Measurement of the Neutron-Electron Interaction by the Scattering of Neutrons by Lead and Bismuth

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The atomic scattering length of lead and the nuclear scattering lengths of lead and bismuth were measured with high accuracy. From the results we obtained b_c(Pb atom) $= 9.4003 \pm 0.0014$ fm, b_N(Pb nucleus) $= 9.5121 \pm 0.015$ fm, b_N(Bi nucleus) $= 8.6412 \pm 0.015$ fm, and from the previously reported b_c(Bi atom) we obtained two new values for the neutron-electron scattering length: $b_{n,e} = -(1.364 \pm 0.025) \times 10^{-3}$ fm from the Pb experiment, and $b_{n,e} = -(1.393 \pm 0.025) \times 10^{-3}$ fm from the Bi data.

The nonmagnetic neutron-electron interaction can be investigated by measuring the amplitude for the scattering of slow neutrons by electrons. The corresponding scattering length b_{ne} is related to the slope $dG_{En}(0)/dQ^2$ of the electric form factor of the neutron at zero four-momentum transfer ($Q^2 = 0$) by

$$\frac{dG_{En}(0)}{dQ^2} = \frac{dF_{1n}(0)}{dQ^2} - \frac{F_{2n}(0)}{4m^2} = -(14.41\text{ fm})b_{ne},$$

where F_{1n} and F_{2n} are the Dirac and Pauli form factors, respectively. The derivative of $F_{1n}(0)$ is a measure for the intrinsic charge distribution of the neutron. The constant $F_{2n}(0)/4m^2 = -0.02115\text{ fm}^2$ is called "Foldy term," which corresponds to the scattering length $b_F = -1.468 \times 10^{-3}$ fm.[1,2]

When one considers the average of all existing exact experiments as given in Table II, the magnitude of $\langle b_{ne} - b_F \rangle$ is a little different from zero, i.e., the charge distribution seems to be caused not only by the Foldy term alone. However one should notice that there are discrepancies between the results which are much larger than the errors. It is the purpose of this note to present a new value which indicates clearly a nonvanishing intrinsic charge distribution of the neutron.

The determinations of the (n, e) interaction are based on the scattering of neutrons by heavy atoms in a neutron energy region where the scattering from the nucleus is fully or partly coherent with the scattering from the electron shell. The scattering length consists of a combination of the coherent scattering by the nucleus (b_N) and by the Z electrons: $b(E) = b_N + Zf(E)b_{ne}$. $f(E)$ denotes the average x-ray atomic form factor depending on the neutron energy E.

In principle, b_{ne} can be obtained by measuring $b(E)$ at two different energies as $Zb_{ne} = (b_1 - b_2)/(f_1 - f_2)$. The most favorable case, where $f_1 = 1$ and $f_2 \simeq 0$, is realizable by measurements of the atomic coherent scattering length b_c and the nuclear scattering length $b(E)$ at a neutron energy E for which $f_2(E)$ becomes very small. $b(E)$ can be derived from total-cross-section values $\sigma_{tot}(E)$ measured at energies in the eV region. In doing so, corrections are necessary with respect to elastic incoherent scattering (σ_{inc}), energy dependence of nuclear scattering due to resonances and the effective-range contribution, Schwinger scattering, corrections due to solid-state effects, interference effects, and the Doppler correction. The theoretical aspects related to the interpretation of the cross-section measurements were treated by Binder.[3]

In our experiments on lead and bismuth we measured the total cross sections by means of transmission experiments. Monoenergetic neutrons were selected from the spectrum of a neutron beam by means of special, continuously operating resonance detectors,[4] composed of rotating rhodium foils (resonance energy $E_R = 1.257$ eV) or silver foils ($E_R = 5.19$ eV). Liquid samples of molten lead (99.9995%) and bismuth (99.999%) were used because solid samples may include gases and inhomogeneities in density and crystalline structure. This would result in an additional uncertainty as shown by measurements on polycrystalline and single-crystalline samples in the same setup.[5]

The coherent scattering length of lead was measured by mirror reflection of very slow neutrons from liquid lead (normal Pb, 99.99% pure) using the neutron gravity refractometer.[6-8] In this device neutrons emerging from the reactor are affected by gravity along their 100-m flight path. At the end they hit the Pb mirror (N atoms/cm^3) which is positioned at a vertical distance h below the culmination point of the neutron parabolic path. Neutrons are totally reflected if the height of free fall h is smaller than a critical height h_0 which is determined by the coherent scattering length according to $Nb_c = m^2 2gh_0/4\pi\hbar^2$, where g denotes the effective gravitational acceleration acting on the neutron (mass m). It has been demonstrated in our experiments[7,8] that free neutrons fall under the action of gravity just like normal matter. At the reflection process, on the other hand, the neutrons behave as matter waves according to the de Broglie equation, as recently verified once more by Overhauser, Colella, and Werner.[9] The reflection measurements on the liquid Pb mirror yielded a critical height $h_0 = 740.40 \pm 0.06$ mm and $Nb_c = (2.9049 \pm 0.0003) \times 10^9$ cm^{-2}.

In order to obtain an accurate value for the atomic density N we performed a new determination of the density of liquid lead. By means of pycnometer measurements in a vacuum oven we found the following temperature-density relation in the region between $t = 330°\text{C}$ and $t = 360°\text{C}$: $D(t) = 10.6595 - 0.001\,352(t - t_m) \pm 0.0010$ g/cm^3, where $t_m = 327.4°\text{C}$ is the melting temperature. This result agrees with the values previously reported by Nücker[10] and by Lucas.[11]

With the Nb_c value and the density, we calculated the coherent scattering length of the bound Pb atom to be $b_c(\text{Pb}) = 9.4003 \pm 0.0014$ fm. The coherent scattering length of bismuth was previously measured by Nücker[12] who also used the neutron gravity refractometer. Using more recent values of the physical constants[13] we corrected his result to read $b_c(\text{Bi}) = 8.5256 \pm 0.0014$ fm. The errors given are standard deviations.

The results obtained from our experiments on liquid samples are compiled in Table I in which the single steps in calculating the (n, e) scattering length are demonstrated. A possible uncertainty is due to the value of the incoherent cross section (line 6) for bismuth. We used the value measured by Scherm,[14] which is in agreement with a calculation based on the known resonance parameters. On the other hand, Glättli[15] reported on pseudomagnetic measurements of spin-incoherent scattering lengths (e.g., Roubeau *et al.*[16]) which led to $\sigma_{\text{inc}}(\text{Bi}) \leq 0.02$ mb. Taking account

TABLE I. Calculations of the (n,e) scattering lengths using the measured total cross sections and scattering amplitudes.

	element	Pb		Bi	
	neutron energy	1.26 eV	5.19 eV	1.26 eV	5.19 eV
	in barns:				
1	σ_{tot}	11.2357(45)	11.2554(44)	9.2566(42)	9.2830(40)
2	σ_{abs} (Ref.21)	- 0.0241(1)	- 0.0119(1)	- 0.0047(6)	-0.0023(3)
3	σ_{corr}^{calc}	+ 0.0040(2)	- 0.0033(2)	+ 0.0038(2)	+0.0014(2)
4	$\sigma_{sc,free}$	11.2156(46)	11.2402(45)	9.2557(43)	9.2821(41)
5	σ_b	11.3251(46)	11.3499(45)	9.3452(43)	9.3719(41)
6	σ_{inc} (Ref.14)	- 0.0013(5)	- 0.0013(5)	- 0.0071(6)	-0.0071(6)
7	$4\pi\, b^2(E)$	11.3237(47)	11.3486(46)	9.3381(44)	9.3648(42)
	in fm:				
8	$(b_N + f\, Zb_{ne})$	9.4927(20)	9.5031(20)	8.6203(20)	8.6326(20)
9	$(b_N + Zb_{ne})$	9.4003(14)	9.4003(14)	8.5256(15)	8.5256(15)
10	$(1-f)\, Zb_{ne}$	-0.0924(25)	-0.1028(25)	-0.0947(25)	-0.1070(25)
11	$(1-f)Z$	68.0(2)	75.12(10)	68.8(2)	76.0(1)
12	b_{ne}	$-1.36(4)\cdot 10^{-3}$	$-1.37(4)\cdot 10^{-3}$	$-1.38(4)\cdot 10^{-3}$	$-1.41(4)\cdot 10^{-3}$
13	$\sigma_{inc}=0{:}\,b_{ne}$	$-1.37(4)\cdot 10^{-3}$	$-1.38(4)\cdot 10^{-3}$	$-1.42(4)\cdot 10^{-3}$	$-1.45(4)\cdot 10^{-3}$
14	b_N	9.5117(21)	9.5125(21)	8.6399(21)	8.6425(21)
15	b_N (mean)	9.5121(15)		8.6412(15)	
16	$Z \cdot b_{ne}$	-0.1118(21)		-0.1156(21)	
17	b_{ne}	$-1.364(25)\cdot 10^{-3}$		$-1.393(25)\cdot 10^{-3}$	

of this uncertainty we present in line 13 of Table I also the b_{ne} values computed under the assumption $\sigma_{inc}=0$. They are larger by 1 standard deviation than the values based on $\sigma_{inc}=7.1$ mb.

The results of the liquid-liquid experiments on lead and bismuth, as shown in line 17, are in agreement. They yield a mean value

$$b_{ne}=(-1.378\pm0.018)\times10^{-3}\text{ fm}.$$

This result might be affected by systematic errors in the very different experimental methods used. Therefore we tested the procedure by a large series of experiments of the described kind on light and medium elements. In some cases we had to combine our results with corresponding values from previously reported measurements, in which other precise techniques were used.

The evaluation of this program led to the (n, e) scattering lengths given for some elements in the first six lines in Table II. All results are consistent within the limits of error with the mean value $b_{ne}=-1.4\times10^{-3}$ fm. Moreover the differences in the measured and calculated effect (Zb_{ne}) fluctuate around zero with a standard deviation of ±0.0016 fm, which can be completely explained by the experimental random errors of the six individual determinations. Consequently we may state that a systematic error must be smaller than the experimental error.

Our result for b_{ne} departs from the Foldy term b_F by 5 standard deviations. From the difference $b_{ne}-b_F=(+0.09\pm0.02)\times10^{-3}$ fm the value for the derivative of the Dirac form factor $dF_{1n}(0)/dQ^2=(-0.13\pm0.03)\times10^{-2}$ fm^2 is obtained. This quantity clearly demonstrates the existence of a small intrinsic charge contribution to the electrical structure of the neutron.

For the results b_{ne} of the previous experiments of Krohn and Ringo[17] and Melkonian, Rustad, and Havens,[18] we give corrected values in Table II, corrected from $(-1.30\pm0.03)\times10^{-3}$ fm to $(-1.33\pm0.03)\times10^{-3}$ fm[20] due to Schwinger scattering, and from $(-1.56\pm0.05)\times10^{-3}$ fm to $(-1.49\pm0.05)\times10^{-3}$ fm mainly due to Schwinger scattering and nuclear resonance scattering. Our result is compatible with the corrected value of Krohn and Ringo. Furthermore it is in excellent agreement with the weighted mean $b_{ne}=(-1.39\pm0.06)\times10^{-3}$ fm of the corrected data and even with the mean $b_{ne}=(-1.37\pm0.05)\times10^{-3}$ fm of the uncorrected values.

The same holds for the average $b_{ne}=(-1.40\pm0.05)\times10^{-3}$ fm obtained from all published experiments omitting the given errors.

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TABLE II. Results of (n,e) experiments. The letters in brackets indicate solid (s) or liquid (l) samples as targets for the transmission and b_c measurements.

No	element	Z	$-b_{ne}$ (10^{-3}fm)	weighted mean $b_{n,e}$ (10^{-3}fm)
1	C(s,l)	6	1.9 ± 1.0	
2	O(s,l)	8	1.7 ± 0.9	
3	Al(s,s)	13	1.2 ± 0.8	
4	Si(s,s)	14	1.1 ± 0.3	
5	S(l,l)	16	1.5 ± 0.3	
6	Nb(s,s)	41	2.1 ± 1.0	- 1.36 ± 0.20
7	Pb(l,l)	82	1.364 ± 0.025	
8	Bi(l,l)	83	1.393 ± 0.025	
present work:				- 1.378 ± 0.018
$dG_{En}(0)/dQ^2$ (fm^2)				0.0199 ± 0.0003
in the Fermi convention: V_0(eV)				- 3830 ± 50
Krohn and Ringo (Ref. 17)[a] (b_{ne})				- 1.33 ± 0.03
Melkonian, Rustad and Havens (Ref. 18)[b]				- 1.49 ± 0.05
Hughes, Harvey, Goldberg, Stafne (Ref.19)				- 1.39 ± 0.13
average:				- 1.40 ± 0.05
Foldy (Ref. 1)				- 1.468

[a]Corrected for Schwinger scattering.

[b]Corrected for Schwinger scattering and a resonance contribution.

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Internal Pair Formation Following Coulomb Excitation of Heavy Nuclei*

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Internal conversion of γ rays from Coulomb-excited nuclear levels cannot be neglected compared with the spontaneous and induced positron production in overcritical electric fields. It is shown that both processes are separable by their different distributions with respect to the ion angle and the positron energy.

In overcritical electric fields spontaneous positron production may occur as a result of an unoccupied electronic $1s_{1/2}$ level entering the negative-energy continuum,[1-4] which is equivalent to the decay of the neutral vacuum into a charged one. It has been proposed[4] that the positron emission can be experimentally observed in collisions of very heavy ions with $Z_1+Z_2>Z_{cr}\sim 170$. Because of the nonadiabaticity of the collision process e^+e^- pairs are additionally created by transitions from the negative-energy continuum to the K shell; this "induced decay" increases the cross section by two orders of magnitude.[3]

However, there are several background effects leading to pair formation in heavy-ion scattering that have to be investigated carefully. Among these are conversion of timelike nuclear bremsstrahlung photons, direct pair production by the alternating Coulomb field, and internal conversion of γ rays from nuclear transitions. It was shown by Reinhardt, Soff, and Greiner[5] that the first process can be neglected ($\sigma_{\text{brems}}^{e^+e^-}\sim 10^{-8}$ b) while the second one is expected to be important only for relativistic ion velocities, since there is an exchange of two spacelike photons involved. The dominant background results from the decay of Coulomb-excited nuclear levels. Although the mean lifetime of nuclear quadrupole transitions with $\Delta E>2m_ec^2\sim 1$ MeV ($\tau_{\text{dec}}\sim 10^{-13}$ sec) is much larger than the collision time ($\tau_{\text{coll}}\sim 10^{-20}$ sec) in which the spontaneous and induced positrons are emitted, an experimental separation of both processes seems not to be feasible. If the scattered nucleus and the positrons are measured in coincidence, the differential pair-creation cross section is given by the product of the scattering cross section and the positron emission probability of both nuclei:

$$\frac{d^2\sigma_{\text{Cb}}^{e^+e^-}}{dE_p\,d\Omega_{\text{ion}}}=\frac{d\sigma_{\text{scat}}}{d\Omega_{\text{ion}}}(\vartheta_{\text{ion}})\sum_{1,2}\frac{dW_{\text{Cb}}^{e^+e^-}}{dE_p}(E_p,\vartheta_{\text{ion}}). \tag{1}$$

The probability dW/dE_p is a function of the positron kinetic energy E_p and the scattering angle ϑ_{ion}. It depends on the Coulomb excitation probability P^{Cb} of the initial nuclear level, the branching ratio P^γ for a photon transition into the final state, and the corresponding differential pair-formation coefficient $d\beta/dE_p$:

$$\frac{dW_{\text{Cb}}^{e^+e^-}}{dE_p}(E_p,\vartheta_{\text{ion}})=\sum_{i,f}P_i^{\text{Cb}}(\vartheta_{\text{ion}})P_{if}^{\gamma}\frac{d\beta_{if}}{dE_p}(E_p). \tag{2}$$