DIAMAGNETIC SCATTERING OF SLOW NEUTRONS*

C. Stassis
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 8 May 1970)

We investigate the scattering of slow neutrons by the diamagnetic currents induced in an atom by an external magnetic field. The angular dependence of the diamagnetic scattering amplitude is given by $q^{-1}[df(q)/dq]$ where q is the magnitude of the scattering vector and $f(q)$ the charge form factor of the atom.

The principal electromagnetic interactions of a neutron with an atom are the magnetic interaction with the spin and orbital magnetic moment of the atomic electrons,[1] the neutron spin–neutron orbit term,[2] and the specific neutron-charge interaction.[3] In the presence of an external magnetic field there is, in addition, the magnetic interaction of the neutron with the field-induced diamagnetic currents in the atom. For magnetic atoms the diamagnetic term is small, compared with the normal magnetic interaction, and introduces only a small correction to the total magnetic scattering amplitude. With weakly paramagnetic atoms, however, the diamagnetic scattering is sometimes of significance as has been recognized in studies on vanadium[4] and the Cu:Fe system.[5] In this note the diamagnetic scattering of slow neutrons is examined in some detail.

The induced current density $\vec{j}(\vec{r})$, due to the Larmor precession of the electronic envelope of the atom about the direction of the external constant magnetic field $\vec{H}$, is given by

$$\vec{j}(\vec{r}) = -n(\vec{r})(e^2/2mc)\vec{H}\times\vec{r}, \tag{1}$$

where $n(\vec{r})$ is the electron density in the atom. The magnetic field created by this current density acts on the magnetic moment of the neutron and gives rise to diamagnetic scattering. The scattering amplitude, in the first Born approximation, is given by

$$p_d(\theta) = \mu_n \frac{Ze^2}{2mc^2}\frac{e}{\hbar c}\frac{1}{q^2}\vec{\sigma} \cdot \{[\vec{q}\cdot\nabla f(\vec{q})]\vec{H} - (\vec{q}\cdot\vec{H})\nabla f(\vec{q})\}, \tag{2}$$

where $\mu_n = -1.91$, $\vec{\sigma}$ is the Pauli spin matrix, $\vec{q}$ the scattering vector of magnitude $(4\pi/\lambda)\sin\theta$, 2θ the scattering angle, λ the neutron wavelength, and $f(\vec{q})$ the normalized charge form factor of the atom. For small values of q the scattering amplitude is independent of the scattering angle and, for a spherical atom, can be related to the second moment $\langle r^2\rangle$ of the atomic charge distribution:

$$p_d(0) = -\mu_n\left[-\left(\frac{Ze^2}{6mc^2}\right)\langle r^2\rangle\right]\frac{eH}{\hbar c}\vec{q}_m\cdot\vec{\sigma} = -\mu_n\chi_d\left(\frac{eH}{\hbar c}\right)\vec{q}_m\cdot\vec{\sigma}. \tag{3}$$

In Eq. (3) χ_d is the atomic diamagnetic susceptibility and

$$\vec{q}_m = \vec{e}(\vec{e}\cdot\vec{h}) - \vec{h}, \tag{4}$$

where $\vec{h}$ and $\vec{e}$ are unit vectors along the external magnetic field and scattering vector, respectively. For a spherical atom the diamagnetic scattering amplitude may be written in a form similar to that for paramagnetic neutron scattering:

$$p_d(\theta) = -\mu_n\frac{Ze^2}{2mc^2}\frac{eH}{\hbar c}\frac{1}{q}\frac{df}{dq}\vec{q}_m\cdot\vec{\sigma} = -\mu_n\chi_d\left(\frac{eH}{\hbar c}\right)f_d\vec{q}_m\cdot\vec{\sigma}, \tag{5}$$

where

$$f_d(\theta) = -\frac{3}{\langle r^2\rangle}\frac{1}{q}\frac{df(q)}{dq} \tag{6}$$

is the normalized diamagnetic form factor of the atom. It can be seen from Eq. (6) that the diamagnetic amplitude falls off with increasing angle faster than the scattering factor of the atom[6]; this is illustrated in Fig. 1, where the angular dependence of the diamagnetic scattering amplitude, calculated for Cu, is compared with its atomic charge form factor. This behavior is due to the fact that the current density distribution probed by the magnetic moment of the neutron is more extended in space than the atomic charge distribution, since most of the induced diamagnetic current arises from the outer atomic electrons.

The diamagnetic scattering amplitudes of metallic elements, for a typical laboratory field of 20 kOe, are of the order of 10^{-15}–10^{-17} cm/atom and they are in general larger than the neutron spin–neutron orbit amplitudes. Scattering amp-

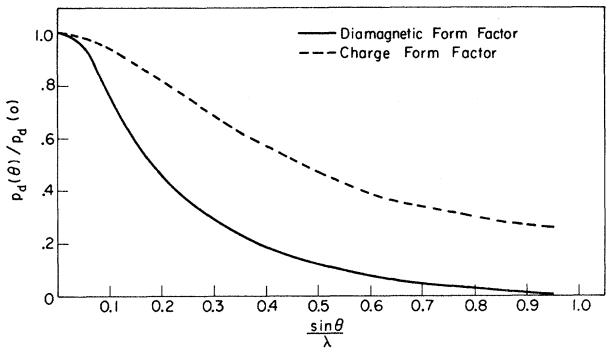

FIG. 1. Angular dependence of the calculated diamagnetic scattering amplitude of Cu compared with that of its atomic charge form factor.

litudes of this size would be very difficult to separate from the nuclear scattering amplitude (10^{-12}-10^{-13} cm/atom) in an unpolarized neutron experiment. However, with the high sensitivity of present day polarized-neutron beam techniques[5,7] and with the availability of superconducting-magnet field strengths, it becomes entirely feasible to study quantitatively the diamagnetic scattering. Such studies are presently in progress in this laboratory on metallic bismuth, a classic diamagnetic material.

The author is indebted to Professor C. G. Shull for many valuable discussions.

*Research supported by a grant from the U. S. Atomic Energy Commission.

[1]F. Bloch, Phys. Rev. 50, 259 (1936); O. Halpern and M. H. Johnson, Phys. Rev. 55, 898 (1939); G. T. Trammell, Phys. Rev. 92, 1387 (1953); J. Schwinger, Phys. Rev. 51, 544 (1957); D. St. James and S. Odiot, Phys. Chem. Solids 17, 117 (1960).

[2]J. Schwinger, Phys. Rev. 73, 407 (1948); S. B. Gerasimov, A. I. Lebedev, and V. A. Putrun'kin, Zh. Eksperim. i Teor. Fiz. 43, 1872 (1962) [Soviet Phys. JETP 16, 1321 (1963)]; C. G. Shull, Phys. Rev. Letters 10, 297 (1963); M. Blume, Phys. Rev. 133, A1366 (1964); G. Obermair, Phys. Letters 22, 573 (1966); G. Obermair, Z. Phys. 204, 215 (1967); S. W. Lovesey, J. Phys. 2, 981 (1969).

[3]L. L. Foldy, Phys. Rev. 83, 688 (1951), and Rev. Mod. Phys. 30, 471 (1958).

[4]C. G. Shull and R. P. Ferrier, Phys. Rev. Letters 10, 295 (1963).

[5]C. Stassis and C. G. Shull, J. Appl. Phys. 41, 1146 (1970); C. Stassis, thesis, Massachusetts Institute of Technology, 1970 (unpublished).

[6]A. J. Freeman and R. E. Watson, Acta Cryst. 14, 231 (1961).

[7]C. G. Shull and R. Nathans, Phys. Rev. Letters 19, 384 (1967).

OPTICAL SURFACE PHONONS IN ZINC OXIDE DETECTED BY SLOW-ELECTRON SPECTROSCOPY

H. Ibach
2. Physikalisches Institut, Technische Hochschule Aachen, Aachen, Germany
(Received 11 May 1970)

Scattering of electrons from surfaces of ZnO single crystals has been studied in ultrahigh vacuum with a high-resolution electron-impact spectrometer ($\Delta E < 20$ meV, impact energy $E_0 = 1$-100 eV). The energy-loss spectrum in specular reflection shows a series of equally spaced loss peaks. The characteristic loss energies [68.8 meV for the $(1\bar{1}00)$ surface and 67.3 meV for the (0001) and the $(000\bar{1})$ surfaces] agree with the energies of optical surface phonons determined by the condition $\mathrm{Re}\epsilon_n(\omega) = -1$.

In the direction perpendicular to the surface of a crystal the translational symmetry is broken. The corresponding wave vector component of a vibration state may become complex and a localized state, a surface phonon, may occur.[1] Dispersion relations of surface phonons have been calculated in some simple models.[2-4] However, no experimental technique has been so far available to study surface phonons on surfaces in the required clean and well-defined state.

Recent progress in monochromatizing low-energy electrons now offers a possibility to investigate clean surfaces with an electron-impact spectrometer. The essential parts of the spectrometer in this work are taken from Ehrhardt et al.[5] The impact energy E_0 is variable between 1 and 100 eV. The optimum resolution was 12 meV. In order to obtain a higher intensity a standard resolution of 20 meV (see Fig. 1) was used in the present experiments.

Figure 1 represents a typical energy-loss spectrum obtained from a ZnO crystal (wurtzite) in specular reflection. The surfaces are prepared by cleaving the crystal in air and heating for 10 min to 300°C in an ultrahigh vacuum of 2×10^{-10} Torr.