Wheeler,[2] that $g_\mu$ and $g_e$ are likely to be equal, the ratio (3) is approximately equal to 4. If, on the other hand, we adopt their best observational values $g_\mu \cong 10^{-49}$ erg-cm$^3$ and $g_e \cong 2.2\times 10^{-49}$ erg-cm$^3$, the ratio is approximately equal to 20. In both cases, there is clear disagreement with recent results at Berkeley,[4] which indicate that the ratio (3) is substantially less than unity.

An estimate for the magnitude of the integral in (2) can be obtained by taking its upper limit to be roughly equal to $Mc$; this is equivalent to assuming that nucleon theory is valid in the non-relativistic domain, and that relativistic intermediate states can be ignored. Alternatively, the self-energy of a $\pi$-meson at rest due to intermediate nucleons can be calculated, and set equal to $mc^2$. The same integral appears (again with neglect of a factor $-mc$ in the energy denominator), and the values obtained for it in the two ways are approximately the same. When the latter evaluation of the integral is used, and $g_\mu$ is taken equal to $10^{-49}$ erg-cm$^3$ in order to obtain agreement with the rate of nuclear capture of negative $\mu$-mesons, we obtain $\tau_{\pi\mu} \cong 2.3\times 10^{-9}$ sec., which is in fair qualitative agreement with the observed value.[5] This makes the computed mean life for $\pi - e$ decay much too small to agree with experiment; while the discrepancy could be removed by the assumption of a direct $\pi - e$ coupling that largely cancels the second-order contribution, this is a rather unlikely possibility. Thus, it would seem that the rate of nuclear beta-decay is too large to be consistent with the small rate of $\pi - e$ decay, if either $\pi - e$ coupling[1] or nucleon-electron coupling is assumed by itself.

The interaction (1) also leads to $\mu - e$ decay as a second-order process, but the rate computed in this way is far too small to agree with experiment.

[1] L. I. Schiff, Phys. Rev. **74**, 1556 (1948); A. S. Lodge, Nature **161**, 809 (1948); S. Hayakawa, Prog. Theor. Phys. **3**, 200 (1948); R. F. Christy and R. Latter (to be published).
[2] J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. **21**, 153 (1949); T. D. Lee, M. Rosenbluth and C. N. Yang, Phys. Rev. **75**, 905 (1949).
[3] R. E. Marshak, Phys. Rev. **75**, 700 (1949). R. Latter and R. F. Christy, Phys. Rev. **75**, 1459 (1949).
[4] Private communication.
[5] J. R. Richardson, Phys. Rev. **74**, 1720 (1948).

## Production of $\pi$-Mesons by High Energy Nucleons*

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In connection with the programs of accelerators under way in this country, it seemed useful to collect as many data as possible about the production of mesons by high energy particles. When looking through the literature we found that for the case where the bombarding particle is a high energy nucleon, two different results had been obtained. Using straightforward third-order perturbation methods, Urban and Schwarzl[1] obtained for the cross section $\sigma$:

$$\sigma = 4(g^2/\hbar c)^3(M/\mu)^2(Mc^2/E_0)^2(\hbar/Mc)^2 \log(M/\mu), \qquad (1)$$

where $g$ is the coupling constant, $M$ the mass of a nucleon, $\mu$ the mass of the $\pi$-meson, and $E_0$ the energy of the bombarding nucleon. Equation (1) and also the following equations give only the first terms in a series expansion in inverse powers of $E_0$. This paper was essentially a corrected version of the paper of Nordheim and Nordheim[2] who had arrived at practically the same result, although using an incorrect expression for the perturbation matrix element. As in the following, a charged scalar field was assumed. Independently, the result of Eq. (1) was obtained by us[3] making the same simplifying assumptions.

A different result, however, was obtained by Wang[4] using the Weizsäcker-Williams method. His result was

$$\sigma = K(g^2/\hbar c)^3(M/\mu)(Mc^2/E_0)(\hbar/Mc)^2, \qquad (2)$$

where $K$ is a constant of the order of magnitude unity.

Since it seemed to us that the Weizsäcker-Williams method should give reliable results for high energies, we have performed the third-order perturbation calculations, now retaining all terms. It then turned out that the final result is essentially identical with Wang's formula. Our final result is

$$\sigma = (\pi/8)(g^2/\hbar c)^3(M/\mu)(Mc^2/E_0)(\hbar/Mc)^2. \qquad (3)$$

It is interesting to note that formula (3) does not give an $E_0^{-2}$ dependence as one might expect from dimensional considerations,[5, 6] thus indicating a dependence of the matrix element on energy. The difference between formulas (1) and (3) arises from the fact that in the evaluation of the matrix elements, Urban and Schwarzl,[1] as well as the present authors in their preliminary calculations,[3] neglected terms arising from the momentum of the virtual meson which were taken into consideration in the calculations leading to formula (3). Recoil was also taken into account, but this did not influence the final result.

We should like to express our sincere thanks to Professor H. Wergeland for discussions on the subject of this letter. Detailed calculations will be published in a report of the Purdue Synchrotron Project to the ONR.

* Partly assisted by the ONR.
[1] P. Urban and F. Schwarzl, Acta Phys. Austriaca **2**, 368 (1949).
[2] L. W. Nordheim and G. Nordheim, Phys. Rev. **54**, 254 (1938).
[3] E. Strick, Phys. Rev. **76**, 100 (1949).
[4] F. S. Wang, Zeits. f. Physik **115**, 431 (1940).
[5] W. G. McMillan and E. Teller, Phys. Rev. **72**, 1 (1947).
[6] D. ter Haar, Science **108**, 57 (1948).

## Note on the Resistivity of Gold at Low Temperatures

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As is well known, the wave function of an electron in a perfectly periodic potential field consists of a plane non-attenuated wave, modulated with the period of the potential. In Bloch's model of a solid, the periodicity of this potential is equal to the periodicity of the lattice ions. It follows, therefore, that in such an ideal solid an electron would experience no scattering or in other words the electrical resistivity should be zero.

The above is a fundamental property of an ideal (i.e., rigorously periodic) lattice and is deduced from quantum mechanics without any approximation being involved. If one now inquires as to how closely any real crystal approximates this model, the following modes of departure may be envisaged:

(1) If the situation is such that the states in the lowest Brillouin zone are completely occupied by electrons, and an energy gap between it and the next higher zone exists (no overlap), we should, in the vicinity of absolute zero, have no net current, i.e., the crystal would be an insulator with an infinite resistivity at 0°K.

(2) In the more pertinent case of a monovalent metal such as gold with a half-occupied first zone, departures of the lattice from perfect periodicity can be due to the following: (a) Finite excitation of the Debye waves. This is temperature dependent and will vanish at the absolute zero. (b) Strains and impurities. (c) Crystallite boundaries in polycrystalline material.

These last three will, of course, be temperature independent at low temperatures. Accordingly, as the temperature approaches absolute zero, the resistivity of a conductor should approach zero or at most become temperature independent due to (b) and (c).

In view of all this, the observation made by de Haas, de Boer, and van den Berg[1–3] some years ago that the resistivity of pure gold increased as the temperature was lowered below about 3°K seems exceedingly strange. While all their measurements were made with polycrystalline specimens, even their purest sample (impurity $\sim 10^{-4}$ percent, mainly Cu and Ag) showed a definite minimum in the resistance-temperature curve, although it is true that less pure material gave a more pronounced effect. The