Rotatory Power of Nickel Sulphate at Low Temperatures*

An investigation of the natural and magnetic rotatory powers of crystalline $\alpha-NiSO_4\cdot 6H_2O$ at liquid-air temperature has been undertaken in this laboratory. Preliminary results for several visible wave-lengths are reported below.

The crystals were cooled by direct immersion in liquid "air" which was assumed to be largely oxygen. Observations were made through the double cylindrical Pyrex glass walls of the container (outside diameter 1.3 cm). The rotations actually measured ranged from 1° to 7° and satisfactory agreement was obtained between visual observations with a Lippich half-shade polarimeter, and photographic measurements by a method previously described.[1] Control measurements indicated that no serious errors arose from double refraction in the glass walls, or from lack of parallelism of the light rays in the crystal.

The results so far obtained, with corresponding room-temperature data for comparison, are given in Table I.

TABLE I. *Rotatory power of nickel sulphate.*

WAVE-LENGTH IN ANGSTROMS	4358	5461	5780
Natural rotatory power, in degrees/mm:			
At 90°K	+1.2	−2.0	−2.3
At room temperature[1]	+1.7	−0.75	−1.25
Difference	−0.5	−1.25	−1.05
Magnetic rotatory power, in min./cm-oerst.:			
At 90°K	+0.072	+0.044	+0.034
At room temperature[2]	+0.044	+0.026	+0.022
Ratio	1.64	1.69	1.54

[1] F. G. Slack and P. Rudnick, Phil. Mag. (7) **28**, 241 (1939); N. Underwood, F. G. Slack, and E. B. Nelson, Phys. Rev. **54**, 355 (1938).
[2] F. G. Slack, R. T. Lageman, and N. Underwood, Phys. Rev. **54**, 358 (1938).

The natural rotations are thus seen to be displaced in the negative (i.e. "abnormal") direction at the low temperature. The magnetic rotations, although in the positive (diamagnetic) direction, are increased at the low temperature, as in the presumably parallel case of $NiSiF_6\cdot 6H_2O$ which has recently been observed and discussed by Becquerel and collaborators.[2] The two values just given for the Verdet constant at 5461A can be represented by the relation:

$$V=0.018+2.3/T,$$

which agrees qualitatively with the earlier observations (see footnote 2 to Table I) made over a much more restricted temperature range.

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PHILIP RUDNICK
F. G. SLACK
JOHN O'CONNOR

Vanderbilt University,
Nashville, Tennessee,
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[1] L. R. Ingersoll, P. Rudnick, F. G. Slack, and N. Underwood, Phys. Rev. **57**, 1145 (1940).
[2] J. Becquerel and J. Van Den Handel, Physica **6**, 1034 (1939); J. Becquerel and W. Opechowski, Physica **6**, 1039 (1939).

Scattering of 20° Neutrons in Ortho- and Parahydrogen

Since our last report on this subject,[1] we have completely rebuilt our scattering chamber and have incorporated several new features in the neutron monochromator.[2] A rotating cadmium shutter was placed immediately in front of the BF_3 chamber to keep neutrons with energies above 50°K from entering the detector. The scattering hydrogen was in the gas phase to eliminate the complicating effects of liquid forces. A jacket of liquid hydrogen boiling at atmospheric pressure maintained the gas at 20.4°K. The scattering chamber was 10 cm in diameter and 46 cm long; it was placed midway between source and detector, which were seven meters apart. The intensity of the beam was monitored by passing it alternately through the scattering chamber and through a dummy chamber. The ratio of neutron transmission through these two chambers was measured for 20°K neutrons to be 1.00 ± 0.01.

Fifty thousand counts were recorded during the experiment and the probable errors computed from the fluctuations agreed well with those expected from the total number of counts. The linearity of counting rate with cyclotron beam intensity was checked before and after each run, and all parts of the experimental set-up worked exceedingly well throughout the course of the experiment. This fact is worth noting in view of the complex nature of the apparatus. The neutron temperature calculated from boron absorption measurements, assuming a $1/v$ dependence, agreed exactly with that obtained from the velocity measurements, i.e., 20.2°K. (This is in sharp disagreement with the work of Fertel, Gibbs, Moon, Thomson and Wynn-Williams,[3] who were unable to observe a change in the boron absorption cross section with neutron velocity.)

The parahydrogen was prepared by allowing liquid hydrogen to remain in contact with active charcoal for 36 hours. The pressure difference between the charcoal chamber and a surrounding liquid hydrogen bath was observed at frequent intervals. This indicated that the equilibrium state was approached very closely. The parahydrogen was then vaporized and the gas passed immediately into the scattering chamber where it was maintained at 20.4°K for the duration of the experiment. We believe that the composition of this sample was certainly within 0.2 percent of the equilibrium value, 99.8 percent parahydrogen.

With one atmosphere of *n*-hydrogen in the scattering chamber $I/I_0=0.238\pm0.005$. With an equal pressure of parahydrogen, $I/I_0=0.868\pm0.01$. The corresponding molecular cross sections are $\sigma_0=103\times10^{-24}$ cm² and $\sigma_p=7.40\times10^{-24}$ cm². To obtain the true scattering cross sections, the capture cross section of two protons per molecule must be subtracted. If one assumes a $1/v$ law, this is 2.24×10^{-24} cm² at 20°K. The scattering cross sections for 20°K neutrons in ortho- and parahydrogen are then

$$\sigma_0=(100\pm3)\times10^{-24}\text{ cm}^2$$
$$\sigma_p=(5.2\pm0.6)\times10^{-24}\text{ cm}^2$$
$$\sigma_0/\sigma_p=19.$$

The earlier work in this field[4-6] gave values of σ_0/σ_p from two to five. It may be concluded, as was suggested by those who performed these experiments that their ratios

were reduced by excess scattering of faster neutrons in parahydrogen. The theoretical implications of these data will be discussed in a companion note by Dr. Schwinger. We had planned to repeat the work, to improve the statistical accuracy and to search for possible systematic errors, but pressure of other work now makes that impossible for some time.

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LUIS W. ALVAREZ
KENNETH S. PITZER

Radiation Laboratory,
Departments of Physics and Chemistry,
University of California,
Berkeley, California,
November 8, 1940.

[1] L. W. Alvarez and K. S. Pitzer, Phys. Rev. **55**, 596 (1939).
[2] L. V. Alvarez, Phys. Rev. **54**, 609 (1938).
[3] G. E. F. Fertel, D. F. Gibbs, P. B. Moon, G. P. Thomson, and C. E. Wynn-Williams, Proc. Roy. Soc. **175**, 316 (1940).
[4] J. Halpern, I. Estermann, O. C. Simpson and O. Stern, Phys. Rev. **52**, 142 (1937).
[5] F. G. Brickwedde, J. R. Dunning, H. J. Hoge, and J. H. Manley, Phys. Rev. **54**, 266 (1938).
[6] W. F. Libby and E. A. Long, Phys. Rev. **55**, 339 (1939).

Neutron Scattering in Ortho- and Parahydrogen and the Range of Nuclear Forces

Experiments on slow neutron scattering in ortho- and parahydrogen[1] have proved useful in distinguishing between the alternative possibilities of a real or a "virtual" singlet state of the deuteron. It is the purpose of this note to stress that experiments of the nature described by Alvarez and Pitzer[2] provide invaluable information concerning the neutron-proton interaction in the triplet state, in particular the effective range of the forces. The information ultimately available from such investigations is embodied in values for the singlet and triplet scattering amplitudes a_0 and a_1, which are related to the corresponding cross section, σ_0 and σ_1, by $\sigma_{0,1}=4\pi a_{0,1}^2$. The sign of a_0 relative to that of a_1 is the experimental criterion for the nature of the singlet state. That the relative sign is negative is the essential result of previous investigation. The magnitude of a_0 coupled with a detailed assumption concerning the range and shape of the singlet interaction potential serves to determine the magnitude of the interaction energy. The magnitude of a_1 and the triplet binding energy will determine both magnitude and range of the triplet interaction energy with a definite assumption concerning the shape of the interaction potential. Thus the essence of the investigation is an accurate determination of the triplet scattering amplitude.

The transition cross sections among the various levels of the hydrogen molecule involve different combinations of a_1 and a_0. The cross sections for transitions among the para-levels are proportional to $(3a_1+a_0)^2$, transitions among the ortho-levels are proportional to the combination $(3a_1+a_0)^2+2(a_1-a_0)^2$, while transitions between the ortho- and para-level systems involve $(a_1-a_0)^2$. Only the quantity $(3a_1+a_0)^2$ is sensitive to the precise numerical value of a_1, for a_0 is large and of opposite sign compared to $a_1(a_0/a_1\sim-4)$. Parahydrogen at the low temperatures required for the nonexcitation of rotational levels, irradiated by neutrons of energy insufficient for excitation is therefore the experimental medium appropriate to the determination of this quantity; for this enables one to measure the elastic scattering cross section of parahydrogen in its ground rotational level, free from contamination by other, large, cross sections, save for the small capture cross section. To avoid the disturbing influence of molecular binding forces, it is necessary to use molecular hydrogen in the gaseous phase. This, however, introduces a complication occasioned by the large thermal motion of the molecules. If the target molecules are not stationary, but possess a distribution in the molecular velocity $\mathbf{u}$, the effective cross section for a neutron of velocity $\mathbf{v}$, $\sigma_{\text{eff}}(\mathbf{v})$, is not the usual cross section $\sigma(\mathbf{v})$, but rather

$$\sigma_{\text{eff}}(\mathbf{v})=\frac{1}{v}\int|\mathbf{v}-\mathbf{u}|\,\sigma(\mathbf{v}-\mathbf{u})N(\mathbf{u})(d\mathbf{u}).$$

Here $N(\mathbf{u})$, the molecular velocity distribution function, represents the Maxwellian distribution appropriate to the temperature of the gas, T. Thus, were the actual cross section independent of velocity,[3] the effective cross section would exhibit a velocity dependence represented by[4]

$$\sigma_{\text{eff}}(E)=\sigma\left\{\left(1+\frac{1}{2\xi^2}\right)\Phi(\xi)+\pi^{-\frac{1}{2}}\frac{1}{\xi}e^{-\xi^2}\right\},\quad \xi=(2E/kT)^{\frac{1}{2}}$$

considered as a function of the neutron energy E. Under the conditions employed by Alvarez and Pitzer ($E/k=T=20°\text{K}$), this yields $\sigma_{\text{eff}}=1.247\sigma$. The actual correction factor for parahydrogen will be only somewhat smaller, since the cross section decreases but slightly in the small energy range under consideration ($E=0.00173$ ev).

The cross section curves necessary for the evaluation of σ_{eff} have been computed by Schwinger and Teller,[5] with extensions and improvements by Hamermesh.[6] The effective cross section for the $0\to0$ rotational transition, the elastic scattering of para H_2, is simply

$$\sigma_{\text{para}}=\sigma_{0\to0}=6.473(3a_1+a_0)^2.$$

The cross section for scattering by orthohydrogen will consist additively of the elastic scattering cross section ($1\to1$) and the cross section for the inelastic process in which the molecule is converted to parahydrogen in its ground state ($1\to0$). For these, one obtains

$$\sigma_{1\to1}=6.291[(3a_1+a_0)^2+2(a_1-a_0)^2]$$
$$\sigma_{1\to0}=1.447(a_1-a_0)^2.$$

Combined with the experimental results of Alvarez and Pitzer,

$$\sigma_{\text{para}}=(5.2\pm0.6)\times10^{-24}\ \text{cm}^2,$$
$$\sigma_{\text{ortho}}=(100\pm3)\times10^{-24}\ \text{cm}^2,$$

these formulae imply that

$$(3a_1+a_0)^2=0.803\times10^{-24}\ \text{cm}^2,\quad (a_1-a_0)^2=6.77\times10^{-24}\ \text{cm}^2.$$

These equations have four sets of solutions but may, by the theoretical prediction that a_1 be of negative sign, be restricted to the two sets:

(I) $a_1=-4.26\times10^{-13}$ cm, $a_0=21.8\times10^{-13}$ cm,
(II) $a_1=-8.74\times10^{-13}$ cm, $a_0=17.3\times10^{-13}$ cm.

Had we used the lower limit of the experimental para cross