Experimental Determination of the Nonmagnetic Neutron-Electron Interaction*

E. MELKONIAN, B. M. RUSTAD, AND W. W. HAVENS, JR.
Columbia University, New York, New York, and Brookhaven National Laboratory, Upton, New York

(Received January 21, 1959)

A precise set of measurements of the variation of the transmission of liquid bismuth with energy in the range 0.1 ev to 10 ev has been made. After correction for neutron capture, Doppler effect and liquid diffraction, a value of $V_0=-4.34\pm0.14$ kev is obtained as the depth of the potential well having a radius equal to the classical electron radius. This gives -0.26 ± 0.14 kev as the strength of the intrinsic neutron-electron interaction after subtraction of the Foldy term.

INTRODUCTION

THE strength of the nonmagnetic neutron-electron interaction has been the subject of numerous experimental and theoretical investigations. The measurements to date have yielded an attractive interaction of the order of 4000 electron volts expressed as the effective potential acting over a sphere having a radius equal to the classical electron radius. Foldy[1] has pointed out that a spin and velocity independent interaction of 4080 electron volts is expected purely on the basis that the neutron possesses an anomalous magnetic moment. The difference between this value and the observed interaction strength is denoted by the term intrinsic neutron-electron interaction and is expected to arise if the neutron virtually dissociates part of the time into two oppositely charged particles, as is postulated by current meson theories concerning nuclear structure.[2] All measurements to date indicate that the intrinsic neutron-electron interaction is small or zero to within the experimental error of a few hundred electron volts. Calculations of the expected value of the intrinsic neutron-electron interaction based on current meson theoretical ideas of the structure of the neutron indicate a much larger value for this interaction. Thus the magnitude of the intrinsic neutron-electron interaction provides a stringent test for any meson theory, and the accurate experimental determination of this quantity is of prime importance.

The cross section for the nonmagnetic neutron-electron interaction is about 10^6 smaller than ordinary neutron-nucleon interactions and cannot be detected directly by current methods. The three methods which have been successfully used have taken advantage of the considerably larger interference term between the scattering of neutrons by the nucleus and by the electrons of the same atom. The first results were given by Havens, Rabi, and Rainwater,[3,4] who measured the energy dependence of the total cross section of liquid lead and liquid bismuth and interpreted their results in terms of the variation of the interference term as the neutron wavelength is changed. Fermi and Marshall[2] and later Hamermesh *et al.*[5] observed the angular dependence of the scattering of neutrons from krypton and xenon. The latest reported results were by Hughes *et al.*,[6] who measured the total reflection of neutrons from the interface between bismuth and liquid oxygen. An account of these measurements, as well as a detailed treatment of the theory involved, are given in an excellent review paper by Foldy.[7]

The measurements of Havens, Rabi, and Rainwater were made with the neutron velocity spectrometer system in conjunction with the Columbia 36-inch cyclotron where, because of low intensities, it was difficult to obtain sufficient statistical accuracy. By the use of the same method and the much higher neutron fluxes available with a neutron crystal spectrometer at a nuclear reactor, results with much higher statistical accuracy were expected. This paper presents the results of such a set of measurements on liquid bismuth. A preliminary account of this work has been reported previously.[8]

METHOD

For an isolated atom, the scattering amplitude is given by

$$a=a_N+Za_{ne}f,$$

where $a_N\equiv$nuclear scattering amplitude, $a_{ne}\equiv$nonmagnetic neutron-electron scattering amplitude, Z $=$atomic number, and $f\equiv$electronic form factor. Integration of a^2 over all directions gives the total scattering cross section in the center-of-mass system:

$$\sigma=\sigma_N+2Z(\sigma_N\sigma_{ne})^{\frac{1}{2}}\bar{f}+Z^2\sigma_{ne}\langle f^2\rangle_{\text{Av}}.$$

The last term gives a negligible contribution within the limits of error of these measurements and will henceforth be omitted. The method of measuring σ_{ne} consists, then, of measuring the cross section at several neutron energies and determining the coefficient of $\bar{f}$, which is assumed to be a known function of energy. Before the

* This work partially supported by the U. S. Atomic Energy Commission.

[1] L. L. Foldy, Phys. Rev. **87**, 693 (1952).
[2] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).
[3] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[4] Havens, Rabi, and Rainwater, Phys. Rev. **82**, 345 (1951).
[5] Hamermesh, Ringo, and Wattenberg, Phys. Rev. **85**, 483 (1952).
[6] Hughes, Harvey, Goldberg, and Stafne, Phys. Rev. **90**, 497 (1953).
[7] L. L. Foldy, Revs. Modern Phys. **30**, 471 (1958).
[8] Melkonian, Rustad, and Havens, Bull. Am. Phys. Soc. Ser. II, **1**, 62 (1956).

latter can be done, however, corrections must be made for neutron capture by the nucleus, the effect of thermal motion, and the effect of liquid diffraction. Each of these effects will be discussed subsequently.

Since the interference term is only a small percentage of the main nuclear term, cross section measurements to better than 0.1% must be made in order to obtain significant results. The choice of material for investigation must also be made carefully since most materials exhibit large variations of cross section with energy from other effects, and these mask the effect to be measured. Liquid bismuth was chosen for these measurements because (a) it has a small and adequately well-known capture cross section, (b) it does not have the crystal diffraction effects exhibited by most solids, (c) it has negligible spin incoherence, (d) it has a high atomic number, giving a relatively large effect, (e) its large atomic weight reduces the amount of Doppler correction and hence minimizes possible uncertainties arising from this correction, (f) it is monoisotopic, and (g) it is readily available. The only other available material which appears suitable for this type of investigation is gaseous argon at high pressure. Although argon is superior to liquid bismuth in many respects, it has not been used because the desired effect is smaller and its appreciable capture cross section is not sufficiently well-known. However, recent work[9] on the Columbia University crystal spectrometer at the Brookhaven National Laboratory reactor, extending its range to 11 A, may make it possible to determine the capture cross section with adequate accuracy.

EXPERIMENTAL EQUIPMENT

The Spectrometer

The Columbia University neutron crystal spectrometer in conjunction with the BNL reactor was used as a source of monochromatic neutrons for these measurements. This spectrometer is similar to other single crystal spectrometers which are used for high precision neutron spectroscopy.[10] A sodium chloride crystal (200 planes) was used as a neutron monochromator. A proportional counter filled with $B^{10}F_3$ was used for neutron detection. The main requirement of this determination is accurate measurement of transmission. Therefore, the various factors concerned were extensively studied:

(a) The knowledge of the neutron energy and the lack of perfect resolution contributed a negligible amount to the uncertainty of the final results of this experiment since the observed transmission of liquid bismuth varied very slowly with neutron energy.

(b) The contamination of the diffracted neutron beam with higher order neutrons was determined by

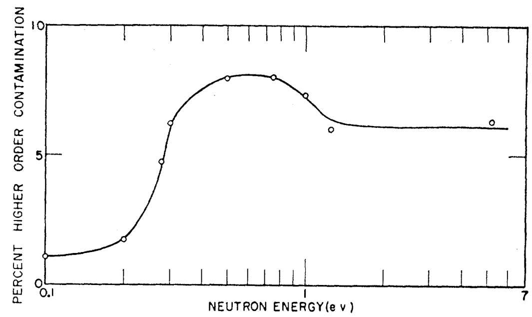

FIG. 1. Higher order contamination in reflection from the pile neutron beam incident on the 200 plane NaCl crystal monochromator of the neutron crystal spectrometer.

measuring the transmission of various thicknesses of cadmium in the region below 1 ev. A few measurements were made at energies above 1 ev by observing the counting rate at resonance through thick samples of indium, gold, and silver. These results, which were used for correcting the data for higher order contamination, are shown in Fig. 1. It is apparent that uncertainties in the amount of contamination are unimportant because of the slow variation of the transmission with energy.

(c) It was observed for this system, as for an earlier one,[11] that the counting rate produced by the BF^3 detection system was not strictly proportional to the intensity of neutrons reaching the BF^3 counter. The counting rate loss was determined from measurements of the transmission of a standard piece of solid bismuth taken at the full intensity of the spectrometer and at an intensity reduced to about one-third by a bismuth filter placed in the neutron beam. Repeated measurements over the course of three years indicated that the counting rate loss corresponded to a dead time, calculated in the usual way, of 3.0 ± 0.3 microseconds and did not change appreciably. At the maximum intensity of the spectrometer, this correction can amount to 3% for a transmission of about one-quarter. Although the counting losses were approximately proportional to the neutron intensity, as for true dead time, possible variations from this behavior were not determined with high precision. Instead, the neutron intensity was always reduced by suitable filters to a value such that the dead time correction was less than 0.2% and, therefore, the uncertainty in this correction negligible.

(d) Corrections for background were determined at frequent intervals during each transmission measurement by rotating the crystal one or two degrees off the diffraction peak and subtracting these results from measurements made with the crystal on peak.

The Liquid Bismuth Cell

A diagram of the sample holder used to contain the liquid bismuth for these measurements is shown in

[9] Gould, Taylor, and Havens, Phys. Rev. **100**, 1248A (1955).

[10] See, for example, Sailor, Foote, Landon, and Wood, Rev. Sci. Instr. **27**, 26 (1956).

[11] E. Melkonian, Phys. Rev. **76**, 1744 (1949).

Fig. 2. The neutron beam passes through the compartment in contact with a platinum resistance thermometer. A mixture of He with 2% H_2 is used to move the liquid bismuth out of this compartment for a "sample out" measurement or into this compartment for a "sample in" measurement. Earlier measurements, which used He without the H_2, resulted in oxidation of the liquid bismuth from the small contamination of O_2 in the He. Those portions of the cell which come into contact with liquid bismuth were fabricated of low carbon steel, which is one of the best structural materials for containing molten bismuth from the point of view of corrosion resistance. The vacuum jacket and radiation shields help to maintain the sample at a uniform temperature by reducing heat losses to a minimum. A temperature regulating device, which uses a platinum resistance thermometer as a sensing element, maintains the cell at a temperature within $\frac{1}{2}$°C of the required temperature, a range which produces negligible change in transmission. The bismuth sample was supplied by American Smelting and Refining Company and was claimed to be of purity better than 99.99%. It received special handling throughout to avoid contamination with material having high capture cross sections.

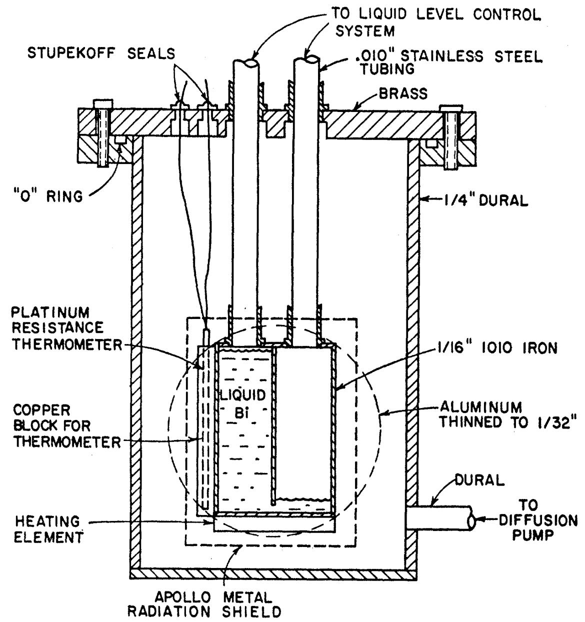

FIG. 2. Diagram of liquid bismuth cell. Stupekoff seals in the brass plate are used for the electrical connections.

RESULTS

Ten separate determinations on two samples of liquid bismuth were made over the course of about two years. Each determination consisted of a series of transmission measurements at three or four widely spaced values of the neutron energy. To eliminate possible variations of the sample in the time taken for one series of runs, all of the data at a particular energy were not taken at once but rather broken up into five to ten determinations interspersed with measurements at the other energies. Each transmission measurement consisted of many cycles following the pattern, open—sample—sample—open, in order to minimize reactor drifts. Background data in the same pattern were taken periodically. Data were computed on the 409.2 *R* Remington-Rand computer at Brookhaven National Laboratory. After a preliminary calculation using all of the data from one run at a particular energy, those cycles were rejected whose deviations from the mean exceeded 2.5 times the standard deviation. The number of cycles rejected in this manner, without determining the cause of the high deviation, was about the number expected from statistical considerations. The remaining cycles were used to compute the final average transmission for that particular run. The distributions of cycle by cycle transmissions of each set of data were found to be acceptable on the basis of Pearson's chi-squared test. The standard spectrometer corrections for dead time and order contamination were then made and cross sections computed on the basis of g/cm^2 of sample obtained from the density of liquid Bi and the cell dimensions. The results, after corrections to be described, are listed in Table I. There is some decrease of calculated cross section with time. This is attributed to an effective decrease of the sample thickness resulting from a buildup of deposits on the walls of the chamber. This uncertainty in sample thickness makes calculation of absolute cross sections unreliable. However, the measurement of the magnitude of the neutron-electron interaction depends primarily upon the variation of the cross section with energy, and the procedure of taking data described above eliminates the effect of a long term change of sample thickness. The results were ultimately normalized to a free bismuth atom cross section of 9.29 barns.[12]

CORRECTIONS

There are three major corrections to be made on the cross section data in order to interpret them in terms of neutron-electron interaction. These corrections are (a) neutron capture, (b) Doppler effect, and (c) liquid diffraction. Correction implies subtraction of these effects from the observed cross section values to give the results which would have been obtained had these effects not been present.

Neutron Capture

A correction for radiative neutron capture was made on the basis of 32 millibarns[12] at kT and a $1/v$ behavior, i.e., $\sigma_c = 0.0178\ \lambda$ barns, where λ is the neutron wave-

[12] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325, (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), second edition.

TABLE I. The cross section data for liquid bismuth corrected for neutron capture, Doppler effect and liquid diffraction, and the derived values of the neutron-electron interaction for each run.

Sample No.	Temp. °C	$E=0.1$ ev	$E=0.28$ ev	$E=1.0$ ev	$E=4.0$ ev	$E=10.0$ ev	σ_0 (barns)	$-b$ (barns)	V (kev)	V_0 (kev)[a]
#1	300°	9.1542±0.0043		9.2302±0.0116		9.2853±0.0164	9.2904±0.0133	0.2861±0.0303	4.41±0.47	4.41±0.47
#1	500°	9.1420±0.0050	9.2304±0.0116	9.2285±0.0082			9.2973±0.0133	0.3182±0.0325	4.91±0.50	4.91±0.50
#1	500°	9.1705±0.0038	9.2134±0.0033	9.2457±0.0041			9.2967±0.0068	0.2604±0.0192	4.02±0.30	4.02±0.30
#1	500°	9.1627±0.0046	9.2046±0.0067	9.2406±0.0062			9.2915±0.0100	0.2687±0.0263	4.15±0.41	4.15±0.41
#1	500°	9.1601±0.0038	9.1934±0.0041	9.2348±0.0039			9.2798±0.0067	0.2568±0.0187	3.96±0.29	3.96±0.29
#2	300°	9.1197±0.0029	9.1659±0.0034	9.2099±0.0031	9.2430±0.0050		9.2643±0.0040	0.3147±0.0119	4.86±0.18	4.87±0.18
#2	300°	9.0806±0.0042	9.1260±0.0034	9.1674±0.0034	9.1852±0.0094		9.2202±0.0055	0.2893±0.0169	4.46±0.26	4.49±0.26
#2	300°	9.0758±0.0042	9.1263±0.0031	9.1553±0.0031	9.1886±0.0094		9.2085±0.0051	0.2667±0.0162	4.12±0.25	4.16±0.25
#2	300°	9.0837±0.0034	9.1274±0.0036	9.1611±0.0031	9.2081±0.0109		9.2148±0.0050	0.2735±0.0148	4.22±0.23	4.25±0.23
#2	300°	9.0512±0.0038	9.0938±0.0034	9.1283±0.0047	9.1405±0.0076		9.1724±0.0060	0.2479±0.0170	3.83±0.26	3.88±0.26

[a] Normalized to $\sigma_0=9.29$.

length in A. A sample of the same bismuth used for these measurements was investigated by Langsdorf on a pile oscillator[13] and found to have the capture cross section for bismuth listed to within the accuracy stated, which has a standard deviation of 6%.

After these measurements were completed, the capture cross section of the sample used was measured by another method, since no pile oscillators were in operation, to see whether it was still the same, that is, to see whether material having high neutron capture had been dissolved by the liquid bismuth, since this could produce an appreciable error in the deduced value of the neutron-electron interaction. In order to perform this measurement, the liquid bismuth samples used were allowed to solidify and were then machined into the form of a good transmission sample. Measurements were made in the neighborhood of 10 A, which is much larger than the wavelength of the Bragg break. At this energy the large coherent cross section has vanished, and only a residual incoherent temperature dependent cross section and the capture cross section remain. Similar measurements were made on a portion of the original bismuth sample which had been set aside and had not gone through the melting process for this experiment. The results of these measurements are listed in Table II. Data read from the "$T=300°$K" curve in BNL 325[12] are included for comparison. It is evident that there has been no significant change in the capture characteristics of the liquid bismuth sample used during the course of the measurements.

Doppler Effect

In the region of high atomic mass and not too low neutron energy, the Doppler effect on an otherwise constant cross section is fairly small and is given by[14]

$$\frac{\delta\sigma}{\sigma_0}=1+\frac{kT}{2\mu E_0},$$

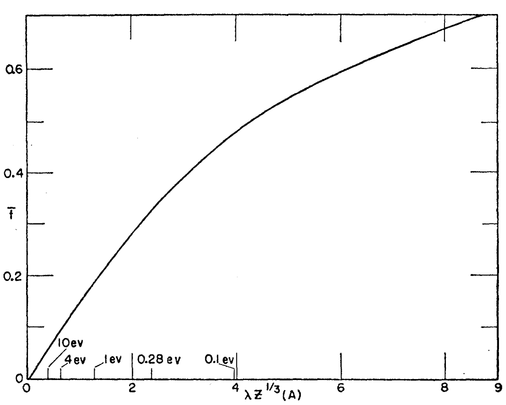

FIG. 3. Electronic form factor as a function of $\lambda Z^{1/3}$. Values of $\lambda Z^{1/3}$ corresponding to this experiment are indicated.

[13] A. S. Langsdorf (private communication).
[14] G. Placzek, Phys. Rev. 86, 377 (1952).

TABLE II. The data for the determination of the capture cross section of the bismuth sample before and after the measurements compared with the standard sample which was not used in the measurements and the standard values from BNL 325.

	λ (A)	E (10^{-3} ev)	σ_{stand} (barns)	$\sigma_{\text{sample 1}}$ (barns)	$\Delta\sigma_1=\sigma_{\text{stand}}-\sigma_{\text{sample 1}}$ (barns)	$\Delta\sigma_1/\lambda$ (barns/A)	$\sigma_{\text{sample 2}}$ (barns)	$\Delta\sigma_2=\sigma_{\text{stand}}-\sigma_{\text{sample 2}}$ (barns)	$\Delta\sigma_2/\lambda$ (barns/A)	σ BNL 325 (barns)
	8.75	1.08	0.657 ± 0.025	0.640 ± 0.024	-0.017 ± 0.035	-0.0019 ± 0.0040				0.65
	10.0	0.82	0.557 ± 0.025	0.588 ± 0.022	$+0.031\pm0.033$	$+0.0031\pm0.0033$	0.555 ± 0.020	0.002 ± 0.032	0.0002 ± 0.0032	0.57
	11.5	0.62	0.610 ± 0.025	0.574 ± 0.024	-0.036 ± 0.035	-0.0031 ± 0.0030				0.56
Average						-0.0007 ± 0.0019			0.0002 ± 0.0032	

so that for $\sigma_0=9.29$ b,

$$\delta\sigma=0.0134\,\lambda^2 \quad \text{at} \quad 300°\text{C}$$
$$=0.0181\,\lambda^2 \quad \text{at} \quad 500°\text{C}.$$

Liquid Diffraction

Even though liquid bismuth does not exhibit the diffraction effects shown by crystalline materials, there is a small variation of cross section with energy caused by the diffraction of neutrons arising from the fact that each bismuth atom is surrounded by other bismuth atoms at approximately the same distance so that some regularity exists in the liquid. This effect has been examined in great detail by Placzek *et al.*,[15] who give the following formulas for the relative change in cross section arising from the effect of liquid diffraction:

$$\delta\sigma/\sigma_0=-(\lambda_0^2\rho^{\frac{2}{3}}/8\pi)I,$$

where λ_0= neutron wavelength (cm), ρ= number of particles/unit volume, $I<3$, ~3 for close packing of particles. The quantity I depends on the liquid structure of the sample. The calculations for many reasonable forms of distribution of atoms indicate that I must be about 2.85. For mercury, Placzek *et al.*[15] analyzed the data of Hendus and found $I=2.82$. It was expected that I would be slightly smaller for bismuth than for mercury; therefore, for bismuth I was taken as 2.80. Using $I=2.80$, the liquid diffraction term becomes

$$\delta\sigma=-0.0976\,\lambda^2 \quad \text{at} \quad 300°\text{C}$$
$$-0.0959\,\lambda^2 \quad \text{at} \quad 500°\text{C}.$$

The question of the effect of interference between the nucleus of one atom and the electrons of another has been raised by Weiss.[16] It was studied in detail by Placzek[17] and was shown to have an insignificant effect on this experiment.

Table III gives the details of these corrections for one case to illustrate their magnitudes. Table I gives the value of the cross section of bismuth at the various energies after corrections for all effects mentioned above.

INTERPRETATION OF RESULTS

An inspection of Table I shows that there is a very definite decrease in the cross section of bismuth with increasing wavelength in each run. To interpret this variation in terms of the strength of neutron-electron interaction, the variation of the average electronic form factor with energy must be known. The average electronic form factor, $\bar{f}$, was computed on the basis of both the Fermi-Thomas model of the atom and the Hartree functions. In the 0.1-1 A region of neutron wavelengths, which is of interest here, both calculations give essentially the same results. Figure 3 shows the dependence of $\bar{f}$, computed from the Fermi-Thomas model, upon the wavelength. For each energy or wavelength at which neutron transmission measurements were made, a value of $\bar{f}$ was determined from an expanded version of Figure 3. The corrected cross section of the bismuth atom is then expected to be a linear function of $\bar{f}$. Figure 4 shows the plot of $\bar{\sigma}$ *vs* $\bar{f}$ for Sample 2. A straight line fits the observed points fairly well, lending confidence to the validity of the corrections made. However, calculations were carried out separately on each of the ten runs and averaged only at the end for the final result. Table I gives a list of the slope and intersections for the ten runs made. The slope b is related to the well depth by

$$b=2Z(\sigma_N\sigma_{ne})^{\frac{1}{2}},$$

TABLE III. Sample calculation for the data on liquid bismuth at 300°C showing the corrections for capture, Doppler effect and liquid diffraction on data.

λ (A)	E (ev)	$\bar{f}$	σ (barns)	$\delta\sigma$ (barns)	Correction: Capture	Correction: Doppler	Correction: Liquid diffraction	Sum of corrections	$\sigma_{\text{corrected}}$ (barns)
0.906	0.10	0.477	9.0307	±0.0034	-0.0161	-0.0110	$+0.0801$	$+0.0530$	9.0837
0.542	0.28	0.330	9.1122	±0.0036	-0.0096	-0.0039	$+0.0287$	$+0.0152$	9.1274
0.286	1.00	0.186	9.1593	±0.0031	-0.0051	-0.0011	$+0.0080$	$+0.0018$	9.1611
0.143	4.00	0.086	9.2089	±0.0109	-0.0025	-0.0003	$+0.0020$	-0.0008	9.2081

[15] Placzek, Nijboer, and Van Hove, Phys. Rev. **82**, 392 (1951).
[16] R. Weiss (private communication).
[17] G. Placzek (private communication).

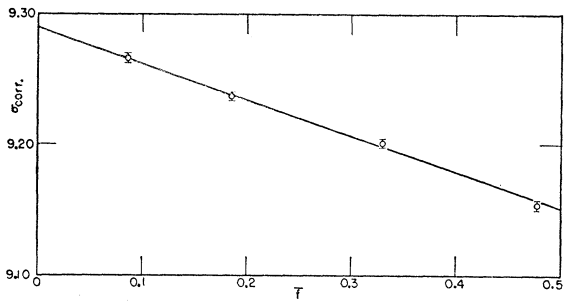

FIG. 4. σ_{corr} *vs* $\bar{f}$ for Sample 2 averaged over the five runs after individual normalization to $\sigma_0=9.29$.

where $\sigma_{ne}=4\pi[\frac{2}{3}(M/\hbar^2)a^3V]^2$ and M=neutron mass, V=depth of potential well, $a=e^2/mc^2=2.82\times10^{-13}$ cm=classical electron radius giving $b=6.48\times10^{-5}$ V, when b is in barns and V is the depth of potential well in ev.

The values of V as computed are listed in Table I. Since only approximate values of the sample thickness were used in calculating the cross sections, the intercepts do not give the true free atom bismuth cross section V_0 is obtained from V by multiplying by the ratio $9.29/\sigma_0$. These values are also included in Table I.

Table IV gives averages for several groups of measurements taken on the same sample and also gives the results for two different temperatures of liquid bismuth as well as the final average for all runs. The differences between the groupings are only slightly outside of the standard deviations and will be assumed to have no significance.

The average result from all ten runs is $V_0=-4.34\pm0.09$ kev, when the error is based on counting statistics only. The standard deviation based upon the spread of values about the mean is ±0.12. We will adopt this value as the error arising from the transmission measurements. The only additional significant source of error appears to be the uncertainty of I in the correction for the effect of liquid diffraction. The maximum possible value for I is 3.00, so we take ±0.20 as a reasonable estimate of the outside limit of uncertainty. Division by 2.5 gives ±0.08 as an estimate of the standard deviation on I, giving an uncertainty of ±0.08 on V. The uncertainties in the corrections for capture and the Doppler effect are small compared with the uncertainty in the liquid diffraction correction. The variation of a_n with energy due to the higher energy resonances has also been determined over the energy interval of interest and found to be negligible. Combining errors

TABLE IV. The results of the experiments on the different samples, at two different temperatures, and the average of all runs.

	$\bar{V}_0$ (kev)	$\Delta V=V_{\text{Foldy}}-\bar{V}_0$ (kev)
Sample 1 (300° and 500°)	4.16 ± 0.16	-0.26 ± 0.19
Sample 2 (300° and 500°)	4.42 ± 0.10	
300° (Sample 1 and Sample 2)	4.42 ± 0.10	-0.29 ± 0.20
500° (Sample 1 and Sample 2)	4.13 ± 0.17	
All 10 runs	4.34 ± 0.09[a]	-0.26 ± 0.14

[a] Standard deviation, based upon spread of values about the mean, is ±0.12.

then gives $V_0=-4.34\pm0.14$ kev as the final value. This value is consistent with results obtained from all the other measurements[7] but has a much smaller uncertainty. The difference between this and the Foldy term (-4.08) is -0.26 ± 0.14 kev as the intrinsic neutron-electron interaction. Although this is attractive, as expected, and larger than the uncertainty, it is still not accurate enough to indicate a definite nonzero intrinsic interaction. Averages of these results with those of Hughes *et al.*[6] (-3.86 ± 0.37 kev) and Hamermesh *et al.*[5] (-3.90 ± 0.81 kev) gives $V_0=-4.27\pm0.13$ kev and an intrinsic interaction of -0.19 ± 0.13 kev.

In view of the difficulty of obtaining significantly better statistical accuracy by this method, and the inherent uncertainty of the correction for liquid diffraction, it is probably not worthwhile at this time to perform any further measurements on liquid bismuth.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of T. H. Kruse in the design and construction of the liquid bismuth cell, E. S. Troubetzkoy in the calculation of the form factor, R. Graeser in the taking of the data, and A. S. Langsdorf in making the capture cross section measurements on the bismuth sample used.Thanks are also due to S. A. Clough, G. J. Safford, C. E. Engelke, J. Liebowitz, I. Schroeder, and S. M. Puri for assistance in the calculations. We wish to thank the Watson Scientific Computing Laboratories of Columbia University and the computer group at Brookhaven National Laboratory for the use of their electronic computing facilities.

We are greatly indebted to Dr. George Placzek for many invaluable discussions about the liquid interference effects. His work on liquid interference effects before his recent death contributed invaluably to the interpretation of this experiment.