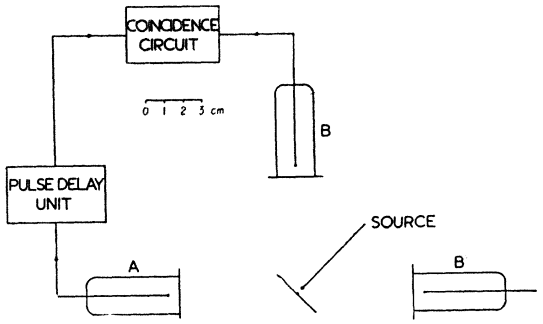

FIG. 1. Schematic diagram of experimental arrangement for measuring directional correlation of delayed radiations.

particle emitter. Since instantaneous coincidences are not recorded, the difficulties mentioned are ruled out. The major experimental difficulty is, in this case, due to the competition of the random with the genuine delayed coincidences. One should endeavor to make the efficiency of the detectors (Geiger-Müller counters) as large as possible and still keep the angular resolution high. Furthermore, the individual counting rates should be kept at a minimum, determined by the maximum practical time of the experiment. For half-lives shorter than about one μsec. the random coincidences are less troublesome. However, when the lifetime is shorter than 10^{-7} sec., the fluctuations in the time lag between the entrance of the ionizing radiation into the Geiger counter and the recording of the corresponding electrical pulse impose a limitation to the accuracy of the result.

With the experimental arrangement of Fig. 1 we have recorded delayed coincidences from a Hf^{181} source at angles 90° and 180° between the counters. The delay introduced in channel A was 2 μsec., while the sum of the effective pulse lengths in the two channels was 1.9 μsec. The Geiger counters in the A and B channels had mica windows of 3 and 1.6 mg/cm^2, respectively. The angular resolution was about $\pm 9°$.

It has been shown that the β^--decay of Hf^{181} leads directly to a 20-μsec. metastable state in Ta^{181}.[2] The β-transition is once-forbidden,[2] and the maximum energy is 0.405 Mev.[3] The Σ-radiation emitted in the decay of the metastable state has an energy of 0.130 Mev and is highly internally converted. It is probably a mixed electric octopole and magnetic quadrupole radiation.[2] Further internally converted γ-rays follow the 0.130-Mev transition, but they are probably of less importance in this experiment.

It is apparent that the observed delayed coincidences are mainly due to β-particles entering counter A and conversion electrons (chiefly from the 0.130-Mev transition) entering counter B. The genuine delayed coincidence rates were found to be 0.018 ± 0.0017 (p.e.) min.$^{-1}$ and 0.02 ± 0.0029 min.$^{-1}$ in the 90° and 180° positions, respectively, before the experiment had to be discontinued for some months. The random coincidence rate amounted to one-fourth of the genuine coincidence rate. A possible deviation from isotropic distribution must therefore certainly be less than 15 percent. It is, of course, quite probable that the distribution actually should be symmetrical owing to the following reason: In our delayed coincidence experiment we have selected the transitions in which the nuclei, decaying by β-emission to the metastable state, remain in this state for between two and four μsec. During this time an originally existing anisotropy could have been removed by external fields which may be acting on the magnetic moment of of the nucleus. The most likely effects would be the coupling between the nucleus and the atomic electrons, or the influence of other fields existing within the crystals or molecules in the source material.[4] On the other hand, if any appreciable alignment of the nuclear magnetic moments with respect to these fields occur, the relaxation time for the process may be rather long. It is therefore our purpose presently to measure angular correlations of the radiations preceding a short-lived state (e.g., Ta^{181*}, Te^{121*}, $Tm^{169*\text{ or }171*}$, Re^{187*}, Po^{213*}, RaC′*, ThC′*, etc.) and the radiations emitted from this state after the lapse of different time intervals. This can easily be achieved by introducing a variable delay in channel A (Fig. 1). It should then be possible to get an indication of the relaxation time for the alignment process, which further may give us some information about the fields acting on the nucleus.

By applying a magnetic field to the sample under low temperature it may even be possible to influence the angular distribution by external means. The corresponding relaxation times may then be studied.

[1] Kikuchi, Watase, and Itoh, Zeits. f. Physik **119**, 185 (1942); R. Beringer, Phys. Rev. **63**, 23 (1943); W. M. Good, Phys. Rev. **70**, 978 (1946); E. L. Brady and M. Deutsch, Phys. Rev. **72**, 870 (1947); A. H. Ward and D. Walker, Nature **163**, 168 (1949).
[2] A. Lundby, Phys. Rev. (to be published). See also S. DeBenedetti and F. K. McGowan, Phys. Rev. **74**, 728 (1948); Bunyan, Lundby, Ward, and Walker, Proc. Phys. Soc. **61**, 300 (1948).
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On the Polarization of Slow Neutrons

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RECENT measurements[1] of Bloch's polarization cross section, p, for thermal neutrons in cold-rolled iron yield a value $p=3.1$ barns, about a factor of 3 larger than the latest previous theoretical value,[2] and one might think that there is a serious disagreement here, requiring some drastic correction in the magnetic interaction law. It has been pointed out, however,[3] that a critical revision of some factors entering the theory leads to a different conclusion. It is the purpose of this note to give a more detailed account of this work.

We are concerned here with an analysis of the "single transmission experiment." A beam of slow neutrons is detected after passing through a slab of iron. The experiment is performed alternately with the iron unmagnetized, and magnetized in a direction perpendicular to the neutron beam. For unmagnetized iron the scattering cross section for both spin orientations of the neutrons is the same. However, when the iron is magnetized, there is an additional contribution from the scattering of the neutrons on the magnetically active d electrons, which is of opposite sign for the two spin orientations: $\sigma_+=\sigma+p$; $\sigma_-=\sigma-p$. If a neutron beam of intensity I_0 passes through a slab of unmagnetized iron d cm thick, with N atoms per cubic cm, it will emerge with intensity $I_u=I_0e^{-Nd\sigma}$. When the iron is then magnetized, the transmitted intensity increases:

$$I_m=I_0/2[e^{-Nd\sigma_+}+e^{-Nd\sigma_-}]=(I_0/2)e^{-Nd\sigma}[e^{+Ndp}+e^{-Ndp}],$$
$$I_m/I_u=\cosh Ndp.$$

The experiment therefore measures p.

The theoretical determination of p, which is somewhat complicated by crystal effects, has been carried out by Halpern, Hamermesh, and Johnson.[4]

For saturated iron:

$$p=\left(\frac{\sigma_{\text{coh}}}{4\pi}\right)^{\frac{1}{2}}\frac{e^2}{mc^2}\mu_n\mu_e\left(\frac{\lambda}{2a}\right)^2\sum_{l<2a/\lambda}\frac{N(l)}{l}\left(1+\frac{l^2\lambda^2}{4a^2}\right)F(l), \qquad (1)$$

where

σ_{coh} = coherent scattering cross section of the iron nucleus,
μ_n = neutron magnetic moment in nuclear magnetons,
μ_e = magnetic moment of all unpaired electrons, in electronic magnetons,
= 2.18 for iron,
λ = de Broglie wave-length of the neutrons,
a = lattice constant of the iron = 2.86×10^{-8} cm,

$$F(l)=(a/2\pi l)\int_0^\infty \sin(2\pi lr/a)\varphi^2 r dr \Big/ \int_0^\infty \varphi^2 r^2 dr,$$

φ = wave function of d electrons (electrons with unpaired spin).

The summation is extended over all positive numbers l, such that $l^2=2n$, $n=1, 2, 3\cdots$.

$N(l)$ is a weight factor for the Debye ring l and is equal to twice the number of ways in which three integers (positive, negative, or zero) can be chosen such that the sum of their squares is equal to l^2. Actually formula (1) is somewhat simpler than the one derived in reference 2. In (1) the reduction in the elastic scattering due to the thermal motion of the lattice points has been neglected. This is done for the following reason. The scattering p is due to the interference between the nuclear scattered wave and the magnetic wave. This interference is preserved in the inelastic scattering. Now whenever the elastic scattering is diminished by the thermal motions, the inelastic scattering is increased by *approximately* the same amount. It is, therefore, a good approximation to say that that which disappears from the elastic scattering reappears in the inelastic scattering. Both effects are, therefore, neglected. Previously only the reduction in elastic scattering had been taken into account, resulting in too low a value for p.

TABLE I. Form factors $F(l)$ as calculated with different wave functions.

l^2	Free atom (Hamermesh[2])	Atom in solid, exchange taken into account, $\varphi=0$ at atomic radius	Atom in solid, exchange taken into account, $\partial\varphi/\partial r=0$ at atomic radius
2	0.48	0.605	0.572
4	0.28	0.453	0.381
6	0.19	0.315	0.269
8	0.12	0.223	0.192
10	0.08	0.157	0.135
12	0.053	0.123	0.104
14	0.035	0.082	0.067

The greatest difficulty in evaluating p comes from the uncertainty in the d electron wave functions which occur in the form factors $F(l)$. Hamermesh[2] has used the Hartree wave functions for free iron atoms. If one tries to improve this slightly by recalculating the wave functions with a Wigner-Seitz boundary condition, one gets hopelessly large positive energies for the d electron states. Evidently the Hartree approximation is insufficient, and it is necessary to take the exchange interaction into account. This has been done roughly in the following way. The d electrons are supposed to move in the potential of the nucleus which is shielded by the inner shells and by 7 $3d$ electrons. The shielding potentials are those of the Hartree calculation for the free atom. To this are added the Fock exchange integrals of a $3d$ electron with all other shells and with its own. In this potential 2 new wave functions are calculated, one zero, and the other with zero derivative at the atomic radius. The first corresponds to the top, the last to the bottom of the d band. There is some reason to believe[5] that the magnetic d electrons are near the top of the band and that the first wave function should be used. However, p has been computed for both. The wave functions are shown in Fig. 1 and the form factors in Table I.

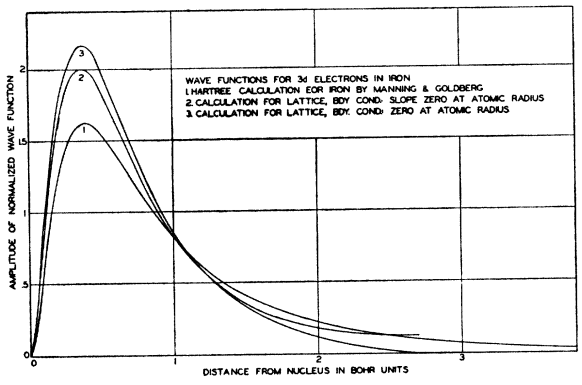

FIG. 1. Wave functions for the $3d$ electrons in iron. 1. Hartree wave function for a free iron atom. Exchange not taken into account. 2. Wave function with zero slope at the atomic radius and exchange taken into account. 3. Wave function zero at the atomic radius and exchange taken into account.

The third and only other change which has been made is in the value of σ_{coh}, the cohrerent scattering cross section of the iron nucleus.[6] Transmission measurements on fast epithermal neutrons give for the scattering cross section of an iron nucleus a value $\sigma=11.0$ b.[7] In order to obtain σ_{coh} one must subtract from σ the incoherent part σ_{inc} associated with isotopic disorder and random orientation of the nuclear spins. The main difficulty in the past has been in estimating this incoherent cross section. Recent work indicates that it is quite small.[8,9] We assume a tentative value $\sigma_{inc}=1$ b, then

$$\sigma_{coh}=(11.0-1.0)\text{b}=10\text{ b}$$

which is considerably higher than the value 6.75 b which was apparently used by Halpern and co-workers.[2,4]

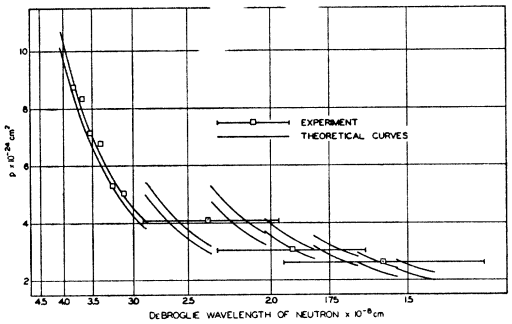

FIG. 2. Observed and calculated values of the magnetic scattering cross section as a function of the neutron wave-length. The experimental points are those of Hughes.

The result of the three improvements described is to bring the theoretically calculated value of p into quite close agreement with the experimental results. Both have been plotted as a function of the velocity of the neutrons in Fig. 2. The agreement is closer than can be justified by the inadequate knowledge of the $3d$ wave functions.

The chief pleasure in this work cam from illuminating discussions with Drs. Fermi, Hughes, Placzek, and Teller.

[1] Hughes, Wallace, and Holtzman, Phys. Rev. **73**, 1277 (1948); experimental values $p\sim2$ b and $p\sim2.2$ b, lower than the recent value of Hughes *et al.*, but definitely higher than the old theoretical value, had already been reported previously by the Stanford group, see Bloch, Condit, and Staub, Phys. Rev. **70**, 972 (1946).

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[3] J. Steinberger and G. C. Wick, Phys. Rev. **74**, 1207 (1948).

[4] Halpern, Hamermesh, and Johnson, Phys. Rev. **59**, 986 (1941).

[5] See for instance J. C. Slater, Phys. Rev. **52**, 198 (1937).

[6] Independently of our communication (see reference 3) the need for a revision of σ_{coh} in connection with neutron polarization has been pointed out by J. M. Cassels, Phys. Rev. **74**, 111 (1948).

[7] W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **75**, 1296 (1949). See also Havens, Rainwater, Wu, and Dunning, Phys. Rev. **73**, 963 (1948), as well as the high velocity part of Fig. 2 in the paper of Hughes *et al.* (reference 1).

[8] Measurements below the crystal cut-off of Hughes *et al.* (reference 1, see especially p. 1281) give a value ~1.5 b for the sum of the incoherent cross section σ_{inc} and the thermal inelastic scattering cross section, which is of the order of 0.5 b. Hence a (very crude) estimate of $\sigma_{inc}=1$ b. A direct measurement of the incoherent cross section as being 0.8 b is mentioned by J. M. Cassels and R. Latham, Phys. Rev. **74**, 103 (1948). Moreover, Burghy, Hughes, and Woolf, Phys. Rev. **76**, 188 (1949) from measurements on single crystals arrive at the conclusion that σ_{inc} is much smaller than the thermal inelastic scattering cross section.

[9] H. Staub has kindly informed us of transmission measurements on a single crystal which also lead to our estimate $\sigma_{inc}=1$ b. We are very indebted to Dr. Staub for communicating these and other results on neutron polarization to us before publication.