forenoon but failed on June 19. Weak transmission by scattered reflections also failed. Absorption of E transmission from W8XAL (6060 kc/s, 650 km distant) was greater than normal on June 19. The F_2 virtual heights were very high when $f_{F_2}{}^x$ began to increase above $f_{F_1}{}^x$ from 1400 to 1600 EST June 19.

This example of correlation of the condition of the ionosphere with a magnetic storm corroborates previous evidence obtained by us: (1) Disturbed radio conditions correlate much better with disturbances of the Z than with disturbances of the H component. (2) A severe magnetic disturbance beginning during the daytime may show little correlation with radio data while a severe magnetic disturbance before sunrise is accompanied by disturbed radio conditions during the whole of the following day. (3) The disturbed radio conditions include lowered critical frequencies, increased absorption, and increased virtual heights, indicating a diffusion of the ionosphere. (4) During a magnetic disturbance the higher part of the ionosphere is the most disturbed.

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On the Magnetic Scattering of Neutrons

The direct experimental evidence of the neutron, obtained so far, indicates its mass and the range of forces within which it interacts with other heavy particles. The angular moments of nuclei make it practically sure that it has an angular momentum $\frac{1}{2}h/2\pi$. Furthermore there are good theoretical reasons to believe that it should have a magnetic moment of the same order of magnitude as the measured moment of the proton but having the opposite direction with respect to the angular momentum; these conclusions are partly based on Fermi's theory of the β-decay, partly on the known magnetic moment of the deuteron. Since the Stern-Gerlach method may meet considerable difficulties when applied to neutron beams, we want to propose a different way of obtaining information about the magnetic moment of the neutron which seems considerably simpler and promising in several other respects.

Consider an atom (or molecule) which in its ground state has a total magnetic moment $\boldsymbol{\mu}$ caused by the spin or the orbital motion of the atomic electrons. The magnetic field around and within the atom can in any case be described by an average dipole density distribution $\boldsymbol{\mu}g(\mathbf{r})$ with $\int g(\mathbf{r})d\tau=1$. It will scatter neutrons on account of two reasons:

(1) Because of the interaction of the neutron with the atomic nucleus (or nuclei);
(2) Because of the inhomogeneous magnetic field in its surrounding acting on the magnetic moment of the neutron.

Although the forces on the neutron due to the second cause have to be assumed to be extremely much weaker than those due to the first cause, they act on distances so much larger that the scattering effect of both on slow neutrons becomes of the same order of magnitude. Treating the interaction due to both causes as small disturbances of the plane waves, which represent the incoming and scattered neutron one readily obtains a formula for the magnetic influence on the scattering process.

Let Θ be the angle between the orientation of $\boldsymbol{\mu}$ and the direction of incidence of a neutron with velocity v, $\gamma_n=\mu_n/[(e/Mc)\cdot(h/4\pi)]$ the magnetic moment of the neutron μ_n, measured in units of the Bohr magneton, divided by the ratio of masses M/m of the neutron and electron and $\mathbf{q}=\mathbf{k}_0-\mathbf{k}_1$ the difference between the vectors of propagation of incident and scattered wave, both having equal magnitude $k_0=k_1=2\pi Mv/h$. The cross-section ϕ_ω per unit solid angle for scattering under an angle ϑ against the direction of incidence and an azimuth φ against the common plane of $\boldsymbol{\mu}$ and $\mathbf{k}_0$ is then given by

$$\phi_\omega=\sigma_\omega\left|1\pm\frac{\gamma_n\gamma_e}{2(\sigma_\omega)^{\frac{1}{2}}}\frac{e^2}{mc^2}\left(\sin\theta\cos\frac{\vartheta}{2}\cos\varphi-\cos\theta\sin\frac{\vartheta}{2}\right)^2F(\mathbf{q})\right|^2, \quad (1)$$

where γ_e is the absolute magnitude of the atomic moment μ, measured in units of the Bohr magneton, and

$$F(\mathbf{q})=\int\exp\,(i(\mathbf{q}\cdot\mathbf{r})g(\mathbf{r})d\tau \quad (2)$$

is an atomic form factor, determined by the distribution of magnetism in the atom, which approaches unity for $1/q$ being large compared with atomic dimensions. The plus or minus sign in formula (1) is valid for neutrons with a magnetic moment oriented parallel or antiparallel to $\boldsymbol{\mu}$, respectively.

Formula (1) for the scattering cross section per atom remains practically valid also for the case of a ferromagnetic polycrystalline substance, the only difference being that for the determination of $\mathbf{q}$ only such neutron velocities v are to be used for which the condition of interference at microcrystals with properly chosen orientation can be satisfied. Furthermore one has to consider that γ_e becomes temperature dependent:

$$\gamma_e(T)=\gamma_e(0)\frac{I(T)}{I(0)} \quad (3)$$

[$I(T)$ = Intensity of magnetization at saturation and at absolute temperature T] because of the decreasing average magnetization per atom as the temperature T approaches the Curie point; at saturation the angle θ in (1) is the angle between the magnetizing external field and the direction of incidence of the neutrons. While for fast neutrons the second term in (1) is negligible, it is quite considerable for neutrons with thermal energy, for which the wave-length is comparable with atomic dimensions, since $F(\mathbf{q})$ has then the order of magnitude one. The importance of the magnetic effect is measured by the number $k=(\gamma_n\gamma_e/2(\sigma_\omega)^{\frac{1}{2}}\cdot(e^2/mc^2)$ which, for example for magnetized iron with $\gamma_e\cong 2$, $(\sigma_\omega)^{\frac{1}{2}}$ = radius of the iron nucleus $=5.10^{-13}$ cm and assuming $\gamma_n=1$ becomes $k\cong 0.7$.

Since for $T>$Curie temperature γ_e vanishes, one can obtain for temperatures of the ferromagnetic scatterer above the Curie point independent information about σ_ω alone. For temperature below the Curie point the effect then depends solely on the product $\gamma_n F(\mathbf{q})$ since all other quantities in the second term of (1) are known.

We suggest the following applications.

(a) Measurement of γ_n and thus of the magnetic moment of the neutron by measuring the scattering cross section for very slow neutrons or under small angles, so that $q\cong 0$ and $F(\mathbf{q})$ becomes practically one.

(b) Production of polarized neutron beams by letting neutrons pass through magnetized iron and observing that due to the cross product in the expansion of (1) the weakening of the beam due to scattering is different for neutrons with opposite orientation of their magnetic moment with respect to the magnetizing field. For example, the intensity of a neutron beam after having passed through two plates of iron should be different whether both are magnetized parallel to the beam or one is magnetized parallel and the other antiparallel.

(c) An experimental study of the distribution of the magnetizing electrons in ferromagnets, particularly whether they are conduction electrons or belong to inner shells, by investigating the scattering for different values of $\mathbf{q}$ and thus obtaining some information about the function $F(\mathbf{q})$ or the magnetic distribution function $g(\mathbf{q})$ related to it by Formula (2).

Experiments are under way here to test the predicted effect and its implications. Even if no magnetic scattering could be observed this should lead to the interesting conclusion that the magnetic moment of the neutron is considerably less than that theoretically to be expected.

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July 6, 1936.

On the Probability of γ-Ray Emission

The radiation of a system of charged particles can be described, according to its symmetry properties, as dipole, quadrupole, etc., radiation. For each higher order of symmetry, the probability of emission generally decreases by a factor (wave-length of radiation/dimension of radiating system)^2. In particular for γ-rays of about 1 MEV emitted by radioactive nuclei one should expect the ratio of dipole and quadrupole intensities to be about $(10^{-10}/10^{-12})^2=10^4$. The investigation of the internal conversion of γ-rays[1] has shown that both types of transitions actually occur; however, they are known to be of about equal intensity. Furthermore, the comparison of the probability of γ-ray emission with that of long range α-particles[2] seems to indicate that the probability of radiative nuclear transitions is that of quadrupole lines. These facts show that for atomic nuclei the probability of dipole transitions is for some reason reduced by a factor of several thousands.

We want to point out here that this may be understood by taking into account the exchange of charge between neutrons and protons which, according to the present views[3] is to a large extent responsible for the binding forces between nuclear constituents. In fact the frequency ν_0 of this exchange is very large compared to the frequency ν of radiative oscillations. Considering for simplicity a proton and a neutron oscillating against each other inside the nucleus, it can be easily seen that due to this mechanism the effective dipole moment will be reduced by a factor $A\cong\nu_0/\nu$; in the limiting case of $A=\infty$ there will remain only a quadrupole moment corresponding to two positive half-charges oscillating relative to each other. This circumstance reduces the probability of dipole transition by a factor $(\nu_0/\nu)^2$, while it leaves that of quadrupole radiation practically unchanged. In order to estimate the magnitude of A one has to consider that $h\nu_0=U_0$ is of the order of magnitude of the potential energy between neutron and proton which can be estimated[4] to be at least 30 MEV. Thus for γ–radiation of about 1 MEV the intensity of dipole radiation has to be reduced by approximately a factor 1000 and so becomes just about that of quadrupole radiation.

The reduction factor for the radiation of the nucleus as a whole depends on the adopted nuclear model and cannot easily be calculated. But it seems plausible that the total effect will be essentially the same as for two particles.

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July 9, 1936

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Continuous Spectrum Observed in Raman Scattering

It has been found that, in addition to the Stokes and anti-Stokes lines, a continuous spectrum is observed in Raman scattering.[1] A satisfactory explanation of this has not yet been offered.

I believe it can be explained very simply as follows. A molecule in a solid or a liquid can be considered as confined to a small space due to the mutual repulsion of molecules at close approach. If we consider such a space to be force-free and regard its boundary to be an infinite field of force preventing the molecule from escaping from the space, we can look upon the molecule in the space as similar to the case of an "electron shut up in a box." In such a case, regarding the space to be a square, the molecule, according to wave mechanics, can have quantized energies given by

$$E=(h^2/8ma^2)(n_x^2+n_y^2+n_z^2).$$

This part of the energy of a molecule can increase or decrease in discrete units corresponding to changes of quantum numbers, n_x, n_y or n_z by one or more units. Since a large number of such changes are possible in the interaction of light quanta with the molecules, it is natural that we should expect what, in effect, appears to be a continuous spectrum.