Measurement of the Electric Polarizability of the Neutron

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The electric polarizability of the neutron was determined to be $\alpha_n = (1.20 \pm 0.15 \pm 0.20) \times 10^{-3}$ fm^3 from its characteristic influence on the energy dependence of the neutron-^{208}Pb scattering cross section, as measured in a neutron time-of-flight transmission experiment at the Oak Ridge Electron Linear Accelerator pulsed neutron source.

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As established by electron-nuclear-scattering experiments at high energy, hadrons and especially the nucleons (neutrons and protons) are not pointlike objects. Characteristic of their charge structure are the electric (α) and magnetic (β) polarizabilities.[1] They are defined such that a particle placed in an external electric (magnetic) field $\mathbf{E}$ ($\mathbf{B}$) acquires an induced electric (magnetic) dipole moment $\mathbf{d} = \alpha \mathbf{E}$ ($\mathbf{d} = \beta \mathbf{B}$) giving an interaction potential $V = -\frac{1}{2}\mathbf{d}\cdot\mathbf{E} = -\frac{1}{2}\alpha E^2$ ($V = -\frac{1}{2}\mathbf{d}\cdot\mathbf{B} = -\frac{1}{2}\beta B^2$). Since the net neutron charge is zero, it is a good candidate for determining nucleonic electric polarizability.[2,3]

Electric and magnetic polarizabilities of elementary particles have been calculated recently in the framework of various models. The simple valence quark model provides a qualitative description, and values of $\alpha \sim 10^{-3}$ fm^3 were obtained.[4] Bag models, of various sizes, lead to similar results.[5] Using a chiral bag model with a valence quark core surrounded by a pion cloud, Weiner and Weise[6] found that the quark core contributes only 20% to the total polarizability, most of which comes from the distortion of the surrounding pion cloud in an external electric field. Their calculations give $\alpha \sim (0.7\text{–}0.9) \times 10^{-3}$ fm^3 and $\beta < 0.2 \times 10^{-3}$ fm^3 for the nucleon. Another calculation in a chiral soliton model leads to $\alpha = 1.34 \times 10^{-3}$ fm^3 and for $\beta = -0.11 \times 10^{-3}$ fm^3.[7] In recent work, attempts were made to calculate the electric polarizabilities of hadrons in a quenched lattice QCD model.[8] In the light-quark limit, a value of $\alpha \sim 1 \times 10^{-3}$ fm^3 was obtained.

Because of the smallness of the electric polarizability of the neutron α_n, a measurement using macroscopic laboratory fields seems far beyond the possibilities of present technology. However, in nature electric fields up to 10^{23} V/m are found near the surface of heavy nuclei like lead. The interaction potential due to the electric polarizability of the neutron near the nuclear surface is given by $V = -\frac{1}{2}\alpha_n Z^2 e^2/r^4$. The corresponding scattering amplitude was first calculated by Alexandrov and independently by Thaler, and also by Breit and Rustgi.[9] In a more detailed calculation,[10,11] the neutron-atom scattering cross section up to a few hundred keV neutron energy was calculated, including all interference terms between different interactions. The neutron-nucleus potential and resonant scattering were considered in the framework of R-matrix theory.[12] Schwinger scattering (spin-orbit scattering), the neutron-electron interaction, and the electric polarizability for the electric interactions of the neutron were calculated in the Born approximation assuming a homogeneously charged sphere with radius R_N and total charge Z for the nucleus. For the atom, electron form factors from Ref. 13 and from relativistic Hartree-Fock calculations[14] were used. Scattering due to the electric polarizability of the neutron is dominated by the nuclear Coulomb field. The atomic contributions are smaller by the ratio $R_N/R_e \approx 10^{-5}$ and can be neglected (R_e being the charge radius of the atom). For the complete scattering amplitude f_{pol} (which is nearly proportional to $Z^{5/3}$) we find, for $qR_N \ll 1$,

$$f_{\mathrm{pol}}(q) = \alpha_n Z^2 \frac{e^2 m}{\hbar^2} \frac{1}{R_N} \left[\tfrac{6}{5} - \tfrac{1}{4}\pi q R_N + \tfrac{1}{7}(qR_N)^2 - \tfrac{1}{540}(qR_N)^4 + \cdots \right], \quad (1)$$

where the second term (proportional to qR_N) is characteristic of the long-range $1/r^4$ interaction potential of an induced electric dipole moment in the Coulomb field of a spherical charge. This term, linear in the momentum transfer $\hbar q$, gives the best possibility to separate $f_{\mathrm{pol}}(q)$ from the nuclear scattering amplitude which is about 2 orders of magnitude larger. The total neutron-nucleus potential scattering cross section σ_s, below 100 keV ($k < 0.1$ fm^{-1}), can then be parametrized by

$$\sigma_s(k) = \sigma_s(0) + ak + bk^2 + O(k^4), \quad (2)$$

where $k = 2.1968 \times 10^{-4}\sqrt{E}A/(A+1)$ (k in fm^{-1} and E in eV) is the wave vector of the incoming neutron. The parameter a depends only on the electric polarizability of the neutron. b and higher-order parameters in the expansion (2) come mainly from the effective range of the neutron-nucleus interaction. In the region $E < 50$ keV, the characteristic term proportional to the momentum $\hbar k$ of the incoming neutron in Eq. (2) can be separated from effective-range effects ($\propto k^2$) in neutron-nucleus scattering. In an experiment on a heavy nucleus like ^{208}Pb, an accuracy of 1 part in 1000 for the cross section is required for 100 energies over the energy range 50 eV–40 keV to achieve a statistical uncertainty of 0.2×10^{-3} fm^3 in α_n.

In this Letter we present results of a vastly improved experiment to determine the electric polarizability of the neutron, explicitly using the characteristic q dependence of the scattering amplitude described above. Since only the energy dependence of the scattering cross section is important, normalization problems are avoided by measuring $\sigma_s(E)$ over the whole energy range in one neutron time-of-flight transmission experiment. The total cross section $\sigma_t = \sigma_s + \sigma_a$ is computed from the measured transmission $T = \exp(-n\sigma_t)$, where n is the sample thickness.

^{208}Pb was chosen for our experiment because it provides by far the best properties for a heavy isotope to separate the potential scattering and the term proportional to k in Eq. (2) from the resonant scattering contribution. Furthermore, it has a negligible thermal-absorption cross section $\sigma_a = (0.49 \pm 0.02)\times10^{-3}$ b.[15] In ^{208}Pb there are only p-wave [which give corrections $O(k^2)$ in Eq. (2)] and d-wave [which give corrections $O(k^4)$ in Eq. (2)] resonances below 500 keV.[16] The resulting energy-dependent resonance corrections are smaller by more than an order of magnitude compared to the previous experiment, using lead in its natural isotopic composition.[2]

Six transmission experiments were carried out using solid lead samples of various isotopic compositions and thicknesses. Three were made with 325 g of separated-isotope ^{208}Pb, coming from two different separations with enrichments of 99.14% and 99.75%, respectively. Three other measurements were carried out with 2700 g of radiogenic ^{208}Pb (25.97% ^{206}Pb, 1.63% ^{207}Pb, 72.40% ^{208}Pb). In these experiments a thin natural-Pb (1.34% ^{204}Pb, 24.15% ^{206}Pb, 22.08% ^{207}Pb, 52.43% ^{208}Pb) sample was added to the radiogenic ^{208}Pb and a sample of radiogenic ^{206}Pb (88.46% ^{206}Pb, 8.56% ^{207}Pb, 2.98% ^{208}Pb) was used in the open beam to compensate for ^{206}Pb and ^{207}Pb in the combined sample, as described in Ref. 16. The measured transmission was that of an effectively pure ^{208}Pb sample (see Table I).

Data were taken at the Oak Ridge Electron Linear Accelerator (ORELA) neutron source[17] for six weeks on the separated-isotope samples (25-mm sample, 20-mm beam diameter) and four weeks on the compensated samples (60-mm sample, 45-mm beam diameter) located 10 m from the neutron source. A schematic of the experimental setup is shown in the inset in Fig. 2. Two neutron detector systems were used, a ^{10}B-loaded liquid scintillator (BC-523A, 120 mm diameter and 20 mm thick) mounted on a Hamamatsu R1250 phototube at 81 m, and a ^{6}Li glass scintillator (NE-912, 110 mm diameter and 12 mm thick) viewed sideways by two RCA 8854 phototubes at 79 m. ORELA operated at 400 or 325 Hz and 20-ns pulse width, delivering an average of 20 kW of beam power to the target. Samples with transmissions ranging from 50% down to 2% were measured. A ^{10}B filter significantly reduced the neutron flux below 10 eV and only a very small overlap was observed and corrected for. Additional high-resolution data (four weeks, 3-ns pulse width, 800-Hz repetition rate) were taken in the neutron energy range above 60 keV for the separated-isotope ^{208}Pb sample using an NE110 plastic scintillator at the 200-m flight station. The transmission data were collected using a fast 10-ns dead-time multiparameter time-of-flight system, based on fast emitter-coupled logic and a 100-MHz flash analog-to-digital converter for the analog signal measurement.[18] Detector variations, bias shifts, and other irregularities were easily recognized and corrected for in the two-parameter pulse-height versus time-of-flight histograms.

The background was evaluated using neutron resonance filters, a polythene absorber, and the known detector pulse-height distributions. Typical signal-to-background ratios were 500:1 or better for the ^{10}B-loaded liquid scintillator in the whole energy range above 100 eV, for the ^{6}Li glass scintillator in the energy range from 50 eV to a few keV, and for the NE110 scintillator above 60 keV. All background data are well described by a simple model, including γ-ray transmission coefficients

TABLE I. Samples used in the measurements, and their final results for α_n. Samples 1–3 are highly enriched separated-isotope ^{208}Pb samples, 4–6 are the compensated samples (Ref. 16), where only the effective isotopic compositions are given. Negative abundances indicate overcompensation.

Sample number	Isotopic compositions (%) ^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	Thickness (atoms/b)	α_n (10^{-3} fm^3) ^{10}B liquid	^{6}Li glass
1	<0.05	0.20	0.05	99.75	0.0664	1.43(0.30)	1.18(0.45)
2	<0.05	0.17	0.69	99.14	0.1196	0.88(0.35)	1.05(0.85)
3=1+2	<0.05	0.18	0.46	99.36	0.1860	0.45(0.60)	1.81(1.15)
4	0.09	−0.07	−0.02	100.00	0.0621	1.00(0.30)	1.55(0.50)
5	0.09	−0.11	−0.01	100.03	0.1241	1.38(0.40)	1.57(0.65)
6=4+5	0.09	−0.10	−0.01	100.02	0.1862	1.88(0.65)	0.52(0.95)

for different filters and samples.[19] After dead-time and background corrections ($<0.2\%$), the transmissions were calculated and an energy-dependent correction ($<0.12\%$) for the air removed by the samples not measured in vacuum, evaluated from the data of the ENDF/B-VI (Ref. 20) evaluation, was applied.

The whole set of data up to 600 keV was then analyzed with REFIT (Ref. 21) and new highly accurate resonance parameters for Γ_n were extracted, which will be published elsewhere. The resonance corrections for each time-of-flight channel (Fig. 1), including all resolution effects, were calculated by subtracting the theoretical transmissions with and without resonances. After correcting each transmission point for resonance scattering the cross sections were calculated and corrected for Schwinger and neutron-electron scattering. The evaluation of Eq. (2) for the whole set of data in the energy range from 50 eV to 40 keV ($1.5\times10^{-3}<k<45\times10^{-3}$ fm^{-1}) yields for the total scattering cross section of ^{208}Pb (see also Fig. 2)

$$\sigma_s(k)=11.508(5)+0.69(9)k-448(3)k^2+9500(400)k^4, \tag{3}$$

where the uncertainties are due to statistics only. From the term proportional to k the electric polarizability, including systematic uncertainties, is evaluated to be

$$\alpha_n=(1.20\pm0.15\pm0.20)\times10^{-3}\,\mathrm{fm}^3. \tag{4}$$

Systematic uncertainties come mainly from the background correction ($<0.2\times10^{-3}$ fm^3). Uncertainties from multiple scattering and the forward-peaked Schwinger scattering (calculated using the neutron brightness distribution of the ORELA target[22]), from the resonance correction, and from the neutron-electron scattering were found to be smaller than 0.05×10^{-3} fm^3. Overall, we estimate systematic uncertainties to be $0.2\times10^{-3}\,\mathrm{fm}^3$ or less.

Our experiment gives for the first time a definite nonzero value for the electric polarizability of the neutron and is significantly more accurate than the previous values of $\alpha_n=(1.2\pm1.0)\times10^{-3}$ fm^3 (Ref. 2) and of $\alpha_n=(0.8\pm1.0)\times10^{-3}$ fm^3.[23] This result can be related to the dynamic (also called Compton) polarizabilities $\bar\alpha=\alpha+\Delta\alpha$ and $\bar\beta=\beta+\Delta\beta$, accessible in Compton scattering and by the two-times-subtracted Kramers-Kronig dispersion relation giving $\bar\alpha+\bar\beta$ in photoabsorption experiments.[1,24] The differences

$$\begin{aligned}\Delta\alpha&=\frac{e^2}{3m}\langle r_E^2\rangle+\frac{e^2}{4m^3}(1+\kappa^2)\,,\\ \Delta\beta&=-\frac{e^2}{3m}\langle r_E^2\rangle-\frac{e^2}{2m^3}(1+\kappa+\kappa^2)\end{aligned} \tag{5}$$

are due to retardation effects and corrections for the anomalous magnetic moment κ [m is the mass and $\langle r_E^2\rangle=-0.113\,\mathrm{fm}^2$ (Ref. 25) is the mean-square charge radius of the neutron].[26] Given the sum-rule-result estimate $\bar\alpha_n+\bar\beta_n=(1.58\pm0.05)\times10^{-3}$ fm^3 (Ref. 1) and $\Delta\alpha=0.03\times10^{-3}$ fm^3 and $\Delta\beta=-0.04\times10^{-3}$ fm^3 from above, we find $\bar\alpha_n=(1.23\pm0.15\pm0.20)\times10^{-3}$ fm^3 and can give for the first time an estimate of the magnetic polarizability of the neutron, $\beta_n=(0.35\pm0.16\pm0.20)\times10^{-3}$ fm^3 and $\bar\beta_n=(0.31\pm0.16\pm0.20)\times10^{-3}$ fm^3. Our result for $\bar\alpha_n$ can be compared to a recent experiment by Rose *et al.*[27] from Compton scattering on the neutron in the deuteron where they find $\bar\alpha_n=(1.17^{+0.47}_{-1.71})\times10^{-3}$ fm^3, and to an early theoretical estimate from

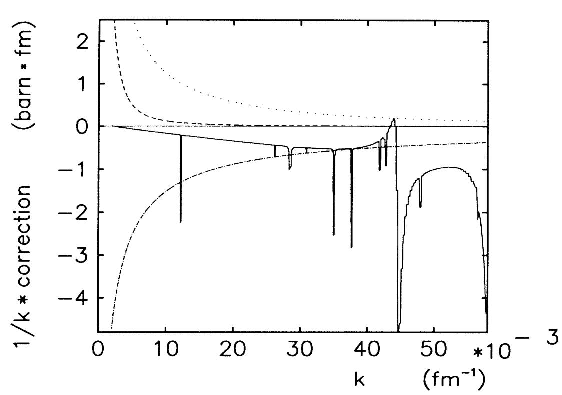

FIG. 1. Corrections to the total cross section multiplied by $1/k$ to show their effect on the evaluation of the electric polarizability based on the characteristic term proportional to k in Eq. (2). The corrections due to resonance (——), Schwinger (-·-·), neutron-electron scattering (---), and the air correction (····) are shown. In calculating Eq. (3), regions around the resonances were excluded from the data evaluation.

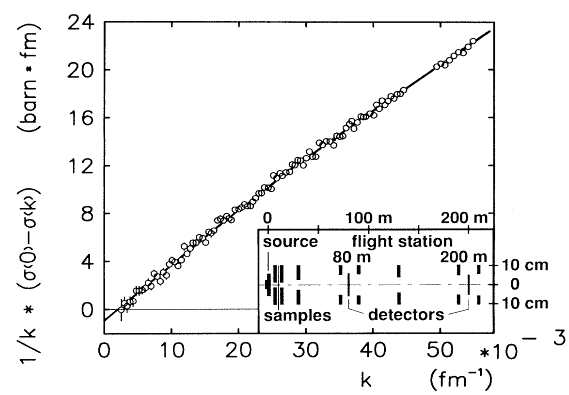

FIG. 2. Change in the corrected total cross section of ^{208}Pb multiplied by $1/k$. The effect of the neutron electric polarizability on the cross section due to the characteristic term proportional to k in Eq. (2) can be seen from the extrapolation of the data to $k=0$. Inset: A sketch of the measurement geometry.

single-pion photoproduction, 0.5×10^{-3} fm$^3<\bar{\alpha}_n<1.4\times10^{-3}$ fm^3.[28]

In conclusion, the present experiment provides for the first time an experimental value for the electric polarizability of the neutron and an estimate for its magnetic polarizability, given a new test to be met by quark-model calculations.

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