

Polarization in Mott Scattering of Multi-MeV Electrons from Heavy Nuclei

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To aid fundamental studies on the polarization of electrons in beta decay, measurements were made of the spin dependence in the scattering of 14 MeV electrons from Pb as a function of scattering angle and foil thickness. The experiment made use of a beam of polarized electrons from a strained GaAsP cathode. A simple theoretical model based on plural scattering explains the observed dependence of the analyzing power on foil thickness. The results extrapolated to infinitely thin targets are in excellent agreement with theory if the finite nuclear size is taken into account. [S0031-9007(98)08134-4]

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In 1929, Mott proposed electron scattering from heavy nuclei to test whether free electrons have a magnetic moment as predicted by the Dirac theory [1]. The idea was that the motion of the nucleus relative to the electron would produce a magnetic field in the rest frame of the electron, leading to a corresponding spin-orbit interaction. Consequently, the scattered electrons would acquire a polarization p normal to the scattering plane, which could be detected as a left/right count rate asymmetry $\varepsilon = (N_L - N_R)/(N_L + N_R) = pA_0$ in a second scattering. Here, spin sensitivity of the scattering process is represented by A_0 , which, in modern terminology is called the analyzing power or—specifically for electron scattering from thin foils—the Sherman function. Observation of the asymmetry in double scattering, in principle, allows a model-independent determination of A_0 since, at a given momentum transfer q , $p(q) = A_0(q)$ as long as time reversal symmetry holds and the energy loss in scattering is negligible. Once $A_0(q)$ is known, an unknown electron polarization can be determined. In a typical Mott polarimeter, the asymmetry ε in the scattering from a thin gold or lead foil is detected at a scattering angle near 120° where the analyzing power is large.

Mott scattering from heavy nuclei plays an important role in the study of spin-dependent processes of electrons in atomic, molecular, and condensed-matter physics. In nuclear physics, the polarization of electrons emitted in beta decay is of fundamental interest to the study of weak interactions. Much of what is now known about the two-component neutrino theory is based on such measurements [2]. Recently, new limits on time-reversal invariance in the beta decay were established [3] by searching for a transverse polarization of electrons emitted from polarized ^8Li (transition end point energy: 13.1 MeV). To obtain high statistical accuracy relatively thick scattering foils were used, which requires a good understanding of plural scattering.

The aim of the present experiment is to provide, for the first time, accurate measurements of the analyzing power in the scattering of multi-MeV electrons from heavy nuclei over a wide range of angles and foil thicknesses. Previous measurements were limited to energies below 1 MeV. A theoretical model for a decrease of the analyzing power due to plural scattering is developed, which may have application in atomic, molecular and condensed-matter physics as well. By comparing the experimental results to Mott theory, the effects of the finite nuclear size on the analyzing power are detected for the first time.

The present experiments were made possible by the extraction of highly polarized electrons from a strained GaAsP photocathode [4] illuminated with circularly polarized light. The electron polarization was reversed every second by reversing the circular polarization of the photons [5]. The spin axis of the electrons at 100 keV energy was rotated in an arrangement of solenoids and electrostatic deflectors [5] to ensure transverse polarization at the Pb target. The beam was accelerated to 14 MeV by a linac and the first stage of the Mainz Microtron and focused ($\phi 6$ mm) on the Pb target placed in air.

A set of four triple-detector telescopes based on plastic scintillators was used to determine the left/right scattering asymmetry. We used 0.5 and 1 mm thick transmission detectors and 10 cm thick stopping counters. The angular distribution of the asymmetry was determined at eight angles in the backward hemisphere (126° – 172°), where the polarization effects are large. One pair of the telescopes was moved to the selected angle in a left/right symmetric arrangement, while the other pair was kept at 126° to monitor the polarization of the beam. Asymmetries were measured for nine Pb targets with areal densities between 17 and 238 mg/cm². With a typical beam current of 10 nA a statistical error in the asymmetry of 0.002 was obtained within about 10 min.

Overall positioning accuracy of the beam spot, target and detectors was better than 1 mm. Relative errors of the measured asymmetry (1% to 5%, depending on angle and target thickness) are dominated by counting statistics.

A notorious problem in experiments of this kind is the scattering of stray electrons from the surrounding of the target, such as supports of the beam line, detector mountings, or nearby magnets. These effects were studied carefully and eliminated by removing all possible objects from the vicinity of the target, and by increasing directional sensitivity of the telescope detectors.

The measured spectra were corrected for small electronic dead time and also "target out" background, which was 2–3 orders of magnitude less than the main scattering peak. Asymmetries were determined using the cross ratio method [6], which combines the number of counts in the left and right detector for two polarization states in such a way that solid angles, efficiencies of the detectors and beam intensity variations cancel.

Analyzing powers $A(t)$ for a given target thickness t were obtained by dividing the extracted asymmetries $\varepsilon(t)$ by the beam polarization p , which was measured periodically during the experiment. The value of the beam polarization 0.77 ± 0.02 was determined using a 100 keV Mott polarimeter with Au-film targets, and a routine established during years of development of polarized electron sources at Mainz [7]. The quoted error reflects combined statistical and systematic uncertainties in the analysis and long time polarization drifts. Absolute values of the analyzing powers at this energy were checked within 1% against theory in a very difficult double scattering experiment [8].

We observe a strong reduction of the analyzing power $A(t)$ for angles above 160° (Figs. 1 and 2). The question of the exact functional form of the dependence $A(t)$ was repeatedly discussed in the past [9]. The most successful parametrizations were

$$A(t) = A_0 \exp(-\alpha t), \quad A(t) = \frac{A_0}{1 + \alpha t},$$

where A_0 is the analyzing power of an infinitely thin target and α represents the strength of the dilution effects. No clear preference for one of these parametrizations was exhibited by the previous data [9]. Our experiment with unusually thick targets provides for the first time a data set for a wide range of foil thicknesses. Even so, for scattering angles smaller than 160° , the new data are equally well described by the two formulas above. However, a clear distinction in favor of the hyperbolic dependence $A_0/(1 + \alpha t)$ is provided by measurements at the most backward angles 161° , 168° , and 172° , as illustrated in Figs. 1 and 2.

To explain the dependence $A(t)$, we use the following simple model. The count rates $N_{L,R}$ in the left/right detector can be expanded in a Taylor series of the target thickness t :

$$N_{L,R}(t) \propto (1 \pm pA_0)t + \alpha t^2.$$

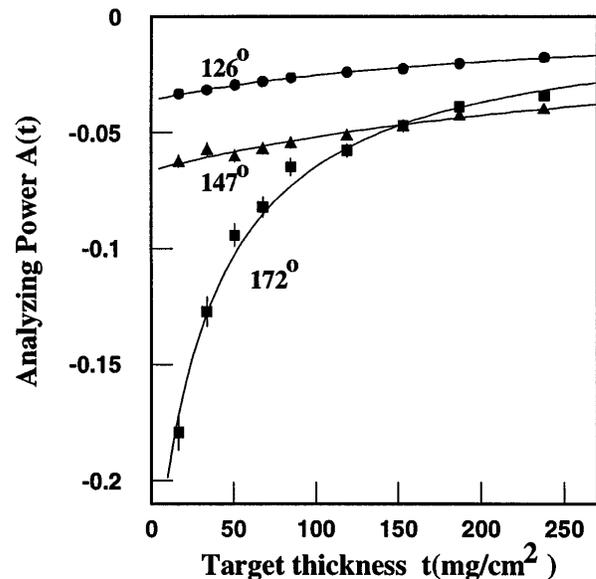


FIG. 1. Dependence of the analyzing power $A(t)$ on the target thickness t at small, intermediate, and large backward scattering angles. Note the much stronger reduction of the analyzing power at 172° . The lines show fits with the hyperbolic dependence discussed in the text.

Here, the first term is due to the polarized electrons that scattered only once in the foil. The second term, yielding an intensity proportional to t^2 , corresponds to electrons which scattered twice; α scales the intensity of this contribution. In the above equation, the spin dependence in double scattering is neglected, based on the following argument. For a beam incident normal to the target, plural scattering involves at least one scattering near 90° , within the target, where the analyzing power is much less than at large scattering angles. Any remaining polarization dependence in double scattering is, in addition, strongly

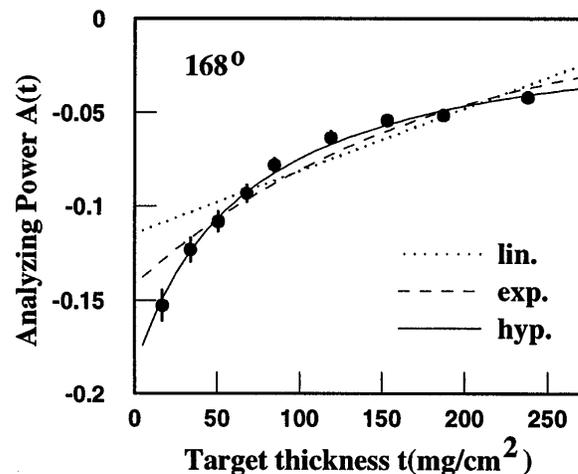


FIG. 2. Fit to the analyzing power $A(t)$ at 168° . A very good description is obtained for the hyperbolic parametrization (see also Fig. 1), while the exponential and linear dependences fail badly.

reduced by integration over azimuthal angles. With the above approximation we obtain

$$A(t) = \frac{\varepsilon(t)}{p} = \frac{1}{p} \frac{N_L - N_R}{N_L + N_R} = \frac{A_0}{1 + \alpha t}.$$

Thus, the simple model provides an explanation for the empirical formula which correctly describes the data. Obviously, $t_{1/2} = 1/\alpha$ corresponds to the thickness of the analyzer foil, for which the analyzing power $A(t)$ has dropped to one-half of the value of A_0 . It is important to note that the figure of merit $A^2(t)t$ of a polarimeter reaches a maximum just at the foil thickness $t_{1/2}$.

The value of α can be obtained from a microscopic calculation of the intensity of single and double scattered electrons. In the experiment, scattering by one large and one small angle, where some analyzing power survives, cannot be discriminated from single scattering. However, this contribution does not change the functional form of $A(t)$ and the extrapolation to an infinitely thin target. The results of such calculations, based on the theoretical cross sections for Mott scattering [10] and neglecting all polarization effects in double scattering, are in good agreement with the values of α obtained from the phenomenological fit to the experimental data (Fig. 3). This provides an additional argument that the chosen parametrization is correct.

The values of A_0 , i.e., the analyzing powers extrapolated to infinitely thin targets, were also determined with varying integration limits in the spectra. Even though the dilution parameter α changes by up to 10%, the analyzing powers A_0 were always well within the limits of the statistical errors. The final results of this experiment are reported in Table I.

The resulting analyzing powers $A_0(\theta)$ were compared to theoretical predictions. Calculations of the Mott analyzing power for a point nucleus were carried out using

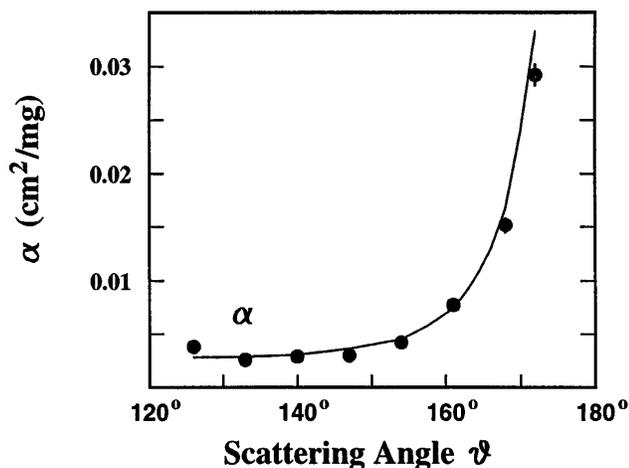


FIG. 3. Angular dependence of the dilution parameter α , determined from fits as shown in Figs. 1 and 2. Note the dramatic increase at angles above 160° . The line shows the results of the double scattering calculations.

TABLE I. Mott analyzing power A_0 for scattering of 14 MeV electrons from Pb nuclei determined in this experiment and in theoretical predictions.

Angle θ	Analyzing power $A_0 \pm \Delta A_0$	Theory	
		Point	Extended
126°	-0.036 ± 0.001	-0.045	-0.035
133°	-0.044 ± 0.002	-0.054	-0.044
140°	-0.055 ± 0.002	-0.066	-0.054
147°	-0.067 ± 0.002	-0.082	-0.066
154°	-0.086 ± 0.003	-0.107	-0.088
161°	-0.128 ± 0.004	-0.148	-0.124
168°	-0.188 ± 0.006	-0.231	-0.195
172°	-0.258 ± 0.010	-0.328	-0.269

Eqs. (2)–(4) from Ref. [11]. To check for numerical accuracy of our calculations, we compared them to the values in Refs. [10,11] and found agreement within 1%. Calculations of the nuclear size corrections are rather tedious and would exceed the scope of the present work. Therefore, we use our theoretical values at 14 MeV for a point nucleus, and correct for the effects due to the finite size of the Pb nucleus by interpolation of the data from Ref. [10]. No large uncertainties are introduced by this procedure, since this correction has a smooth energy dependence and the results of such calculations are not sensitive to the details of the charge distribution within the nucleus.

The angular distribution of the analyzing power at 14 MeV is in excellent agreement with the calculations with extended nuclei (Fig. 4). The precision of this comparison is on the level of 3%, close to the systematic uncertainty in the determination of the beam polarization,

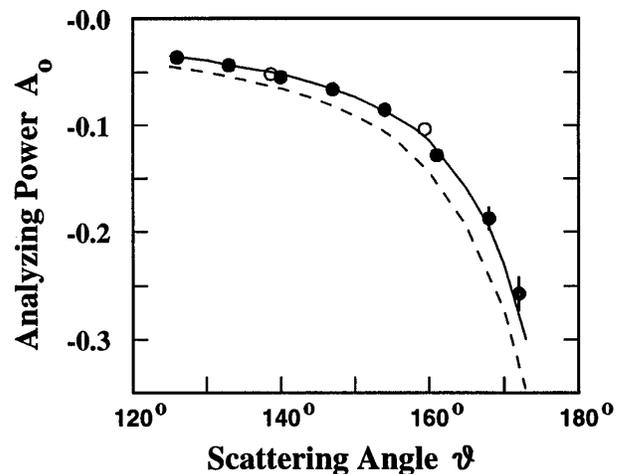


FIG. 4. Analyzing powers for the infinitely thin target and theoretical predictions. Filled dots: final experiment using the strained GaAsP cathode with 77% beam polarization; open dots: test experiment with the conventional cathode and polarization of the electrons of 33% only. Solid line: Effects due to finite nuclear size included; dashed line: point nucleus approximation.

which enters as a normalization factor in our angular distribution data. The point nucleus approximation overestimates the measured analyzing powers by roughly 15% over the entire angular range.

In conclusion, motivated by experiments on fundamental symmetries in weak interactions [3], we performed the first experimental test of polarization effects in Mott scattering of electrons in the multi-MeV energy range. Extensive data are reported, covering a broad angular range and a large range of target thicknesses. Effects of finite nuclear size are observed for the first time in the analyzing power. The results demonstrate that the Mott process may be used with confidence in analyses of the polarization of highly relativistic electrons. The reduction of the analyzing power in thick targets is understood in terms of a simple model taking into account the double scattering of electrons. This adds confidence to such calculations at energies different from the present work, including their applications to experiments in atomic, molecular, and condensed-matter physics. The results of this experiment may also be useful for diagnostics of the beam polarization at the intermediate acceleration stages in high energy electron accelerators. Electron polarimeters based on a Mott scattering in the multi-MeV range are under construction at TJNAF and at MAMI [12].

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