Letters to the Editor

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Solutions of the Meson-Nucleon Equation in the Adiabatic Limit

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THE relativistic meson-nucleon equation,[1] $[(\gamma p+m)(k^2+\mu^2)-I]\psi=0$, upon reduction to three-dimensional form, may be used to examine the stability of meson-nucleon systems (bound and virtual states) as well as scattering. Such an investigation has been made for the isotopic spin 3/2 state, with lowest order interaction (crossed meson graph) in the adiabatic limit, but keeping both "large" and "small" components in the resulting equation. In momentum space, the three-dimensional equation becomes

$$(K-\omega_p-H)\phi_i(\mathbf{p})=\frac{g^2}{(2\pi)^3}\left[\frac{1}{2\omega_p}-\frac{\Lambda_-}{K+\omega_p+E_p}\right]\tau_j\tau_i \int\frac{\beta m+\boldsymbol{\alpha}\cdot(\mathbf{p}+\mathbf{p}')-(\mu_1-\mu_2)K}{m^2+(\mathbf{p}+\mathbf{p}')^2-(\mu_1-\mu_2)^2K^2}\phi_j(\mathbf{p}')d\mathbf{p}', \quad (1)$$

where $K=m+\mu+E$ is the total energy of the system, $\mu_1=\mu/(m+\mu)$, $\mu_2=m/(m+\mu)$, $H=\boldsymbol{\alpha}\cdot\mathbf{p}+\beta m$, and Λ_- is the negative energy free particle projection operator. Multiplying by $K-H+\omega_p$ (to rationalize the kinetic energy term) and returning to coordinate space, one obtains an equivalent Dirac equation of the form

$$(W-H)\phi_i(\mathbf{r})=\int V_{ij}(\mathbf{r},\mathbf{r}')\phi_j(\mathbf{r}')d\mathbf{r}'; \quad W=m+\frac{E(E+2\mu)}{2(m+\mu+E)}, \quad (2)$$

where

$$V_{ij}(\mathbf{r},\mathbf{r}')=\frac{g^2}{4\pi}\frac{\tau_j\tau_i}{4K}[KQ_m(\mathbf{r}+\mathbf{r}')+(K-\beta m-\boldsymbol{\alpha}\cdot\mathbf{p}) \{Q_\mu(\mathbf{r}+\mathbf{r}')-Q_m(\mathbf{r}+\mathbf{r}')\}]\times[\beta m-(\mu_1-\mu_2)K-\boldsymbol{\alpha}\cdot\mathbf{p}']Y(r');$$
$$Y(r)=(1/r)\exp(-r/\rho); \quad Q_\mu(\mathbf{r})=-\frac{1}{2\pi^2}\frac{1}{r}\frac{\partial}{\partial r}K_0(\mu r). \quad (3)$$

The range of the Yukawa well, $\rho^{-1}=[m^2-(\mu_1-\mu_2)^2K^2]^{\frac{1}{2}}$, is energy dependent. The integral operator, $V(\mathbf{r},\mathbf{r}')$, was approximated by a multiplicative exchange potential. In so doing, $mQ_m(\mathbf{r}+\mathbf{r}')$ was replaced by $\delta(\mathbf{r}+\mathbf{r}')$ and the terms proportional to $Q_\mu-Q_m$ were neglected as $Q_\mu-Q_m$ is logarithmic at the origin (and hence not highly singular). The potential for the 3/2 state then becomes

$$V=(g^2/8\pi m)[H-(\mu_1-\mu_2)K]Y(r)P, \quad (4)$$

where P is the exchange operator. The angular parts of the wave function may be separated out in the usual fashion, via the constants of motion J, $K=\beta(\boldsymbol{\sigma}\cdot\mathbf{L}+1)$. The resulting coupled radial equations for the two components u/r, v/r are

$$\left[\frac{d}{dr}-\frac{k}{r}+(-1)^l\frac{g^2}{8\pi m}\frac{\partial}{\partial r}Y\right]u(r) =-\left[W+m-(-1)^l\frac{g^2}{8\pi m}\{2m-\mu-(\mu_1-\mu_2)E\}Y\right]v(r), \quad (5)$$

$$\left[\frac{d}{dr}+\frac{k}{r}-(-1)^l\frac{g^2}{8\pi m}\frac{\partial}{\partial r}Y\right]v(r) =\left[W-m-(-1)^l\frac{g^2}{8\pi m}\{\mu-(\mu_1-\mu_2)E\}Y\right]u(r). \quad (6)$$

In order to examine the structure of the solutions, the Yukawa potentials were replaced by "equivalent" square wells, $\bar{V}$, defined by $\int_0^\infty Vr^2dr=\bar{V}\int_0^\rho r^2dr$.[2] Eliminating $v(r)$ from the equations, one obtains a Schrödinger equation for u of the form

$$\left[\frac{d^2}{dr^2}-\frac{k(k-1)}{r^2}-\frac{2k}{r}a\frac{g^2}{4\pi}+b\left(\frac{g^2}{4\pi}\right) +c\left(\frac{g^2}{4\pi}\right)^2+W^2-m^2\right]u(r)=0, \quad r<\rho \quad (7)$$

$$\left[\frac{d^2}{dr^2}-\frac{k(k-1)}{r^2}+W^2-m^2\right]u(r)=0. \quad r>\rho \quad (8)$$

The coefficients a, b, c are energy dependent. The appearance of a g^4 term in Eq. (7) reflects the elimination of v from Eqs. (5) and (6). Replacing the $1/r$ term in (7) by a square well, one obtains a total well which is repulsive for $j=1/2, 5/2, \cdots$ and attractive for certain ranges of $g^2/4\pi$ for $j=3/2, 7/2\cdots$.

Assuming the V_1^0 particle to be a virtual state of the p, π^- system at an energy $E\sim 40$ Mev, with isotopic spin 3/2 and an angular momentum of $l=5$, a lifetime of 2×10^{-10} second was obtained. The allowed values of the coupling constant that give this result are $g^2/4\pi=9.0, 13.5$. For the latter case no other virtual or bound states can form in the low-energy region.

The above equations were also applied to calculate the total π^+-p cross section at 37 Mev. The result (for $g^2/4\pi=13.5$) is 19.3 mb.[3]

First-order nonadiabatic corrections to the potential have been examined and appear not to change the results qualitatively. More detailed calculations are now in progress.

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[1] S. Deser and P. Martin, Phys. Rev. **90**, 1075 (1953).
[2] The $1/r$ and $1/r^2$ singularities were smoothed to a $\ln r$ and $1/r$ respectively near the origin, as suggested by the integral operator Q_m.
[3] This result may be compared with the experimental values of 10.9 ± 3 mb and 11.8 ± 1.0 mb at that energy obtained by C. E. Angell and J. P. Perry [Phys. Rev. **91**, 1289 (1953); **92**, 835 (1953)], and the value 7.9 ± 2.2 mg obtained at 33 Mev by S. L. Leonard and D. H. Stork [Bull. Am. Phys. Soc. **28**, No. 4, 19 (1953)].

Production of Acceptor Centers in Germanium and Silicon by Plastic Deformation

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PLASTIC deformation of germanium and silicon by bending and in tension has been reported by Gallagher[1] and by Treuting.[2] In recent experiments compression has been used to deform N-type germanium crystals of 5 and 26 ohm-cm resistivity about 5 percent at 500° and 650°C, respectively. X-ray studies showed that the deformation produced a range of orientations grouped about the principal one for the crystal. In both specimens the conductivity was changed to P-type, and the resistivity values for the deformed germanium were 1.5 and 3 ohm-cm, respectively. These changes correspond to the introduction of about 10^{15} acceptor centers/cm^3.

Control germanium specimens that were only heated, and not compressed, were included simultaneously in the furnace. No, or insignificantly small, changes in resistivity were obtained for the controls. This is considered conclusive evidence that the acceptor centers have an origin in the deformation. They may be at dislocations, introduced into the small regions, or on the small angle boundaries between regions, in the deformed structure. Dislocation models in deformed germanium have been discussed by Seitz[3] and by Shockley.[4]

A similar introduction of acceptor centers has been obtained with silicon of N-type and 6 ohm-cm resistivity. When this silicon was compressed 2.5 percent at 725°C, it remained N-type but the resistivity increased to 150 ohm-cm. When the same silicon was compressed 18 percent at 850°C, the resistivity increased to 50 ohm-cm and both N and P regions were found in the sample. These resistivity changes correspond to an introduction of about 10^{15} acceptor centers/cm^3. As in the case of germanium, controls that were heated only were included simultaneously in the furnace. No significant changes in resistivity were obtained in the controls.

Values of mobilities used in calculation were for undeformed material.[5,6] The number of acceptor centers may be different to the extent that mobilities are different in deformed structures.[7]

[1] C. J. Gallagher, Phys. Rev. **88**, 721 (1952); Bull. Am. Phys. Soc. **28**, No. 4, 10 (1953).
[2] R. G. Treuting, J. Metals **4**, 1944 (1952).
[3] F. Seitz, Phys. Rev. **88**, 722 (1952).
[4] W. Shockley, Phys. Rev. **91**, 228 (1953).
[5] J. R. Haynes and W. Shockley, Phys. Rev. **81**, 835 (1951).
[6] J. R. Haynes and W. C. Westphal, Phys. Rev. **85**, 680 (1952).
[7] D. L. Dexter and F. Seitz, Phys. Rev. **86**, 964 (1952).

Thermal Conductivity of Copper between 0.25°K and 4.2°K*

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SOME years ago, Heer and Daunt initiated measurements on the thermal conductivity of metals below 1°K, their first observations being on Sn and Ta.[1] This work led immediately to the practical realization of superconducting thermal "valves"[2] and to an understanding of the significance of lattice conduction at extremely low temperatures. Subsequently, similar measurements by us have been made on Pb[3] and Cu. Whereas many other observations below 1°K on the thermal conductivity of superconducting metals, such as Pb, have since been reported,[4] data below 1°K on normal metals, such as Cu, are unavailable. It is considered that the results, given below, for Cu are of twofold interest, first in relation to the theory of electrons in metals, and second, as a guide in technical problems arising in cryogeny below 1°K.

The experimental arrangements for the observations below 1°K were similar to those used previously,[1] consisting of two approximately equal chromium potassium alum cylinders of about 15 cc each, separated from one another by a distance of approximately 30 cm and connected thermally to each end of the specimen of interest by copper mountings of large cross section. The thermal contact between the salts and their copper mountings was made by high-pressure molding. The two salt cylinders were simultaneously cooled to low, but different, temperatures by the magnetic method, and the thermal conductivity of the metallic specimen linking the two was calculated from observations of the rate at which the cylinders equalized temperature. The dimensions of the specimens were so chosen that the time for equalization was long enough (about 1 hour) to enable observations to be made to at least 0.001°K. The stray influx of heat from the surroundings was kept low in order to minimize errors of computation. The temperatures of the salts were obtained from susceptibility measurements, using an ac bridge method.[5] The ac bridge, using a decade mutual inductance constructed by Hayes,[6] has a sensitivity such that, with a primary field of 0.1 gauss rms at 28 c/s, temperature differences of less than 0.1 milli-degrees can be readily observed at, for example, 0.5°K.

For the temperature range 1°K to 4.2°K, customary steady heat flow techniques were used for the conductivity measurements, employing carbon thermometers and direct ohmic heating.

The thermal resistance between the salts was found to be composed of two terms; (a) the resistivity of the Cu sample and (b) the thermal contact resistances between the salts and their copper mountings. This term (b) was found to be proportional to T^{-2}, as has been discussed previously by Mendoza[7] and by Goodman,[4] and the factor of proportionality was obtained from our observations made at 0.5°K. As will be seen from the table of results given below, this term (b) represented only a small correction to the results down to 0.5°K.

In order to calculate the heat flow between the samples, it was necessary to estimate the heat leak from external sources into each salt individually. On the assumption that these heat leaks were proportional to (*a*) the difference in temperature between each salt and the surrounding chamber, and (*b*) the area of each salt, the constant of proportionality could be obtained by calculation from the observed total heat leak at any one instant. It was found that a unique value of this constant allowed computations to be made, regarding the heat leak, which were in good agreement with the experimental data over periods of time exceeding one hour and corresponding intervals of temperature.

The copper sample was a polycrystalline wire of 27.2-cm length and 0.025-cm diameter, and was of commercial grade high-purity magnet wire, supplied by General Electric Company. The observed thermal conductivity, K as a function of temperature is shown in Fig. 1 and Table I. It will be observed that within the

TABLE I. Observed thermal conductivity as a function of temperature.

Obs. mean temp. °K	Obs. temp. diff. °K	Barrier temp. drop at salt A °K	Barrier temp. drop at salt B °K	Temp. diff. along Cu °K	Corrected mean temp. °K	Thermal cond. of Cu watt units
0.810	0.011	0.001	0.001	0.009	0.810	1.30
0.787	0.059	0.005	0.004	0.050	0.787	1.17
0.672	0.036	0.004	0.003	0.029	0.673	1.09
0.657	0.114	0.014	0.009	0.091	0.660	0.87
0.608	0.108	0.014	0.001	0.093	0.615	0.92
0.416	0.242	0.076	0.023	0.143	0.443	0.91
0.400	0.180	0.047	0.019	0.114	0.414	0.79
0.346	0.046	0.008	0.008	0.030	0.346	0.55
0.259	0.242	0.077	0.010	0.155	0.293	0.53

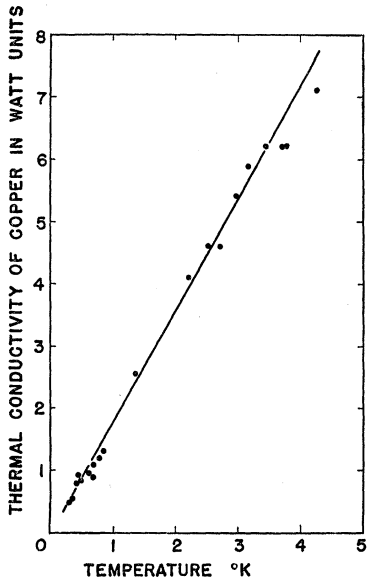

FIG. 1. Thermal conductivity (in watt units) of pure copper as a function of absolute temperature.

limits of experimental error K is a linear function of T down to 0.25°K. If one puts $K=\alpha T$, then our observed value of α is 1.76 watts/cm deg^2. Previous results in the temperature range 1.2°K to 4°K give $\alpha=0.6$;[8] $\alpha=0.58$;[9] $\alpha=4.7$;[10] and $\alpha=2.0$.[11] The fact that our value of α is somewhat less than that observed by the two latter groups of workers is due probably to small differences in purity of the samples.

At temperatures below those reported herewith, the thermal resistance between the salts appeared to include more highly tem-