Energy Distribution of Neutrons Scattered by Liquid Lead*

I. PELAH,† W. L. WHITTEMORE,‡ AND A. W. MCREYNOLDS
John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California

(Received October 10, 1958)

An experiment has been performed to test some of the predictions of a recent theory of neutron scattering by liquids proposed by Vineyard. Neutrons of 0.0685 ev were scattered at 90 degrees by lead at 250°, 330°, and 550°C, and the widths at half maximum of the energy distributions were determined. The width at 250°C for solid lead was obtained for comparison purposes and found to be slightly narrower than would be predicted for a perfect gas model. The results for liquid lead show (1) that the simple diffusion model gives a slightly broader distribution than is observed for neutrons scattered by lead near the melting point and (2) that this model predicts a much larger variation of the width with temperature than is observed experimentally.

IN a recent paper, Vineyard[1] proposed a theory of neutron scattering from liquids in which he makes a basic approximation to the formal treatment of neutron scattering by Van Hove[2] and develops several models for the dynamics of the liquid motion. This treatment predicts the energy distribution of the neutrons scattered by a monatomic liquid, and a diffusion model gives the width of the distribution in terms of the self-diffusion coefficient of the liquid. A specific example is also computed for the case of liquid lead, whose self-diffusion coefficient was previously measured and which can be treated classically because of its large mass. The purpose of the present experiments is to test the predictions of the diffusion model used in this theoretical treatment.

We have performed a time-of-flight experiment to measure the energy distribution of neutrons scattered by lead at three temperatures—250°, 336°, and 551°C. The variation at each temperature was about ±5°C. The two higher temperatures gave results for liquid lead, whereas the low temperature gave, for comparison, results on solid lead. A monoenergetic beam of neutrons was selected from the reactor thermal flux by a lead crystal and was interrupted periodically by a mechanical chopper. After the neutrons had been scattered by a sample through an angle of about 90 degrees, they were detected by a bank of BF_3 counters after a flight path of 162 cm. The distribution in time of flight was analyzed by a twelve-channel time analyzer. In order to get sufficient resolution, narrow time channels were used to scan the distribution a section at a time. A single run was then performed at each temperature, with sufficiently broad channels to give by itself the whole distribution and thus to correlate the higher-resolution runs.

The time-of-flight distribution obtained in the manner described above is shown in Fig. 1 for liquid lead at 336±5°C. Similar distributions were obtained for the scattering from lead at 250° and 550°C. The average energy of the incident beam was measured with the aid of a crystal spectrometer and found to be 0.0685 ev. Figure 2 gives the energy distribution obtained from the time-of-flight measurements and includes a correction for the detector sensitivity. Also shown in Fig. 2 is the distribution of the incident neutron beam as determined by scattering it at 90 degrees from a thin sheet of vanadium. The width at half maximum of this spectrum is 0.0106±0.0005 ev. The experimental values are presented in Table I under the column headed ΔE.

Before the experimental results can be compared with theory, it is necessary to correct each of the energy distributions for the inherent resolution of the equipment, the distribution in incident energy, and the effects

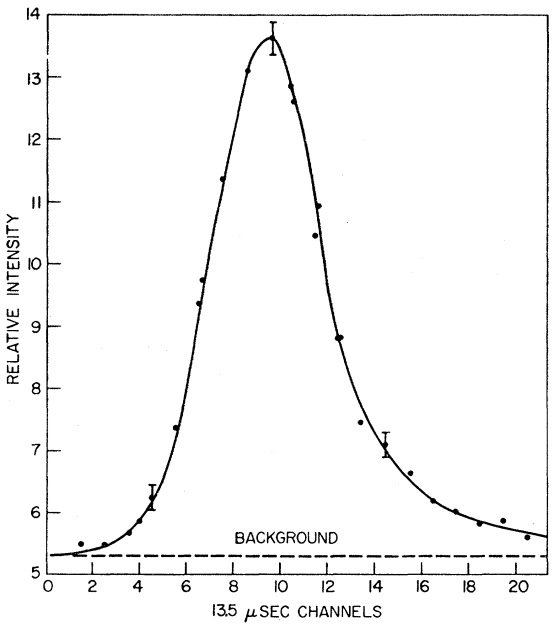

FIG. 1. Time-of-flight spectrum of 0.0685-ev neutrons scattered at 90° by liquid lead at 336°C.

* Work performed under a contract with the U. S. Atomic Energy Commission. Experimental observations were taken at the Brookhaven National Laboratory, Upton, New York.

† Guest physicist at Brookhaven National Laboratory on leave from the Weizmann Institute, Rehovoth, Israel, and the Israeli Atomic Energy Commission.

‡ Guest physicist, Brookhaven National Laboratory, Upton, New York.

[1] G. H. Vineyard, Phys. Rev. **110**, 999 (1958).

[2] L. Van Hove, Phys. Rev. **95**, 249 (1954).

TABLE I. Width at half-maximum of the distributions for lead. ΔE is the experimental value. ΔE_1 is the experimental value corrected for instrumental resolution.

Scatterer	Temperature (°C)	ΔE (ev)	ΔE_1 (ev)
V	24	0.0106±0.0005	
Pb	250	0.0192±0.0010	0.0160±0.0011
Pb	336	0.0214±0.0010	0.0186±0.0011
Pb	550	0.0225±0.0010	0.0198±0.0011

of multiple scattering in the sample. The distribution of neutrons scattered by vanadium gives both the effects of instrumental resolution and the distribution of incident energy. Correcting each of the energy distributions for lead for this effect by considering each a Gaussian distribution, one obtains the data listed in Table I under the column headed ΔE_1. These data can also be corrected for the effect of higher-order scattering by the following considerations. The sample was in the form of a sheet 4.0 mm thick and was tilted to the incident beam at an angle of 45 degrees in a reflecting position. Higher-order scattering[3] from the sample is estimated to be 20% of the first-order scattering and gives rise to an extra broadening of the scattering pattern for lead. An analysis of this effect shows that there is a resulting broadening of about 5% due to multiple scattering. Since this is less than the experimental error, the widths at half maximum given in Table I under ΔE_1 are taken as the single-scattering distributions.

The purpose of the present experiment was to check the predictions of the simple diffusion model. Using the results of this theory and the measured values of the self-diffusion coefficient of liquid lead,[4] we obtain for the widths at half maximum of the energy distribution 0.023 ev and 0.046 ev at 336° and 550°C, respectively. In Table II these values, called ΔE_2, are compared as a function of temperature with the experimental widths of the scattered neutron distribution. It is seen that the diffusion model gives a distribution somewhat too broad near the melting point of lead and increases much too sharply with increasing temperature. For comparison, the widths at half maximum have been computed for the perfect gas model and are tabulated in Table II under ΔE_3. The agreement with experiment here is more satisfactory. This model predicts a somewhat smaller width at the melting point than does the diffusion model and agrees fairly well with the experimental result. The increase of width with temperature, while not so marked as for the diffusion model, is still greater than for the experimental result.

Vineyard has made additional computations[5] using a different combination of models for the liquid. These new results show that an important criterion for the scattering is the time spent by the scattered neutron in the neighborhood of the scattering center. If this time is long, one expects the diffusion model, as used in reference 1, to be appropriate; however, if the time is shorter, other models are required. From a consideration of the momentum transferred in a typical scattering in the present experiment, one sees that the scattering time is too short for the diffusion of lead atoms to be a dominant influence on the scattering process. The scattering time for this case is of such a length that the exact details of the scattering process are complex. Nevertheless, there is some reason to expect that the width at half maximum may be less at the melting point than is predicted for the perfect gas model and may also increase less rapidly with temperature. In addition, the width at half maximum for solid lead at 250°C can also be less than the value predicted for a perfect gas.

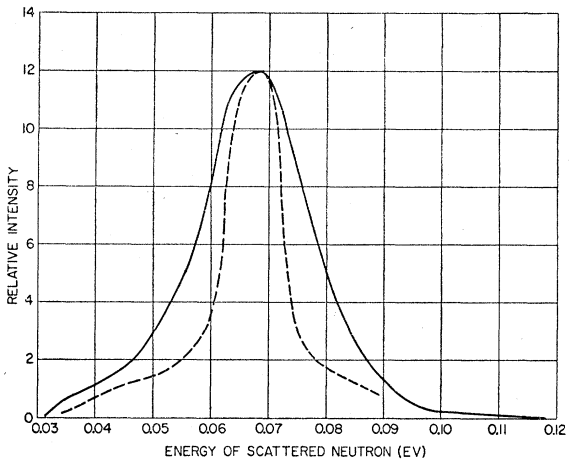

FIG. 2. Energy distribution of neutrons scattered at 90° by liquid lead at 336°C. Energy distribution of incident neutrons is shown as the dashed curve.

TABLE II. Comparison for liquid lead of corrected experimental widths at half-maximum, ΔE_1, with the widths for diffusion model, ΔE_2, and for perfect gas model, ΔE_3. Results for solid lead at 250°C are shown in parentheses for comparison.

Temperature (°C)	ΔE_1 (ev)	ΔE_2 (ev)	ΔE_3 (ev)
(250)	(0.0160)		(0.0182)
336	0.0186	0.023	0.0196
550	0.0198	0.046	0.0228

ACKNOWLEDGMENTS

The authors wish to acknowledge several helpful discussions with G. H. Vineyard of Brookhaven National Laboratory and with M. Nelkin of General Atomic. We also want to thank Dr. L. Slater for many hours of assistance in the accumulation and analysis of data.

[3] G. H. Vineyard, Phys. Rev. **96**, 93 (1954).
[4] L. D. Hall and S. Tothman, Am. Inst. Mining Met. Engrs. **206**, 199 (1956).
[5] G. H. Vineyard (private communication).