Interaction of Neutrons with Electrons in Lead*

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ABOUT ten years ago Condon[1] showed that Dee's[2] estimate of the upper limit for the neutron-electron interaction could be greatly reduced by considering the interaction of slow neutrons with atoms.

These considerations can be greatly extended by considering the interference of the wave scattered by the nucleus with the wave scattered by all of the electrons in the atom as first introduced by Bloch[3] in connection with the magnetic scattering of neutrons. In this case the scattered amplitude consists of the sum of terms due to the nucleus and to the electron

$$\psi=\psi_N+\psi_e+\cdots, \tag{1}$$

and the atomic cross section becomes, to a close approximation,

$$\sigma=\sigma_N+2Z\bar{f}(\sigma_e\cdot\sigma_N)^{\frac{1}{2}}+Z^2(f^2)_{\text{Av}}\sigma_e, \tag{2}$$

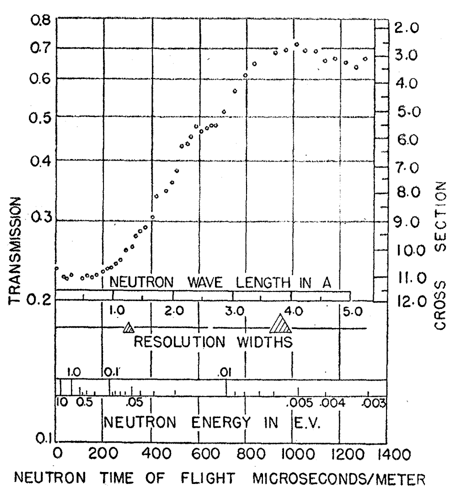

FIG. 1. The slow-neutron transmission of 46.51 g/cm² of solid lead.

where σ_N is the nuclear cross section, σ_e is the cross section per bound electron, $\bar{f}$ is the integrated form factor for the amplitude, and $(f^2)_{\text{Av}}$ for the square of the amplitude of the wave scattered by the bound electrons. For $\sigma_e\ll\sigma_N$ the main contribution to $\Delta\sigma\equiv(\sigma-\sigma_N)$ is from the cross term $2Z\bar{f}(\sigma_N\sigma_e)^{\frac{1}{2}}$. For $Z\bar{f}\sim40$ it is seen that $\sigma_e=6\times10^{-8}\sigma_N$ will give a 2 percent shift in the total cross section. The last term in Eq. (2) can be neglected for subsequent considerations.

The effect here described is not a spin-spin interaction since the total electronic spin of the atom is zero and the effect is thus different from the paramagnetic and ferromagnetic scattering of neutrons.

To study this effect we have measured the total cross section of solid and molten lead as a function of the wave-length of the incident neutrons using the neutron spectrometer.[4] Lead was chosen because of its large value of $Z(Z=82)$ and its small absorption for slow neutrons ($\sigma=0.1\lambda$ in units of 10^{-24} cm²/atom where λ is given in angstrom units). The change of the atomic form factor $\bar{f}$ for the electrons as λ changes from 0.2A to 1.7A, is used for the observation of the effect. The nuclear form factor remains constant and equal to unity since the nuclear scattering is isotropic. The atomic form factor is given sufficiently well for this purpose by the Fermi-Thomas atom model.

The experimental points are given in Figs. 1 and 2. Figure 1 is for the solid and shows the characteristic increase in transparency with λ as is expected for crystalline materials. Figure 2 shows the results for liquid lead at about 350°C and 500°C. A disk of lead metal was used for the solid sample. A sample holder, in which the lead could be poured in and out of the sample position without altering the position of the container in the beam, was used for the liquid sample. The thicknesses (g/cm²) of the liquid samples were

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[1] E. U. Condon, Phys. Rev. **49**, 459 (1936).
[2] P. I. Dee, Proc. Roy. Soc. **A136**, 727 (1932).
[3] F. Bloch, Phys. Rev. **50**, 529 (1936).
[4] Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947).

not known accurately so the cross sections were adjusted to be equal to that of the solid in the region above thermal energies. In any event, it is the *shape* rather than the absolute value of the curve which is of greatest importance. A minimum of uncertainty in the shape of the curve was obtained by the fact that all 16 points on a given curve were taken simultaneously.

The general flatness of the curve shows that the diffraction effects due to the liquid structure are not very important at these neutron wavelengths. Nevertheless, a correction can be made for this effect by the use of the theory of liquid scattering.[5]

From this theory the contribution to $\Delta\sigma$ due to the liquid molecular structure is $(\lambda^2/\lambda_0^2)\Delta\sigma(\lambda_0)$, when λ_0 is taken at some point where the liquid form factor deviates imperceptibly from the atomic form factor. X-ray results indicate that this is true for most monatomic liquids at $\lambda\sim 1.6$A. Since the nuclear scattering is isotropic, the nuclear form factor is always unity, therefore the cross section would be constant with respect to λ in the energy region investigated except for a small correction for the temperature agitation. This correction is under 1 percent in the region in which we are interested from 0.2A to 1.7A and is parabolic in form, therefore this correction can be lumped with the parabolic correction for the liquid-diffraction effect.

In our analysis we have assumed that all of the isotopes of lead scatter with the same phase and approximately the same amplitude, because the capture cross section is small and the scattering cross section is very nearly $4\pi R^2$.[6] However, the recent results of Fermi and Marshall[7] suggest that one isotope has opposite phase and therefore the effective scattering length of lead of normal isotopic composition is about $\frac{1}{2}$ of the expected value. This would reduce the sensitivity of our measurement of the electron-interaction amplitude by a factor of two.

To obtain the true variation of the total atomic scattering (nuclear+electron), we have to subtract the liquid interference effect together with

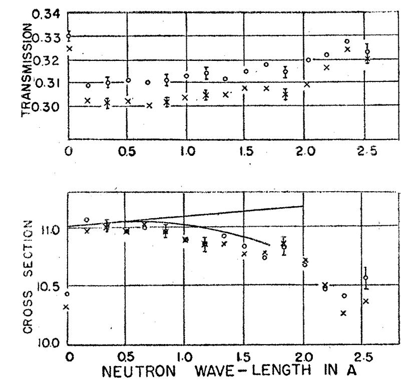

FIG. 2. The slow-neutron transmission and cross section of molten lead as a function of the neutron wave-length. O—temperature ~500°C, X—temperature ~350°C.

the 1/v change in cross section which is due to absorption.

In addition it should be noted that we assume the incoherent scattering to be constant and small over the region because of the great mass of the lead atom and because the temperature of the lead is from 7 to 9 times the characteristic temperature Θ which is 88°K for solid lead; furthermore, the two curves agree closely although one is close to the melting point and the other is about 150°C higher, indicating no great effect because of liquid aggregation. We also neglect spin-orbit interaction which gives an effect which is orders of magnitude less than observable in our experiment.

The net result is given in Fig. 3. The 1/v capture line and the parabolic correction are indicated in Fig. 2. The values of the ordinates of the points in Fig. 3 correspond to the distance of the points from the correction curve in Fig. 2. The magnitude of the parabolic correction is closely

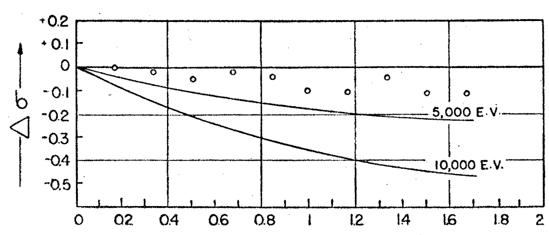

FIG. 3. Comparison of the corrected experimental points with the theoretical electron-neutron interaction curve for two different interaction potentials.

[5] N. S. Gingrich, Rev. Mod. Phys. 15, 90 (1943).
[6] H. Feshbach, D. Peaslee, and V. F. Weisskopf, Phys. Rev. 71, 145 (1947).
[7] E. Fermi and L. Marshall, Phys. Rev. 71, 666 (1947).

determined by comparing the *shape* of the first part of the curve (0.2 to 1A) and the total deviation of the latter part of the curve near 1.7A. The points shown in Fig. 3 are the averages of the values for the two temperatures.

From the Born approximation

$$\Delta\sigma = 2\pi^{\frac{1}{2}}(2M/h^2)(KZ/4\pi)\bar{f}(4\pi/\lambda). \quad (3)$$

K is the interaction function which we take as $4/3\pi a^3 V$ where a is the electron radius e^2/mc, M is the mass of the neutron, and $\bar{f}(4\pi/\lambda)$ is the integrated atomic form factor for the given wave-length which can be evaluated from the curve on page 148 of Compton and Allison.[8]

The two solid lines show what form this curve would take for a potential well of 10,000 ev and of 5000 ev. It is clear that the experimental points are well within the 5000-ev curve which can be taken as a fairly safe upper limit. Perhaps 2500 ev would be a closer fit to the present status of this experiment. At 5000 ev σ_e per bound electron is 4×10^{-31} cm^2. If the effective scattering length of lead is $\frac{1}{2}$ the assumed value,[7] the magnitude of all the interaction potentials given here should be doubled.

The experimental results seem to indicate that the electronic interaction causes a diminution of the scattering cross section. This would mean that the interaction is that of an attraction rather than a repulsion. If, as is supposed in some meson theories of neutron structure, the neutron is part of the time a proton plus a negative meson at a distance of the Compton wave-length of the meson, this would correspond to an attraction.

Experiments of this type can yield exact information which should provide a severe test of the validity of such theories of the structure of the elementary nuclear particles.

[8] A. H. Compton and S. K. Allison, *X-rays in Theory and Experiment* (D. Van Nostrand and Company, Inc., New York, 1935).