it is so small that it might be of either sign. Thus the scattering cross section for neutrons on free protons is:

$$\sigma_{scat} = \frac{4\pi\hbar^2}{M}\left[\frac{3}{4}\,\frac{1}{\epsilon_p + (E/2)} + \frac{1}{4}\,\frac{1}{|\epsilon_a| + (E/2)}\right]$$

where ϵ_p = energy of parallel spins state of the deuteron ϵ_a = energy of antiparallel spins state (virtual) and the 3/4 and 1/4 factors properly weight triplet and singlet states, respectively.

Direct experimental evidence for the existence of singlet and triplet states of the deuteron can be obtained from measurements of slow neutron scattering on hydrogen molecules. The hydrogen molecule can have two forms, "ortho" and "para." In orthohydrogen, the two protons have parallel spins, while in parahydrogen, they are antiparallel. Now a slow neutron (de Broglie wavelength larger than interatomic distance) incident on parahydrogen will be scattered by one proton with spin parallel to the incident neutron spin and by the other with antiparallel spin. The resultant neutron wave will be made up of real state scattering plus virtual state scattering (if the antiparallel spin, singlet state, of the deuteron is virtual). Since on theoretical grounds scattering for real states is 180° out of phase with that for virtual states, it follows that parahydrogen scattering should result in out-of-phase scattering from the two antiparallel spin hydrogen atoms, i.e., a small scattering cross section. Similarly, scattering of slow neutrons on orthohydrogen should result in scattering "in phase" from the two atoms, resulting in a larger scattering cross section. This has been observed experimentally and confirms the hypothesis of a virtual singlet state of the deuteron.

The scattering of neutrons in hydrogen is the basis of an important method for fast neutron detection. If a thin layer of paraffin is exposed to the neutron flux, then each neutron that is scattered gives rise to a recoil proton. The recoil proton has an energy of the same order of magnitude as the neutron energy. The proton, being charged, can be detected by an ionization chamber, as shown at the left in Figure 22. To measure neutron energies a collimating device (right in Figure 22) can be used so that only protons scattered in the direction of the incident neutron flux are allowed to enter the ionization chamber. The pluse in the chamber can be calibrated in terms of proton energy, and in this way the original neutron energies can be determined. Of course, the paraffin must be sufficiently thin to make multiple scattering of the incident neutrons negligible. (This limitation will be understood better after Chapter VI.)

In general, neutron scattering cross sections show complicated variations with energy. These irregularities are related to resonance phenomena not covered in the simple theory of these sections. Cross section versus neutron energy for two important scatterers, carbon and oxygen, are shown in Figure 23. It is not always possible to measure scattering cross sections directly. Generally, *total*, cross sections are measured. For fast neutrons scattering predominates, so that the total cross section is effectively equivalent to the scattering cross section. For lower energies (below 1 Mev) this is not generally true, although for graphite and oxygen scattering predominates.

5.4 THE SCATTERING OF NEUTRONS

Referring to Figure 11, page 21, it is apparent that neutrons with energies less than 1 ev have de Broglie wavelengths of the order of Angstroms (10^{-8} cm) or greater. Since interatomic distances are likewise of the order of Angstroms, it might be expected that slow neutrons scattered by atoms will exhibit interference effects. This is actually the case. The anomalous scattering of slow neutrons by ortho- and parahydrogen, as we have seen, can be explained as an interference effect.

It is possible to study these effects by experiments analogous to those used in the study of x-ray diffraction and interference. Suppose a collimated flux of slow neutrons, Figure 24, is incident

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