PHYSICAL REVIEW VOLUME 84, NUMBER 5 DECEMBER 1, 1951

Neutron Refraction in O_2, N_2, He, A Gases*

A. W. McReynolds
Brookhaven National Laboratory,† Upton, Long Island, New York

(Received August 13, 1951)

The index of neutron refraction of oxygen, nitrogen, helium, and argon has been studied by reflection of a neutron beam from a liquid gas interface and observation of decreasing reflectivity with increasing gas pressure. Results verify that the index for gases is given by the same formulas which hold for liquids and solids. Comparative measurements of the different gases then give values for the coherent bound scattering cross sections: assuming oxygen = 4.2 barns as a standard, nitrogen = 11 barns, helium = 1.1 barns, argon = 0.5 barn.

INTRODUCTION

THE total thermal neutron scattering cross section is the sum of an incoherent and a coherent part, the latter determining all interference effects between neutron waves scattered from different nuclei. Diffraction in crystalline media is therefore the most general means of determining coherent cross sections, and has been applied by Shull and Wollan[1] to a large number of nuclei. Another interference phenomenon which may be used is total reflection from a plane surface, which may also be regarded as zero order diffraction, the critical angle for total reflection being determined by the density and coherent scattering cross section of nuclei, independent of atomic arrangement. This method was demonstrated by Fermi and Marshall[2] with solid mirror surfaces and later applied, by Hughes, Burgy *et al.*[3] to hydrocarbon liquid mirrors, to measure accurately σ_{coh} for hydrogen. Although crystal diffraction measurements are at neutron wavelengths $\sim$1A and total reflection measurements at 4–20A, the coherent cross section should be constant over the thermal range except for a few cases of near-by resonances.

The present paper reports measurements of the index of neutron refraction of a gas, and hence of coherent scattering cross section, by total reflection from an interface between the gas and a plane surface of liquid or solid. For these surfaces, materials were selected which have low indices of refraction either because of low density and cross section or because of cancellation of nuclei with positive and negative scattering phases to give a net small positive scattering amplitude. As gas index of refraction increases with pressure, reflected intensity from the interface decreases. Observations of reflected intensity *vs* gas pressure have a twofold purpose: (1) The usual formulas for index of neutron refraction assume interaction of the neutron with the entire medium rather than with individual nuclei and therefore use the bound atom, coherent cross section, exceeding the free cross section by the reduced-mass factor $(A+1/A)^2$. These formulas are verified for solids and liquids, but it was less certain that they could be extended to gases, where the nuclei are in independent motion, free of intermolecular binding forces. Comparison of cross sections by reflection with those derived from other methods serves as a check on applicability of the theory to gases. (2) By comparative measurements with oxygen, for which σ_{coh} was well known, coherent cross sections could be measured for other gases such as nitrogen, not previously measured accurately by crystal diffraction, and helium and argon, which of course are not amenable to crystal diffraction.

EXPERIMENTAL METHOD

Neutron beams from the Oak Ridge and Brookhaven reactors were defined by two horizontal slits between slabs of lucite and boron carbide. As shown in Fig. 1, the beam was reflected at angles of 3–5 minutes from 10-cm mirrors of liquid, placed inside a pressure tank, and was detected by a BF_3 proportional counter. A slit in front of the counter excluded the direct beam but allowed the entire reflected beam to enter. The reflected beam contains all incident neutrons from zero to a critical energy. Total reflected intensity was measured as a function of gas pressure from 0 to 150 atmospheres in the tank.

When a beam of neutrons heterogeneous in wavelength, strikes a mirror surface at small angle θ, the part totally reflected contains all neutrons of wavelength greater than a critical value[4]

$$\lambda_c = \theta/(n\sigma^{\frac{1}{2}}/2\pi^{\frac{3}{2}})^{\frac{1}{2}}$$

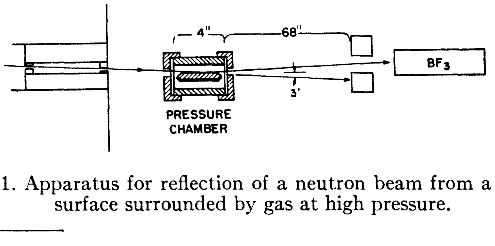

FIG. 1. Apparatus for reflection of a neutron beam from a liquid surface surrounded by gas at high pressure.

---

* Research carried out under contract with AEC.

† Part of work carried out at Oak Ridge National Laboratory.

[1] C. G. Shull and E. O. Wollan, Phys. Rev. **81**, 527–35 (1951).

[2] E. Fermi and L. Marshall, Phys. Rev. **71**, 666–77 (1948).

[3] Hughes, Burgy, and Ringo, Phys. Rev. **77**, 291 (1950).

[4] Reflectivity is not zero for neutrons of less than the critical wavelength, but since the shape of the reflectivity curve is the same for each critical angle, this correction does not significantly alter the reflected intensity *vs* gas pressure curve.

TABLE I. Characteristics of materials used as reference mirrors.

Material	n_0 nuclei/cc	σ_0 barns	$\lambda^2\delta\left(=\frac{n_0\sigma_0^{\frac{1}{2}}}{4\pi^{\frac{3}{2}}}\right)$
Ethylene glycol ($C_2H_6O_2$)	1.13×10^{23}	0.0055	3.9×10^{8}
Triethylene glycol ($C_6H_{14}O_4$)	1.09	0.0212	7.5
Lucite	1.07	0.111	16.0

where $\delta=n\sigma^{\frac{1}{2}}\lambda^2/4\pi^{\frac{3}{2}}=1-$index of refraction, $m=$neutron mass, $n=$nuclei/cc, and $\sigma=$coherent cross section. For a Maxwellian[5] distribution, the total reflected intensity can be computed by integrating

$$I=\int_{\lambda_c}^{\infty}N(\lambda)d\lambda$$

to get

$$I=\text{const}\times(n\sigma^{\frac{1}{2}}/2\pi^{\frac{3}{2}})^{\frac{1}{2}},$$

for long wavelengths, corresponding to $E\ll kT$.

In the case of reflection from an interface between media of indices of refraction $1-\delta_0$ and $1-\delta_1$,

$$I=\text{const}(\delta_0-\delta_1)^2=\text{const}(n_0\sigma_0^{\frac{1}{2}}-n_1\sigma_1^{\frac{1}{2}})^2.$$

Thus the introduction of gas of coherent cross section σ, above a liquid or solid surface decreases the reflected intensity in the ratio

$$\frac{I}{I_0}=\left(1-\frac{n_1\sigma_1^{\frac{1}{2}}}{n_0\sigma_0^{\frac{1}{2}}}\right)^2=\left(1-\frac{P}{P_0}\right)^2. \tag{2}$$

It is seen that σ may be determined by plotting $(I/I_0)^{\frac{1}{2}}$, which is a linear function of P going to zero at the pressure P_0 at which the indices of refraction of the two media are equal. Then

$$\sigma_1=[n_0/n_1(P_0)]^2\sigma_0, \tag{3}$$

where $n_0=$nuclei/cc in liquid or solid mirror; $n_1(P_0)$ $=$nuclei/cc in gas at pressure P_0, and $\sigma_0=$average coherent cross section for nuclei in mirror$=[(\pm\sigma^{\frac{1}{2}})$ average$]^2$, taking account of negative scattering phases.

The materials used as reference mirrors are listed in Table I with values of $\sigma_0^{\frac{1}{2}}$ from best available data;[1,3] and δ computed from Eq. (1).

Several corrections must be applied to the foregoing analysis: (1) Introduction of gas into the pressure chamber decreases intensity of the reflected beam not only by change of the reflectivity of the interface but also by isotropic scattering of the beam in transmission through the gas. This attenuation increases at low energies and represents an appreciable fraction of the total change of intensity, particularly in diatomic gases like oxygen and nitrogen, where molecular effects increase the cross section for low energy neutrons to 20–25 barns. It has been corrected for, both by measurement of attenuation of a beam reflected from a mirror outside the gas chamber, and by application of the data of Melkonian.[6]

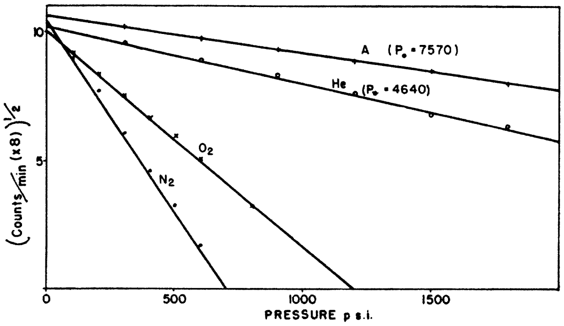

FIG. 2. Intensity of reflected neutron beam from a surface of ethylene glycol at about 3 minutes angle as a function of pressure of surrounding gas. Where $I=0$, index of neutron refraction is equal for gas and liquid.

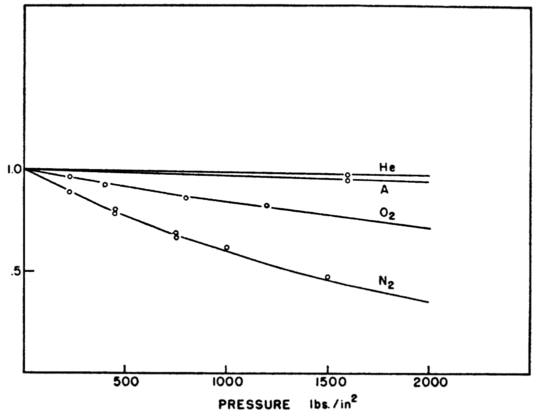

FIG. 3. Attenuation of neutron beam in transmission through the pressure tank. Curves are calculated from Melkonian's[4] data, assuming 2.5A neutron wavelength; points experimental. Correction for attenuation was made in Figs. 2, 4. Path length 10 cm. Total cross section assumed: Helium—0.7b, Argon—1.5b, Oxygen—4.5b, Nitrogen—14b.

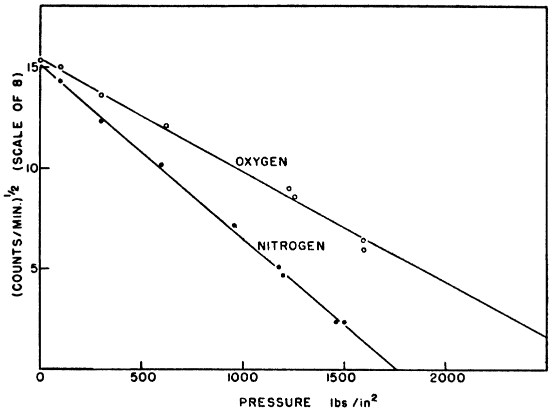

FIG. 4. Intensity of reflected neutron beam from a surface of triethylene glycol, as a function of pressure of the surround gas. Angle of incidence 3 minutes.

---

[5] The flux distribution deviates from Maxwellian form in the vicinity of the graphite cutoff at 6.7 angstroms, but does not alter significantly reflected intensity from the liquid mirrors used, for which critical wavelengths were in the range 2–5 angstroms.

[6] E. Melkonian, Phys. Rev. **76**, 1750–59 (1949).

(2) At high pressures an appreciable quantity of the gas dissolves in liquid mirrors. The density of dissolved gas atoms, however, is never more than a few percent of the gas density. (3) At gas pressures of 100–150 atmospheres densities could not be computed exactly from the perfect gas laws, but required empirical corrections of a few percent, for oxygen and argon. Corrections were negligible for helium and nitrogen.

RESULTS

Mirrors of ethylene glycol were 10 cm long and set at an angle of about 2.7 minutes, corresponding to a critical wavelength of 2.8A at zero gas pressure. In Fig. 2 are shown the curves of variation of reflected intensity with pressure of oxygen, nitrogen, helium and argon. All points are corrected according to Fig. 3 for attenuation of the beam in transmission through the gas. The curves of Fig. 3, calculated using cross sections as indicated from Melkonian's[6] results, assuming wavelength about 2.5A, agree with the experimental points shown.

The linear variation of $(I/I_0)^{\frac{1}{2}}$ for each gas verifies the analysis of the previous section and permits extrapolation of the curves to determine P_0 at which the gas index of refraction equals that of the liquid. A number of intensity *vs* pressure curves similar to those shown in Fig. 2 have been determined. Table II shows the average values of P_0 and corresponding values for the bound coherent scattering cross section, calculated from Eq. (1), taking $\sigma = 4.2$b for oxygen as a standard. Corrections for isotropic scattering in the gas, absorption in the liquid, and deviation from perfect gas laws are included.

TABLE II. Results from total reflection on ethylene glycol mirrors.

Gas	P_0(psi)	σ_{coh}(barns)
Oxygen	1260	(4.2)
Nitrogen	770	11.0±1.5
Helium	4890	1.1±0.15
Argon	7220	0.51±0.1

Similar data were obtained for oxygen and nitrogen using the higher index liquid, triethylene glycol. The effects of helium and argon were too small for accurate measurement in this case. Results are shown in Table III.

In principle the cross section of each gas can be measured by direct comparison to the liquid mirrors, for which calculated refractive indices are shown in Table I. Since this refractive index depends on a delicate balance between positive phase scattering from carbon nuclei and negative phase scattering from hydrogen nuclei, small errors in the cross-section values of these constituents would lead to large errors in the final result. Consequently only a rough cross-section value can be measured. The values of $\lambda^2\delta$ in Table I and of P_0 in Tables II and III give for oxygen

$$\sigma_{\text{coh}} = 2.7 \text{ barns}$$

measured against both ethylene glycol and triethylene glycol, as compared to the accepted value of 4.2 barns.

TABLE III. Results from total reflection on triethylene glycol mirrors.

Gas	P_0(psi)	σ_{coh}(barns)
Oxygen	1800	
Nitrogen	2770	9.7±1.1

In Table IV the present results, shown in the first column, are compared with the results of crystal diffraction by Shull and Wollan and of transmission measurements by Melkonian,[6] and by Bashkin *et al.*[7] References for the data are indicated in each case. Values for nitrogen are in fairly good agreement although slightly higher than Shull and Wollan's value, and are still somewhat lower than the total scattering cross section, as would be expected since nitrogen's spin should lead to some incoherence. The value for argon should equal the total cross section, since argon, being monoisotopic and having zero spin should exhibit no incoherent scattering. In the case of helium the difference between bound and free cross sections, resulting from the reduced mass factor $[\{(A+1)/A\}^2 = 1.55$ for helium$]$ is large enough to attempt to distinguish between them. Transmission measurements give 1.22 and 0.8 barns respectively. The total reflection value of 1.1 barns lies between these two, but in better agreement with the bound value, confirming the recent theoretical analysis of gas index of refraction by Kleinman and Snow.[8]

CONCLUSIONS

Variation of reflected intensity from the mirrors with gas pressure is as expected from theory. Cross sections

TABLE IV. Comparison of present results with other determinations.

	Scattering cross section—barns			
		Crystal diffraction (bound coherent)	Transmission	
Element	Total reflection		Total free	Total bound
Nitrogen	11.0, 9.7±1.5	9.1[a]	9.96[b]	11.5
Argon	0.51±0.1		0.68[b]	0.72
Helium	1.1±0.15		0.8[c]	1.25

[a] See reference 1.
[b] See reference 6.
[c] See reference 7.

---

[7] Bashkin, Petree, Mooring, and Peterson, Phys. Rev. **77**, 748 (1950).

[8] D. Kleinman and G. Snow, Phys. Rev. **82**, 952 (1951).

measured by total reflection agree sufficiently well with those from transmission and crystal diffraction methods to verify the applicability of the usual formulas for solids or liquids, involving coherent cross section, to calculating the index of neutron refraction of a gas. Cross section values were determined for He, A, and N as listed in Tables II and III.

ACKNOWLEDGMENTS

The author is indebted to G. W. Johnson for his collaboration in many of the measurements, to E. O. Wollan of Oak Ridge National Laboratory for the use of facilities and apparatus there and for many valuable suggestions, and to other members of the Oak Ridge and Brookhaven staffs for assistance in the experiments.

PHYSICAL REVIEW VOLUME 84, NUMBER 5 DECEMBER 1, 1951

The Significance of the Absence of Primary Electrons for Theories of the Origin of the Cosmic Radiation

T. M. DONAHUE*
Johns Hopkins University, Baltimore, Maryland

(Received July 11, 1951)

Electrons of energy above 5 Bev appear to constitute less than 0.4 percent of the primary cosmic radiation incident on the earth. An analysis of acceleration mechanisms reveals no distinctions can readily be made in acceleration per se on the basis of sign of charge or mass. The absence of high energy electrons must be explained on the basis of selective absorption. Bremsstrahlung collisions in the galaxy or the solar system and radiation caused by motion in galactic or local magnetic fields are inadequate to account for the large absorption of electrons compared with heavy particles. In collisions between energetic electrons and thermal photons losses approaching the total electron energy occur. An analysis of such collisions reveals that if cosmic rays are confined to the solar system these collisions are so frequent that no electrons should be present at energies higher than 5 Bev. The photon density is too low in interstellar space to cause a similar removal of electrons there. These results favor the solar or stellar origin theories of the cosmic radiation.

I. INTRODUCTION

EXPERIMENTAL evidence is by this time preponderantly against the presence of electrons at energies greater than 5 Bev in detectable numbers among the primary cosmic-ray particles incident on the earth.[1,2] An effect so gross as to exclude completely high energy electrons from the spectrum at the earth should, it would seem, be accounted for unambiguously by any successful theory for the origin of the cosmic radiation. Such an effect is to be sought in an accelerating mechanism which is capable of discriminating against particles on the basis of their mass or, perhaps, their charge, or else in a form of energy degradation which is selective for electrons and can either compete effectively with the acceleration or remove most of the electrons from the high energy spectrum before they reach the earth.

A. Acceleration Mechanisms

To require an accelerator which almost completely discriminates against the emergence of electrons comparable in number and in energy to protons and heavier nuclei seems quite objectionable. Perhaps the most likely requirement for a generator which would discriminate is a minimum injection energy which electrons would not in large numbers be capable of attaining. This, however, merely removes the difficulties to a different range of energies. The only obvious process by which nuclei or nuclear fragments can attain moderately high energies without similar electron acceleration would require already the existence of energetic bombarding particles.

For example, it can be noted that the two most recent proposals for the origin of cosmic rays[3-5] should provide equally well for electron and heavy particle acceleration. Where particles are accelerated in the galaxy by collisions with wandering regions of high magnetic field strength[3] a minimum injection energy is required, it is true, but, as will be shown, this energy is about the same for electrons and protons and, after injection, electrons and protons should be equally well accelerated. On the other hand, there is no apparent reason that electrons should not be available equally with positive ions among the initial particles in a system of local solar or stellar origin.[4,5] The mechanics of the betatron type of accelerator envisioned by Alfvén[5] apply as well to electrons as to heavier particles.

Therefore, it would appear that the explanation for the missing electronic component is most likely to be found by an analysis of the various ways in which

---

* Now at the University of Pittsburgh, Pittsburgh, Pennsylvania.

[1] R. Hulsizer, Phys. Rev. **76**, 164 (1949).

[2] Critchfield, Ney, and Oleska, Phys. Rev. **79**, 402 (1950).

[3] E. Fermi, Phys. Rev. **75**, 1169 (1949).

[4] R. D. Richtmeyer and E. Teller, Phys. Rev. **75**, 1729 (1949).

[5] H. Alfvén, Phys. Rev. **75**, 1732 (1949); **77**, 375 (1950).