The fission pulses were sorted by a simple ten-channel pulse analyzer and recorded on a ten-pen Esterline Angus operation recorder. The distribution obtained in one of the runs is shown in Fig. 1. The energy scale was obtained by comparison with the α-pulses in terms of a pulse signal-generator.[6]

The results of three runs are given in Table I together with data on slow neutron fission.[7] Before any detailed comparison could be made, much longer runs with finer pulse analyzer resolution would be required. Moreover, a thinner source would also be desirable. However, the investigation aimed at seeing if there were any major difference between spontaneous and slow neutron induced fission. Apparently there is not.

* Now at the Atomic Energy Research Establishment, Harwell, England.
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[3] B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), p. 14.
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[5] Bunemann, Cranshaw, and Harvey, Can. J. Research **A27**, 191 (1948).
[6] Because of the very high α-counting rate the α-pulses were compared with the signal generator on a triggered oscilloscope. In spite of the short distance between the source and the grid, enough α-particles left the source sufficiently obliquely to give a well-resolved trace corresponding to the total α-energy.
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Low Temperature Resistance Minimum in Magnesium Measured by a Mutual Inductance Method*

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SOME experiments performed recently by the authors to investigate the low temperature resistance of magnesium have utilized a method which may prove to be useful for many types of low temperature resistance measurements. Owing to the strong influence of impurities and crystal structure on low temperature resistivities, a method was developed which makes it possible to use a bulk sample of material rather than a drawn wire. The principle utilized in this method is that the complex mutual inductance of two coaxial coils surrounding a sample depends on the conductivity of the sample. The mutual inductance is measured with a bridge. The calculations can be easily carried out for cylindrical

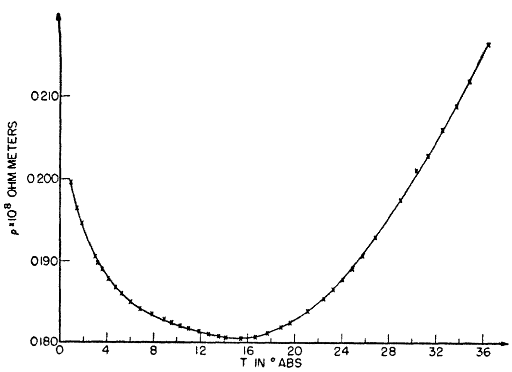

FIG. 1. A plot of resistivity *vs* temperature for a cylindrical sample of magnesium.

symmetry[1] (two coaxial coils containing a cylindrical core of conductivity σ), yielding a relation between the mutual inductance and the core conductivity. Refinements to the calculation can be introduced to correct for the finite length of the coil and the core.

This method has several advantages over the customary measurements made with wires and resistance bridges. No connections to the sample are necessary, thus eliminating contact effects and the possibility of a heat leak down the connecting wires. Single crystal samples can be easily made in a shape suitable for use in conductivity measurements. Further, the bulk resistivity comes fully into play, making small imperfections, which might greatly influence wire measurements, of little importance.

The resistivity of magnesium has been measured by this method in order to study the resistance minimum reported by Garfunkel, Dunnington, and Serin.[2] An illustration of the results is shown in Fig. 1.

At the present time, measurements are under way at this Laboratory to investigate the effect of impurity content and crystal structure on the resistance minimum.

* This work was supported in part by the Signal Corps, the Air Materiel Command, and ONR.
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Detection of Gamma-Ray Polarization by Pair Production*

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IT has been pointed out by Yang,[1] that pair production may provide a method for detecting the polarization of γ-rays in the high energy range: $h\nu \gg mc^2$ (m being the electron mass) where the usual Compton recoil method becomes insensitive. The idea is to utilize the azimuthal dependence of the pair production cross section $d\sigma$, the azimuth ϕ being measured around the direction $\mathbf{k}$ of the incident quantum and from the plane containing $\mathbf{k}$ and the electric polarization vector $\boldsymbol{\varepsilon}$ of the quantum. Actually, of course, one must consider two azimuths ϕ_+ and ϕ_- for the positive and negative electron respectively. Berlin and Madansky,[2] from whose paper our notation is borrowed, have made a careful study of the dependence of $d\sigma$ on ϕ_- when $\phi_+=\phi_-+\pi$. In this case the plane of the pair contains *exactly* the direction $\mathbf{k}$ of the incident quantum, and one can speak simply of the azimuth $\phi=\phi_-$ of the plane of the pair with respect to the plane of polarization. From the experimental standpoint it will be practically impossible to select the pairs which satisfy the Berlin-Madansky condition. Both electrons will be emitted within a narrow cone around $\mathbf{k}$, and the plane of the pair will always make a very small angle with $\mathbf{k}$. No matter whether pairs are observed in a photographic emulsion or produced in a thin target and detected with counters, scattering within the emulsion or target will unavoidably distort the initial directions to a considerable extent. It seems more reasonable, therefore, to set as our goal the measurement of the angle between the plane of the pair and the plane of polarization without any selection. The question then arises whether the case considered by Berlin and Madansky is sufficiently representative to permit a rough prediction of what is to be expected in the general case. The result of the following calculation may indicate that it is not.

The Bethe-Heitler formula for $d\sigma$ has a quite complicated dependence on the various parameters involved, so that the sign and magnitude of the effect to be expected can be seen only at the end of a laborious integration. In order to find a simpler picture we have used the Weizsäcker-Williams approximation.[3] In order to deal with pair production, Williams makes a Lorentz-transformation parallel to $\mathbf{k}$ with velocity $v=c(\xi-1)/(\xi+1)$, with $\xi=h\nu/mc^2$. In the new system the quantum has an energy $h\nu_1=mc^2$. The method can be applied if $\xi\gg 1$ so that v is very close to c; the field of the nucleus can then be approximately substituted by a spectrum $\sim(C/\nu)d\nu$ of virtual quanta, C being a slowly variable function of ν, which we shall treat as a constant. These quanta move in the direction $-\mathbf{k}$, and if one of them, having an energy $h\nu_2>mc^2$, collides with the real quantum, a pair may be produced. It is characteristic of the Weizsäcker-Williams method that the transfer of momentum to the nucleus is represented by the removal of a virtual quantum from the field, and is hence parallel to **k**. Consequently the planes of all pairs produced contain **k** exactly. The difference between this statement and the apparently similar language of the Berlin-Madansky condition may be understood as follows. Presumably in the more accurate theory the probable values of the difference $\phi_+ - \phi_- - \pi$ are rather small; if this is true the procedure we follow is equivalent to averaging the Bethe-Heitler cross section over the previously difference, rather than considering the case when the difference is equal to zero. The virtual quanta are, on the whole, unpolarized. Hence we need the pair production cross section for two quanta moving in opposite directions, one of them linearly polarized, one unpolarized. This is known[4] to be, in the center of mass of the two quanta:

$$d\sigma = (\beta r_0^2/2x^2)\{(1-\beta^2\cos^2\theta)^{-1} - \tfrac{1}{2} + 2\beta^2(1-\beta^2) \times (1-\beta^2\cos^2\theta)^{-2}\sin^2\theta\cos^2\phi\}\sin\theta d\theta d\phi,$$

where βc is the velocity of either electron, $r_0 = e^2/mc^2$, $x = h\nu/mc^2 = (1-\beta^2)^{-\frac{1}{2}}$, θ is the angle between the electrons and the photons, while ϕ is the azimuth of the plane containing electrons and photons measured from the plane of polarization of the polarized photon. We integrate over θ since we are only interested in the dependence on ϕ. Finally we must transform the frequencies to the system in which one of the quanta has an energy $h\nu_1 = mc^2$, and integrate over a spectrum $Cd\nu_2/\nu_2$ for the other quantum. The result is:

$$d\sigma = \tfrac{2}{3}Cr_0^2(1+\tfrac{1}{3}\cos^2\phi)d\phi,$$

which exhibits an azimuthal dependence of comparable magnitude to that found by Berlin-Madansky in their special case. The sign, however, is the opposite: the plane of the pair prefers to be parallel to the electric vector.

The applicability of the Weizsäcker-Williams method to the present problem may be doubted; in particular one may fear that the transverse momentum transfer to the nucleus, which is neglected in this method, might affect the directions of the particles in such a way as to alter the correlation between polarization and directions of motion entirely. It may be pointed out, however, that the transverse momenta of the pair are of the order of mc, while the momentum transfer to the nucleus is much smaller than mc in a majority of the collisions[5] (if $h\nu \ll mc^2$). We believe, therefore, that the Berlin-Madansky conclusions apply only if the condition they postulate ($\phi_+ = \phi_- + \pi$) is strictly satisfied. An investigation of the Bethe-Heitler formula under more general conditions is under way.

* This work was performed under the auspices of the AEC.
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The Masses of the Negative and Positive Electrons*

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BECAUSE of its far-reaching theoretical consequences, great importance attaches to the question whether positive electrons differ in mass from negative electrons and the writer has recently been urged[1] to present such experimental evidence as now exists on this point. With E. R. Cohen, he has been engaged for the last several months in the preparation of a completely new least-squares evaluation of all of the atomic constants in the light of a number of new and very precise measurements in the microwave and other fields. These results will soon be released in the form of a preprint. It appears from this study that the present "best" value of the Compton wavelength $h/(mc)$ is

$$\lambda_c = h/(mc) = (2.426067 \pm 0.000032)\times 10^{-10} \text{ cm.} \quad (1)$$

In this equation, m is clearly the mass of the negative electron because the measurements used involved negative electrons only.

On the other hand, a recent direct measurement[2] by DuMond, Lind, and Watson with the 2-meter curved crystal gamma-ray spectrometer at this Institute of the wavelength λ_A of the annihilation radiation from Cu^{64} yielded the result

$$\lambda_A = (2.4271 \pm 0.0010)\times 10^{-10} \text{ cm} \quad (2)$$

larger than λ_c by about four parts in 10^4 with an *assigned* uncertainty of about the same order as the difference, $\lambda_A - \lambda_c$.

The uncertainty of the measurement of the annihilation radiation wavelength was very conservatively, perhaps *too* conservatively, estimated with a large allowance for unknown systematic errors. On the basis of only *the internal consistency* of the seven measurements, a calculation of the probable error yields

$$\lambda_A = (2.4271 \pm 0.00012)\times 10^{-10} \text{ cm,} \quad (3)$$

which is only about one-eighth the error claimed in the paper. In fixing our assigned uncertainty at the higher value, $\pm 0.001 \times 10^{-10}$ cm, two considerations determined our estimate. (1) We were aware of a discrepancy of this order between our observed λ_A and the value of λ_c from the DuMond and Cohen[3] 1947 least-squares evaluation of the constants. (The new reevaluation of the constants has not materially changed this discrepancy.) (2) The uncertainty we assigned (and the discrepancy) correspond to a motion of our source carriage and precision wavelength screw of only 0.01 mm and this did not seem to be an unreasonable safe *upper limit of systematic* error although *we have no direct evidence that errors this large exist.* The difference between λ_c and λ_A corresponds to a quantum energy difference of a little over 200 ev.

Three possible theoretical sources of difference between λ_A and λ_c have been considered and rejected as probably[4] insufficient to explain the discrepancy. Two of these were discussed briefly (pages 1226 and 1237) in the DuMond, Lind, and Watson paper: (1) A possible shift because of the potential energies and (2) a possible shift because of the kinetic energies of the members of the recombining pairs. The low kinetic energies, which we derived from our own observation of the Doppler broadening of the annihilation line itself, have since been further verified in a beautiful independent method by De Benedetti, Cowan, and Konneker[5] with results in accord with ours. The third possible source of shift from Compton modified scattering in the source material has also been analyzed by the author in a recent letter to the editor[6] and shown to be too small to explain the discrepancy.

A possible source of systematic shift has recently been suggested to us by L. Alvarez. Since the line exhibits an observable spectral breadth at half-maximum of the order $\Delta\lambda_A/\lambda_A = 0.004$ there will be an appreciable difference in the intensity response of the instrument on the two sides of the line, (1) because, as Lind, West, and DuMond have shown,[7] the reflecting power of the crystal varies about as λ^2, (2) because the multi-cellular counter efficiency depends on some power of the wavelength. This last is difficult to estimate since it depends on the absorption of the radiation in the counter partition walls on the one hand and on the ratio of the range of the ejected electrons to the wall thickness on the other hand. If we assume an over-all instrumental response increasing as λ^3 then the line center at half-maximum height would be shifted toward longer wavelengths by about $0.009a$, where a is the half-breadth at half-maximum, or by a proportionate wavelength shift, $\delta\lambda/\lambda = 3.8\times 10^{-5}$ which is a ten times smaller quantity than the discrepancy in question. For an instrumental response obeying a higher power of λ then the cube, $\delta\lambda/\lambda$ would only be increased in proportion to the exponent, and it seems very unlikely that this will account for the discrepancy.

The annihilation radiation line, since it results from the recombination of positive with negative electrons, should have a wavelength

$$\lambda_A = h[\tfrac{1}{2}(m^+ + m^-)c]^{-1}. \quad (4)$$