It is a by-product of the considerations reported above that spaces with an odd number of dimensions would behave in a quite different manner from spaces with an even number of dimensions when subjected to inversions (the relations $\gamma^\mu\gamma^5+\gamma^5\gamma^\mu=2\delta_{\mu 5}$, with $\gamma^5=\gamma^1\gamma^2\gamma^3\gamma^4$, can be extended only to the latter). This supports the view expressed by several authors that, should our world become too limited with only four dimensions, the natural generalization of it would be a six-dimensional, rather than a five-dimensional world.

Coming back to physics, we wish to point out, finally, that the rejection of the Majorana theory for the neutrino would not forbid the interpretation of double beta-decay phenomena, should they be definitely proved to occur. Some suggestions have already been made in this direction;[3,9] others may be advanced, in our opinion, but a discussion of this matter is, perhaps, premature.

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An Experimental Search for Self-Trapped Electrons in the Alkali Halides*

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TWO detailed calculations have been made on the self-trapped electron problem in ionic crystals originally proposed by Landau. Frohlich, Pelzer, and Zienau[1] treated the dielectric as a continuous medium with a single vibrational frequency for long longitudinal polarization waves. They concluded that the energy levels of these electrons do not exist below the conduction band and, in fact, differ little from the free electron. Thus, electrons would never be self-trapped but would move through the lattice almost as the free electron. Markham and Seitz[2] considered the dielectric as a discontinuous medium and utilized a self-consistent field method. Their calculations for NaCl gave thermal and optical activation energies of -0.13 ev and -0.68 ev, respectively. Therefore the self-trapping centers should be stable at 4.2°K, provided that the smearing out of the electron over several lattice sites does not permit it to diffuse rapidly through the crystal until it forms a more stable, e.g., F, center.

Since there is a fundamental difference in these approaches to the problem, it seemed advisable to perform an experimental observation on NaCl and KCl at 5°K. Crystals[3] produced by the Harshaw Chemical Company were mounted in a low temperature optical cell[4] and then x-rayed at 5°K[5] using a Machlett C-524A, molybdenum target x-ray tube operated at 50 kv and 48 ma. That this released large numbers of electrons into the conduction band was evidenced by the rapid growth of the F-band. The crystals were x-rayed in the dark for periods up to two hours and their absorption spectrum then measured at 5°K on three instruments to cover the spectrum from the F-band to about 15μ. This was necessary since the calculated optical activation energy of -0.68 ev (about 1.8μ in the absorption spectrum) is only an approximation. The spectral region 0.4μ to 1.2μ was measured on a Beckman Model DU Spectrophotometer taking care not to expose the crystal to any radiation except during the actual measurements. For the region from 1.0μ to 3.5μ a rapid scanning spectrometer[6] was used. A shutter arrangement permitted a complete spectrum to be obtained within 0.01 second after the light from a Nernst glower source first struck the crystal, thus preventing the possibility of optically bleaching the centers before a spectrum was obtained. The spectrum beyond 3.5μ was obtained with a Perkin-Elmer infrared spectrophotometer using a Golay detector. Here it was necessary to expose the crystal to the globar source continuously.

This experiment was repeated three times for NaCl and once for KCl. With the exception of a possible small F'-band in NaCl no bands were found to the infrared side of the F-band. KBr was also x-rayed at 5°K (1 hour at 50 kv and 20 ma) and its spectrum run only on the Beckman and Perkin-Elmer. Again no bands were found to the infrared of the F-band.

These measurements suggests that if the self-trapped electron exists, it diffuses easily through the lattice, even at 5°K, and thus that the binding energy is not greatly affected by the mean location of the electron, i.e., it can jump from a position of minimum binding energy to another even at these low temperatures, as suggested by Markham and Seitz. Perhaps at lower temperatures one might be able to freeze the electron at a lattice point long enough to be observed. In any event, the results appear to provide a strong justification for disregarding the lattice structure of the crystal above 5°K as was done by Frohlich, Pelzer, and Zienau.

The author would like to thank Dr. J. J. Markham for suggesting the problem and for his continued interest, and Mr. B. W. Bullock and Dr. S. Silverman for the use of their scanning spectrometer.

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Energy Dependence of $(n, 2n)$ Reactions in Ni^{58}, Cu^{63}, and Tl^{203} from 11 to 19 Mev*

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THE energy dependence of the $Ni^{58}(n, 2n)Ni^{57}$, $Cu^{63}(n, 2n)Cu^{62}$, and $Tl^{203}(n, 2n)Tl^{202}$ reactions has been investigated, using neutrons from the $D(T, n)He^4$ reaction[1] produced by the Los Alamos 2.5-Mev electrostatic accelerator.

A 1-cm long gas target[2] filled to 23-cm Hg pressure of deuterium was bombarded with a monatomic triton beam of approximately 1 microampere having an energy of 1.80 Mev in the center of the target gas volume. This gave a yield of about 1.4×10^7 neutrons/sec. Energies of the neutrons from the reaction varied from 18.5 Mev at 0° to 11.3 Mev at 180°. In the measurements presented here, it has been assumed that the neutron flux is symmetric in the laboratory coordinate system, which is true within experimental error of ±10 percent for triton bombarding energies near 1.2 Mev.

Samples were positioned accurately as to angle and distance from the center of the target gas volume by means of a light aluminum ring clamped near the end of the target tube. The nickel samples were folded strips 0.002-in. thick and weighing about 2 grams, while the copper samples were rolled strips 0.020-in. thick and weighing 20 grams. Four blocks of thallium, about 0.4 cm$\times$1 cm$\times$1 cm and weighing 5 grams each, were stacked at the angular positions corresponding to the neutron energies indicated in Fig. 3. The nickel and thallium samples were irradiated for 26 hours, the copper samples for 20 minutes.

After irradiation each nickel strip was wound in a helix around the outside of a thin-wall Geiger counter, and the activity was followed for 80 hours. In each case the 36-hour Ni^{57} decay was clearly observed as well as an activity of about 2 hours half-life, apparently due to the $Ni^{61}(n, p)Co^{61}$ reaction. Figure 1 shows the

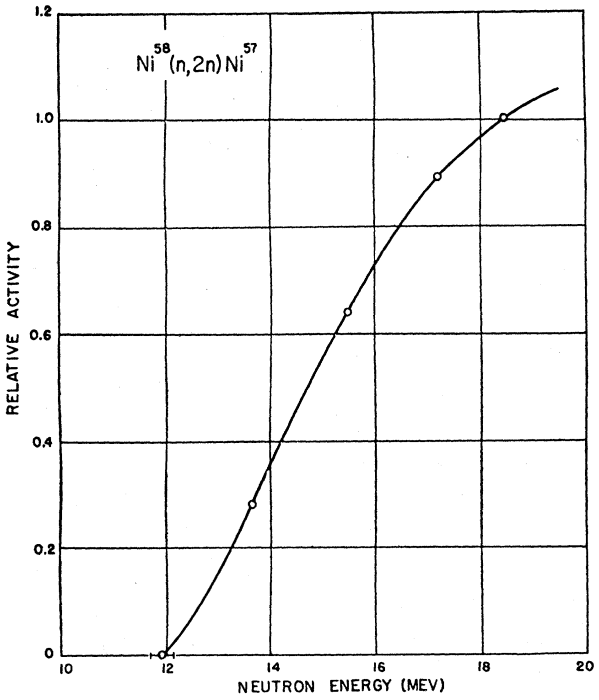

FIG. 1. Energy dependence of the $Ni^{58}(n, 2n)Ni^{57}$ reaction. Error in the relative activities is approximately ±5 percent.

relative 36-hour activities of the samples corrected for counter efficiencies and small sample weight differences. Relative efficiencies of the four Geiger tubes were determined by counting a uranium-glass source. Target length and sample size give a maximum spread in neutron energy of approximately ±1 Mev for each data point; the threshold indicated is that reported for the (γ, n) reaction,[3] corrected for the small center-of-mass effect. Counting rates were too low to permit a satisfactory measurement of the 72-day activity from the $Ni^{58}(n, p)Co^{58}$ reaction. A few percent of this activity could be present without noticeably distorting the 36-hour decay.

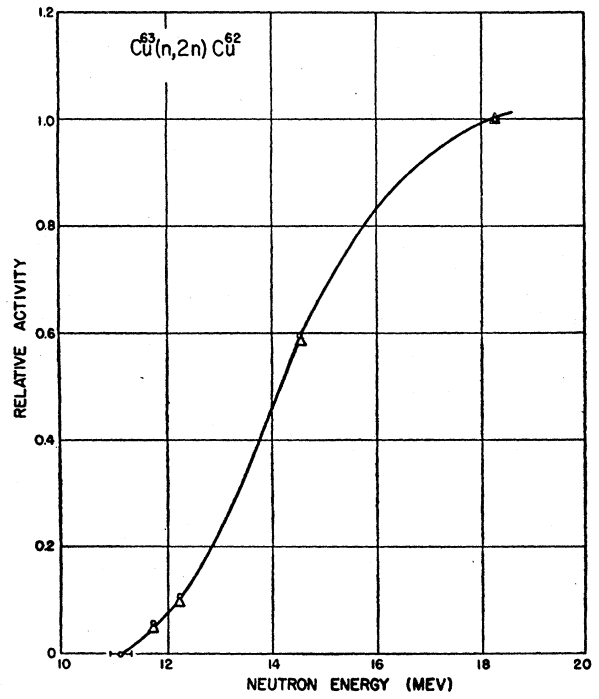

FIG. 2. Energy dependence of the $Cu^{63}(n, 2n)Cu^{62}$ reaction. The ordinate error at high energies is approximately ±3 percent, and for the points near threshold, ±10 percent.

Two sets of copper samples were irradiated and counted in the same manner as the nickel. The activities yielded 9.8-minute decay curves in each case and were followed for several half-lives with no longer lived activities becoming apparent. The relative induced activities due to the $Cu^{63}(n, 2n)$ reaction are shown in Fig. 2, with a maximum neutron energy spread of about ±0.2 Mev at each point. Data from the two sets of samples are normalized at the highest neutron energy; the threshold indicated is again taken from the reported (γ, n) threshold.[4] The absolute value of the $Cu^{63}(n, 2n)Cu^{62}$ cross section near the threshold has been investigated by Fowler and Slye,[5] who report a cross section increasing somewhat more sharply with energy than the present data indicate.

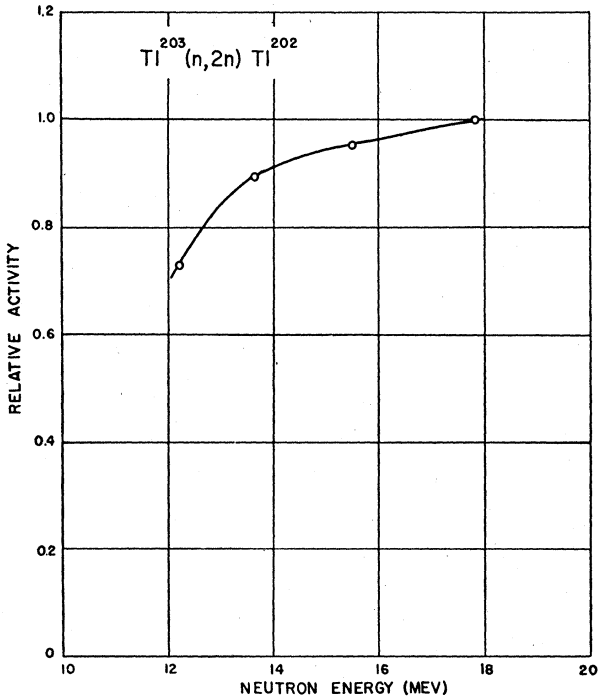

FIG. 3. Energy dependence of the $Tl^{203}(n, 2n)Tl^{202}$ reaction. The ordinate error is approximately ±6 percent. The threshold for this reaction is approximately 7.5 Mev.

For counting, the thallium samples were mounted about 1 mm from the surface of a $1\frac{1}{2}$-in. diameter ×2-in. long crystal of a NaI(Tl) scintillation detector. A single channel analyzer was used to count pulses in the photopeak for the 431-kev thallium gamma-ray. The counting rate due to the Tl^{202} activity was initially about five times background. Each day the gain of the detector system was adjusted by observing the photopeak from the Cr^{51} gamma-ray and then the single channel analyzer was set to count on the photopeak of the Tl^{202} gamma. The decay of the thallium gamma-ray was followed for three half-lives and best fitted a 300±15 hour half-life in agreement with the measurement of 296±4 hours made by Prestwood[6] but not in good agreement with the 276 hours observed by Wilkinson.[7] The energy of the thallium gamma-ray was measured by comparison with the gammas of Cr^{51} (323 kev) and Cs^{137} (663 kev) and was found to be 431±10 kev, which is in agreement with the value 435±5 kev found by Wilkinson.[7]

The relative induced activities due to the $Tl^{203}(n, 2n)Tl^{202}$ reaction are shown in Fig. 3. The maximum neutron energy spread

is about ±1 Mev at each point. The statistical errors in counting, as well as variations in relative activities as observed from day to day are small compared to effects of uncertainties in positions of samples during the irradiation.

The authors are indebted to Miss Violet Kissee for counting the thallium samples, and to the electrostatic accelerator group for the irradiation.

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The Neutron-Electron Interactions

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FOLDY[1] has recently shown that the magnetic moment of the neutron can interact with the electrostatic field of an electron. This interaction is usually expressed as a uniform potential extending over a distance equal to the classical electron radius. If one chooses the neutron moment as −1.91 nuclear magnetons, the interaction is attractive, and its strength is 3900 ev. This surprisingly large value has its origin in the "zitterbewegung" of the magnetic moment of the neutron, which is assumed to be a Dirac particle. This effect does not constitute, however, the total neutron-electron interaction. There is another attractive potential whose physical origin stems from the fact that the neutron is sometimes a proton with a negative meson charge cloud surrounding it.

The two effects differ as follows: They arise from the interaction of the field of the electron with the neutron polarization current in the first case, and with the neutron convection current in the second. Each of these effects can be calculated from meson theory. Although they depend separately on the coupling constant, their ratio is independent of it.

This ratio has been calculated, assuming an interaction of the neutron with symmetric pseudoscalar mesons. Equations (5.10) and (6.11) of Borowitz and Kohn[2] have been used in conjunction with a meson mass of $282m_e$. The result is that $\delta j_{\mu p}\cdot A_\mu/\delta j_{\mu c}\cdot A_\mu$ is equal to 3.23; here $\delta j_{\mu p}$ and $\delta j_{\mu c}$ are the corrections to the neutron polarization and convection currents, respectively. If one fixes the coupling constant in order that the theory yield the phenomenological value for the neutron moment, the convection current contribution to the neutron-electron interaction is 1208 ev. The total interaction would thus be equal to 5108 ev. The Slotnick and Heitler[3] formulas give 5073 ev if one uses the same meson mass and fixes their coupling constant to give the correct value of the neutron moment. These results are in good agreement with previously reported values,[4,5] and with the one recently measured by Hughes,[6] 4200±700 ev.

This agreement, while interesting, is probably fortuitous for the following reasons: (1) The anomalous proton moment using the same coupling constant in the same theory would be about eight times too small. (2) It is unreasonable to suppose that a second-order perturbation calculation is correct, when the expansion parameter is so large.

Foldy's[1] conjecture that Slotnick and Heitler,[3] and Dancoff and Drell[7] have included both parts of the neutron-electron interaction in their results is thus supported. The discrepancy between their results and those of Case[8] and of Borowitz and Kohn[2] is largely resolved.[9]

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Energy Available for Double Beta-Decay of Sn^{124}†

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THERE has been considerable interest in the possibility that double beta-decay may occur with a measurable half-life. This interest has been heightened by Fireman's observation[1] of a half-life of $0.4\text{–}0.9\times10^{16}$ years for the Sn^{124}—Te^{124} transition. However, this observation has not been confirmed,[2–4] and studies of other potential double beta-emitters have yielded[5–7] negative results. Since the energy available for the decay is an essential datum for estimating the half-life, we have undertaken to measure this quantity with a mass spectrograph.

The Sn^{124}—Ni^{62} and Te^{124}—Ni^{62} doublets, photographed at mass number 62, yield the following mass differences: $\frac{1}{2}Sn^{124}-Ni^{62}=0.02378\pm12$ amu and $\frac{1}{2}Te^{124}-Ni^{62}=0.02297\pm19$ amu. The Sn^{124}—Te^{124} mass difference is, therefore, 0.00162±44 amu, or 1.5±0.4 Mev. This value, according to the experiments[2] of Kalkstein and Libby, gives a lower limit for the lifetime of the Sn^{124} double beta-decay of $2.1\pm0.3\times10^{17}$ years.

This measurement was in part undertaken at the suggestion of K. G. Standing. The authors wish to acknowledge a most helpful conversation on this general subject with W. F. Libby.

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Theory of Antiferromagnetic Resonance in a Crystal of Rhombic Symmetry at the Absolute Zero

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THE observed antiferromagnetic resonance phenomena in copper chloride, $CuCl_2\cdot2H_2O$, are only slightly dependent upon temperature at temperatures below about 3°K.[1] It appears to be possible to account for them on the basis of the analysis of antiferromagnetism in a crystal of rhombic symmetry at the absolute zero proposed by Gorter and Haantjes.[2]

We divide the lattice of magnetic ions into two sublattices i and j. An ion i is supposed to have a moment of momentum $(\hbar/2)\boldsymbol{\sigma}^i$ and a magnetic moment $(\mu_1\sigma_1{}^i,\ \mu_2\sigma_2{}^i,\ \mu_3\sigma_3{}^i)$. Let the exhange energy between two neighboring ions i and j be $\Sigma_k(\gamma_k/z)\sigma_k{}^i\sigma_k{}^j$ (z is the number of nearest neighbors).

Introducing $h_k=\mu_kH_k$ (**H** is the external field), Gorter and Haantjes, who follow the phenomenological treatment of Néel[3] and Van Vleck,[4] find at each value and direction of **h** three solutions for the magnetic moments which are mathematically permissible. They show which of these solutions will be realized physically. On this basis the resonance problem has been treated following the method used by Kittel[5] and Nagamiya.[6]

The equation of motion for the sublattice averages of the moments is

$$\alpha\bar{\sigma}_1{}^i/dt=(2/\hbar)[\bar{\sigma}_2{}^i(h_3-\gamma_3\bar{\sigma}_3{}^i)-\bar{\sigma}_3{}^i(h_2-\gamma_2\bar{\sigma}_2{}^i)]$$

(cyclic, and the same for i and j interchanged). Taking the variation of this equation and assuming the dependence upon time of the variations of the variables to be $\exp(i\omega t)$, one finds the resonance condition by putting equal to zero the determinant of the coefficients of the variations of $\bar{\sigma}_1{}^i$, $\bar{\sigma}_2{}^i$, $\bar{\sigma}_3{}^i$, $\bar{\sigma}_1{}^j$, $\bar{\sigma}_2{}^j$, $\bar{\sigma}_3{}^j$. To find the resonance condition in the form of a direct relation between **h** and ω one has to substitute the physically realized solution of Goerter and Haantjes into the equation which is obtained.