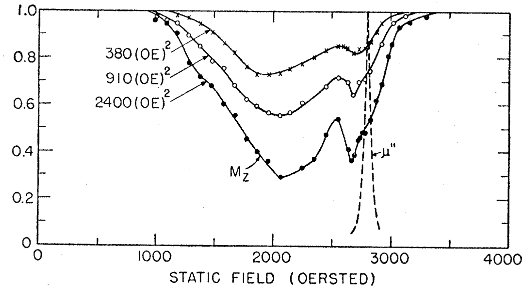

Fig. 2. Normalized results for M_z *vs* H_0 along a [110] axis, H_1^2 being a parameter. The dashed curve is the normalized resonance for μ'' at small values of H_1^2.

From the classical equation of motion[1] for an assembly of magnetic spins, one expects that at resonance μ'' should decrease in proportion to M_z. This is not confirmed by the experimental data shown in Fig. 1. The value for the spin-lattice relaxation time derived from the M_z-curve is $T_1=3\times10^{-8}$ sec.

The dependence of μ'' and M_z on the static field, H_0, is shown in Fig. 2. The changes in M_z occurred over a broad range of H_z, but no effect was observed for field strengths greater than that at which the narrow resonance for μ'' occurs. A second sample gave essentially the same results. Crystalline anisotropy shifted both the μ''- and M_z-curves a few hundred gauss when the sample was rotated, but had no other effect.

The unexpected results clearly show that the spins cannot be treated as a single system with a macroscopic equation of motion for the magnetization vector. On the basis of the spin-wave model, the microwave field creates only spin-waves of very long wavelength. There are only a limited number of these states, and when they are nearly filled, a decrease of μ'' is observed, although the total magnetization has hardly changed. Polder noted that the direct interaction of these long spin-waves with the lattice is weak ($T_1\sim10^{-3}$ sec).[3] It is proposed that the energy of the long spin-waves is transferred to shorter spin-waves, and the rate of this process determines the saturation for μ''.

The transitions at still higher microwave power cause a change in the total magnetization M_z. These transitions, occurring mostly at lower static fields than the regular resonance, represent a breakdown of the selection rule that only spin-waves of zero wave number can be created. Theory and experiment indicate that the presence of lattice imperfections is important for these transitions. In a way which is not understood at present, the quanta absorbed in these processes are readily communicated to the whole spin system. In the steady saturated state the total number of quanta absorbed per unit time is balanced by the number of quanta transferred from the spin system to the lattice, which is equal to the number of spins divided by the relaxation time. In this way a value $T_1=3\times10^{-8}$ sec is obtained. This general argument is independent of any particular model. The spin-wave model is essentially a zero-temperature approximation and is, strictly, not applicable to these experiments where the spins are brought to a very high temperature. Other theoretical treatments[4] also make the approximation that the ferromagnetic spins are not highly excited, and are therefore not very helpful in this case.

The measurements will be extended over a range of temperatures to obtain more information about the relaxation process.

* This work was supported by the ONR.
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[2] Supplied through the courtesy of Bell Telephone Laboratories, Murray Hill, New Jersey.
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[4] J. H. Van Vleck, Phys. Rev. **78**, 266 (1950).