A Bent Crystal Neutron Spectrometer and Its Application to Neutron Cross-Section Measurements

R. B. SAWYER,* E. O. WOLLAN, S. BERNSTEIN, AND K. C. PETERSON**
Clinton Laboratories, Oak Ridge, Tennessee

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The high neutron fluxes now available as a result of the development of chain reacting piles has made it possible to obtain monoenergetic neutron beams of considerable intensity by the method of crystal diffraction. One of the first practical applications of this method has been in the study of neutron resonance cross sections for low energy neutrons.

To increase the useful intensity and hence the energy range over which measurements can be made with good resolution, we have adapted the Cauchois type bent crystal spectrometer for use in neutron diffraction. The instrument gives good resolution of neutron resonance peaks of about 0.1 ev width at half maximum at energies up to 1 ev and work can be done at higher energies with a corresponding loss in resolution. As samples of work done with this instrument, absorption measurements on cadmium and iridium are discussed.

1. INTRODUCTION

THE fact that neutrons can give rise to interference effects is an obvious consequence of the wave properties of matter. The effects of neutron interference have shown themselves in a number of experiments. A classic example is embodied in the work on the scattering of neutrons by para and orthohydrogen as a function of average neutron energy.[1–4] The diffraction of neutrons by crystals[5] was first reported to be observed with cyclotron produced neutrons slowed down in paraffin. The neutron intensities obtainable in this way were presumably just sufficient to demonstrate the effect.

The development of chain reacting piles has now given us sources of neutrons of sufficient intensity to put neutron diffraction in a category comparable with that of x-ray diffraction. One of the first applications of the diffraction of neutrons by crystals was in the study of low energy resonance absorption levels. Studies of resonance absorption have been made for some time with the modulated cyclotron.[6,7] This method and the crystal diffraction method have their own particular advantages and disadvantages which, however, will not be discussed here. Work along this line has been carried on simultaneously since 1945 at Clinton Laboratories and at the Argonne Laboratory.[8–11]

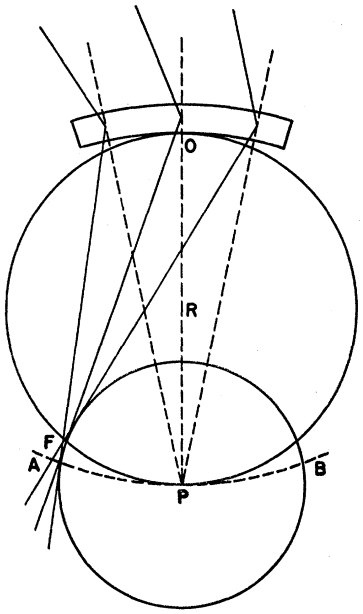

FIG. 1. Diagram of spectrometer focusing conditions.

* Now at Lehigh University, Bethlehem, Pennsylvania.
** Now a student at University of Wisconsin.

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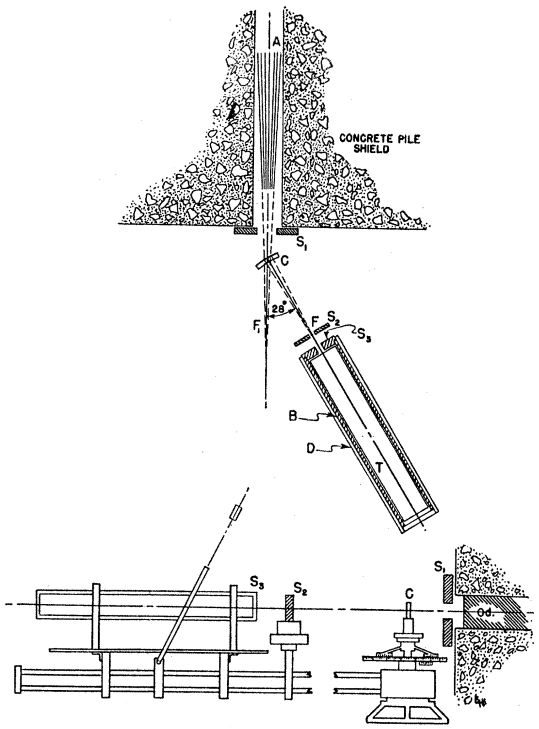

FIG. 2. (upper) Horizontal section of spectrometer.
FIG. 3. (lower) Vertical section of spectrometer.

Our first work was done with a large single crystal. The resolving power of the instrument and the obtainable neutron flux are very satisfactory when the measurements are made near thermal energy. If one desires to make measurements at neutron energies greater than 1 ev, the neutron intensity and the resolving power of the instrument decrease rapidly. Neutrons of 1-ev energy have a wave-length $\lambda=0.28$A and for a crystal of rocksalt this corresponds to $\sin\theta=0.05$ where θ is the Bragg angle for the (200) reflection.

To obtain a higher intensity and a better resolving power at small angles we have built a transmission type bent crystal spectrometer. This type of spectrometer which was developed by Cauchois[12] for x-ray work is well adapted for work at small angles, the focusing properties becoming better as the angles become smaller.

2. DESCRIPTION OF APPARATUS

The principle upon which the spectrometer operates is illustrated in Fig. 1. A crystal C, having atomic planes normal to its surface, is bent to a radius of curvature R. If a beam of convergent neutrons falls upon the convex side of this crystal, those neutrons which have the proper wave-length and glancing angle to satisfy the Bragg condition

$$n\lambda=2d\sin\theta, \quad \text{where} \quad \lambda=h/mv, \qquad (1)$$

will be reflected from the internal planes of the crystal and brought to an approximate focus on the circle OPF of radius $R/2$. In x-ray work this method has been used with photographic detection, and the photographic film is made to lie along the circle OPF. The focus here is not quite perfect but becomes more perfect as one goes to small glancing angles. In the neutron spectrometer a proportional counter (filled with BF_3 enriched in the B^{10} isotope) is used as a detector. It would be somewhat difficult mechanically to make the counter follow the circle of best focus, so we have mounted the bent crystal on the crystal table of an x-ray spectrometer with the counter arranged to rotate about the point 0 as center. The axis of the spectrometer passes through this point. At the small angles used in neutron spectrometer work the focusing achieved with this arrangement is exceedingly good.

A top view of the apparatus is shown in Fig. 2 and a side elevation in Fig. 3. The only neutrons useful in an arrangement of this sort are those which, before they passed through the crystal, were moving in directions which would bring them to a focus at the point F_1, such that the distance CF_1 is equal to R. When the crystal is oriented so that the center of curvature coincides with F_1, such neutrons will pass through the crystal parallel to the internal planes and therefore will not be deviated. When the crystal is rotated through an angle θ to a position such as that shown in the figure, the neutrons of some particular energy satisfy the conditions for Bragg reflection and are deviated, coming to an approximate focus at F, where $CF=CF_1$. At the point F is placed the entrance slit S_2 to the counter tube T. The jaws of this slit were made of $\frac{1}{4}$-inch thick sheets of a plastic impregnated with boron carbide.

A sodium chloride crystal, obtained commercially, was used in the present work. It was about 2.5 cm$\times$2.0 cm in area and about 0.3 cm

[12] Arthur H. Compton and Samuel K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, New York, New York, 1935), p. 750 *et seq.*

thick, with all surfaces being (200) cleavage planes. It was bent while immersed in a saturated solution of NaCl and retained its shape well even after removal from the clamp in which it was bent. The radius of curvature was about 60 cm. The internal (200) planes were used to reflect the neutrons.

In order to work at small angles without interference from the direct neutron beam, a multiple slit system must be used with this type of bent crystal spectrometer. The nature of this slit system which was located inside of the 4″×4″ channel in the pile shield can be seen from Fig. 2. It was constructed of 30 sheets of cadmium 100 cm long, 3 inches wide, and 0.010 inch thick. The sheets were separated at the top and bottom by tapered steel strips 0.5 inches wide, 0.070 inch thick at the one end, and 0.047 inch thick at the other end. This assembly was held together by heavy tapered steel plates with bolts through the top and bottom of the laminated assembly. The steel plates were split longitudinally and held in alignment by $\frac{3}{8}$-inch pins, and screws through the top half of the steel plate permitted the cadmium sheet to be stretched to form very flat laminations. Such a long slit system having closely spaced laminations must be maintained straight to about 0.001 inch in order not to reduce appreciably the transmitted intensity. This slit when located as in Fig. 2 gives a beam of convergent neutrons which come to a good focus at F_1. All neutrons of a given energy whose angle of incidence on the crystal could not approximately satisfy the Bragg condition for a particular crystal setting are lost in the slit system by absorption or scattering by the cadmium sheets. Although one has a wide incident beam falling on the crystal, the width of the beam at F_1 is very narrow and measurements can be made to very small angles.

There are also other advantages to this arrangement: (a) If measurements of absorption cross sections are to be made on rare materials, small samples can be used by placing the sample holder in front of the entrance slit to the counter, which in our work has usually been made 1 mm wide. (b) The resolving power of the instrument can be made independent of imperfections in the crystal and of the accuracy with which the crystal is bent to the proper radius of curvature. This is the case since the wave-length of the radiation entering the counter is determined by the angle between the incident beam and the position of slit S_2. With the multiple slit system used here the maximum horizontal angular divergence between two cadmium sheets is 9′ and the angle subtended at the crystal by a 1 mm counter slit is 6′. The sum of these two angles (15′) is approximately the maximum deviation in 2θ permitted by the system, and this should represent the minimum width of the rocking curve obtainable from a perfect crystal by rotating the crystal while the counter is held fixed. Imperfections in the crystal would add to the width of the rocking curve but would not decrease the resolving power of the instrument, which is limited only by the two angles already mentioned. Figure 4 shows a rocking curve obtained with a crystal of NaCl. From Eq. (1) it can be shown that

$$\Delta E/E = 2 \cot\theta \Delta\theta.$$

Table I gives the maximum values of $\Delta E/E$ to be expected with NaCl crystals, taking $\Delta\theta = 7.5'$.

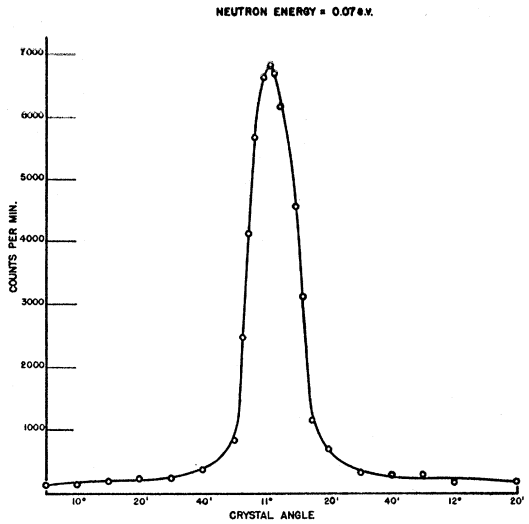

FIG. 4. Rocking curve, bent rocksalt crystal.

TABLE I. Maximum values of $\Delta E/E$ for NaCl crystals, assuming $\Delta\theta = 7.5'$.

Energy, ev	θ	$\Delta E/E$
0.05	13° 07′	0.019
0.1	9° 14′	0.027
0.5	4° 07′	0.061
1.0	2° 55′	0.081
2.0	2° 03′	0.122

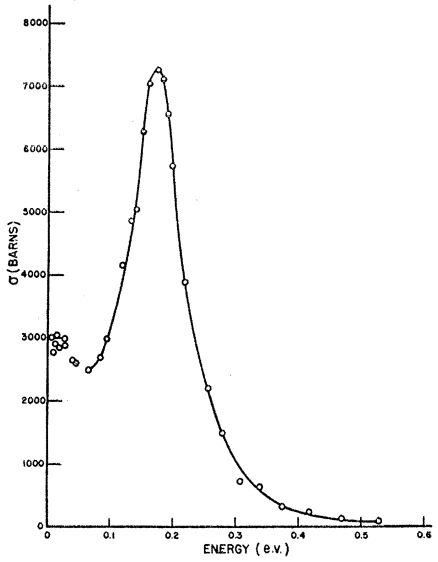

FIG. 5. Cadmium cross section as a function of energy.

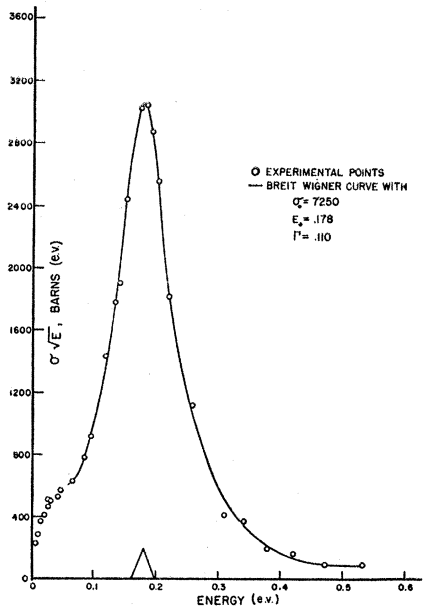

FIG. 6. Curve of $\sigma\sqrt{E}$ *vs.* E for cadmium.

With this instrument neutron beams of energies from about 0.005 ev to more than 2.0 ev have been used in absorption measurements. There is no reason why measurements cannot be made to considerably higher neutron energies with a corresponding loss in resolving power. The neutrons coming from the pile through a section of graphite moderator show an approximately Maxwellian distribution, and at the higher energies the intensity falls off rather rapidly; at 1.5 ev, for example, the peak of the rocking curve is only about twice background, necessitating rather long counting times. At the low energy end of the spectrum the useful limit is set at present by the second and higher order reflections of higher energy neutrons which are superposed on the first order of lower energies. Tests with a Pyrex plate have shown that its absorption follows the $1/v$ law down to about 0.07 ev, indicating that higher orders begin to be noticeable at this energy.

3. CROSS SECTION OF CADMIUM

With the instrument here described, measurements of the total cross section of cadmium have been made. The samples used as absorbers were sheets of the metal rolled to appropriate thicknesses. Various thicknesses were used at different energies, the thickness being chosen so as to give transmissions of between 30 percent and 70 percent. At many points several different absorber thicknesses were used.

The method of making the measurements was as follows: For any value θ of the glancing angle on the internal crystal planes, the counter was set at an angle 2θ to the incident beam. The counting rate was first measured with the absorber in place. Then the crystal was rotated through 1° and the counting rate again measured to obtain the background of incoherent scattering which reached the counter through the absorber. The absorber was then removed, the crystal reset to angle θ, and a counting rate measurement made. Finally the crystal was once more displaced through 1° and a background counting rate determined without the absorber. If we let I_0 represent the value of counting rate less background without the absorber and I represent the counting rate less background with the absorber,

$$I_0/I=\exp(Nt\sigma),$$

where N is the number of atoms of the absorber per cm^3, t is the thickness of the absorber in cm, and σ is the cross section per atom in cm^2. From this

$$\sigma=(1/Nt)\ln(I_0/I). \qquad (2)$$

The results for cadmium are shown in Figs. 5 and 6. In Fig. 5 is plotted the cross section in barns (10^{-24} cm^2) as a function of the energy of the neutrons in electron volts. These results offer an experimental check of the Breit-Wigner one-level resonance formula. According to this theory the atomic absorption cross section should be given by the expression

$$\sigma=\frac{\sigma_0 E_0^{\frac{1}{2}}\frac{1}{4}\Gamma^2}{E^{\frac{1}{2}}[(E-E_0)^2+\frac{1}{4}\Gamma^2]}, \tag{3}$$

where σ is the absorption cross section for neutrons of energy E, Γ is the total width of the resonance curve at half maximum height on the assumption that the neutron width is small compared to the radiation width of the level, and σ_0 is the peak cross section which occurs at an energy E_0. If $\sigma\sqrt{E}$ is plotted against E, a symmetrical curve should be obtained. The present data have been plotted this way as the points in Fig. 6. Since the scattering cross section of cadmium is very small in comparison with the absorption cross section, we may take the measured total cross section as being equal to the absorption cross section, and the values should be consistent with Eq. (3). The solid line in Fig. 6 is the Breit-Wigner curve obtained by setting $\sigma_0=7250$ barns, $E_0=0.178$ ev, and $\Gamma=0.110$ ev. It is seen that the agreement is excellent except at energies below 0.05 ev where the effect of higher orders becomes noticeable. The measurements in the vicinity of the resonance peak are not subject to any appreciable errors due to the presence of higher orders. This was verified by running an absorption curve with various thicknesses of cadmium at the Bragg angle corresponding to the resonance energy. This gave a straight line when plotted on semi-log paper, as shown in Fig. 7.

Errors in angle settings, in measurement of absorber thicknesses, and those caused by fluctuations in the neutron flux during the measurements should not cause an error of more than 3 percent in the calculated values of σ in the energy range between 0.05 ev and 0.2 ev but may reach 6 percent above the latter energy. With a value of $\Delta\theta=7.5'$, the corresponding value of ΔE is about 0.008 ev at the peak of the resonance curve. This resolving power is indicated by the triangle

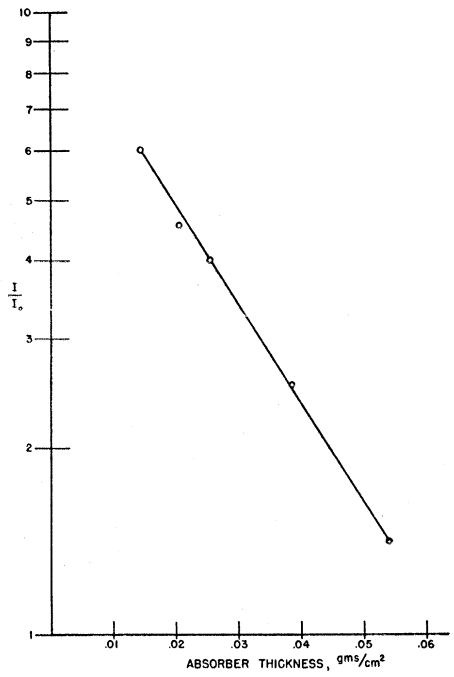

FIG. 7. Neutron absorption curve in Cd at the position of the resonance peak.

drawn on the energy axis and should be sufficient to determine σ_0 with good accuracy.

The Breit-Wigner formula can also be written as a function of both the radiation width Γ and the neutron width Γ_n from which it is then possible to calculate the neutron width. In this form

$$\sigma=\frac{h^2}{16M(EE_0)^{\frac{1}{2}}}\frac{\Gamma_n\Gamma}{(E-E_0)^2+\frac{1}{4}\Gamma^2}\left(1\pm\frac{1}{2i+1}\right)$$

where the $\pm$ sign is taken according to whether the angular momentum of the resonance level is $i+\frac{1}{2}$ or $i-\frac{1}{2}$; for $i=0$ only the $+$ sign is possible. Setting $E=E_0$ and $\sigma=\sigma_0$ we obtain on substitution of the known constants

$$\sigma_0E_0=\left(1\pm\frac{1}{2i+1}\right)1.3\times10^6\frac{\Gamma_n}{\Gamma}$$

where σ_0 is in barns and E_0 is in ev.

From the above experimental values of σ_0, E_0 and Γ for cadmium and taking $i=\frac{1}{2}$ with the $+$ sign, we obtain for the neutron width at the resonance energy $\Gamma_n=0.74\times10^{-4}$ ev. Since

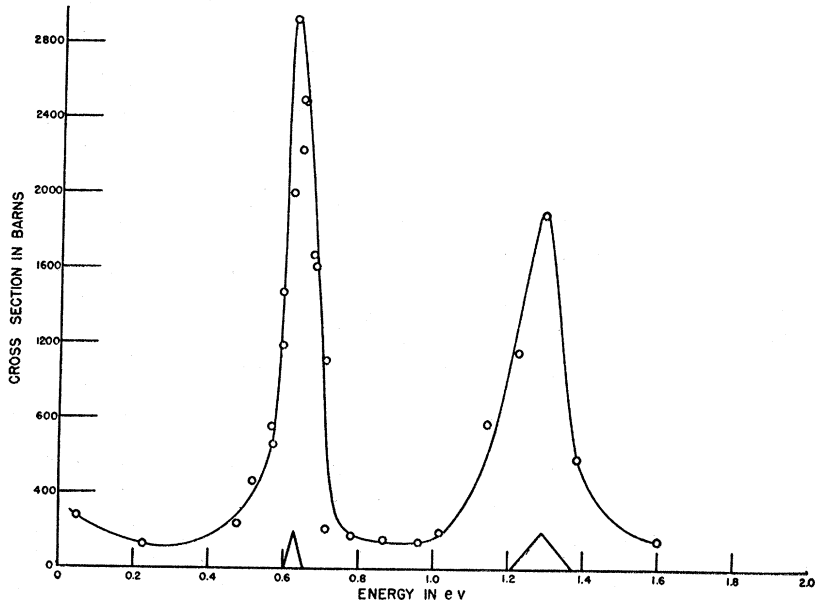

FIG. 8. Total cross section of iridium.

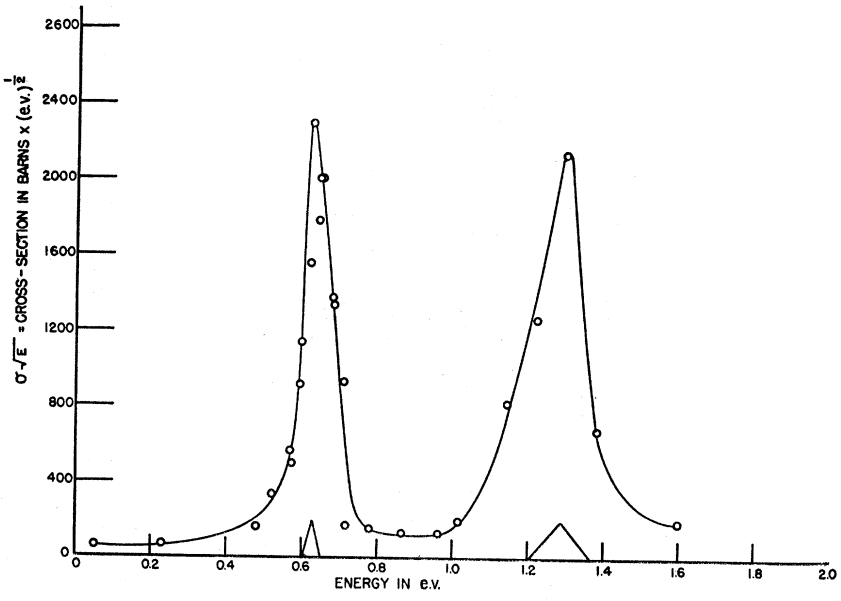

FIG. 9. Curve of $\sigma\sqrt{E}$ *vs.* E for iridium.

$\Gamma_n = a(E)^{\frac{1}{2}}$, we find

$$a = [0.74/(0.18)^{\frac{1}{2}}] \times 10^{-4} = 1.7 \times 10^{-4}.$$

4. CROSS SECTION OF IRIDIUM

The iridium was in the form of a solution of iridium chloride in D_2O contained in a quartz cell. In all, three solutions of different concentrations were used, the lowest concentration being best at the resonance peaks and the more concentrated ones best at energies where σ was small.

The solutions were analyzed for iridium and hydrogen, and the absorption and scattering due to hydrogen, chlorine, and oxygen were compensated for by comparison with a dummy quartz cell containing D_2O, H_2O, and HCl in the proper amounts. In this case, counting rates were taken first with the iridium solution and then

with the dummy cell in the beam, each being accompanied by background readings.

Curves showing the results obtained with iridium are given in Figs. 8 and 9. The resonance levels exist in the region investigated, and they are far enough apart to be quite well represented by the Breit-Wigner equation. Table II shows the values of the constants which give the best fit in each case.

These values of σ_0 and Γ are undoubtedly affected by the resolving power of the instrument, especially at the higher energy peak. The values given for σ_0 must be considered simply as lower limits and those for Γ as upper limits.

TABLE II. Breit-Wigner constants for iridium resonances.

E_0 (ev)	σ_0 (barns)	Γ (ev)
0.620	2930	0.08
1.29	1880	0.14

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Quenching and Depolarization of Mercury Resonance Radiation by Nitrogen and Oxygen

LEONARD O. OLSEN, *Case School of Applied Science, Cleveland, Ohio*

AND

GEORGE P. KERR, JR., *General Electric Company, Nela Park, Cleveland, Ohio**

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The quenching and depolarization of mercury resonance radiation by nitrogen and oxygen in the presence of a weak magnetic field are studied. These effects are proportional to gas pressure. The proportionality constants for each gas are determined. Results of tests on two samples of each gas are given, with generally good agreement between separate tests. Quenching and depolarizing cross sections are computed from the finally selected constants.

The measurements here considered indicate that adiabatic depolarization, a phenomenon tentatively postulated in the theory, is not present in the case of nitrogen and oxygen.

1. INTRODUCTION

A SEMI-CLASSICAL treatment of the theory involved in quenching and depolarization of mercury resonance radiation, and data for a number of common gases were presented in a previous paper.[1] In a subsequent paper by one of the present authors,[2] results for the rare gases were published.

Since the previous study of oxygen was not completed, and the existence of adiabatic depolarization by nitrogen was in some question, these two gases were selected for further investigations. The fact that oxygen very effectively quenches resonance radiation, and nitrogen does not, also makes these two gases a good pair for study.

Much of the same experimental equipment and technique employed in the previous work were again utilized. It was necessary to flame the system before cold traps were installed at the start of each run. This reduced the amount of water vapor released by the walls of the system to a minimum and drove the mercury vapor which had migrated to untrapped portions of the system back into the trapped areas. Agreement with H. F. Olson's[3] data for polarization *vs.*

* The experimental work on the subject presented in this paper was conducted at Case School of Applied Science in partial fulfillment of the requirements for the degree of Master of Science in Physics.

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