Use of thorium as a target in electron-spin analyzers

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Measurements of the effective Sherman function have been carried out for 10–100-keV spin-polarized electrons scattering from a thick thorium target in a retarding Mott analyzer. At 20 and 100 keV the dependence on the maximum energy loss accepted by the detector has been measured. Comparison is made with scattering from a 1250-Å gold film. Thorium is seen to have a $S_{\rm eff}$ up to 30% higher than gold. This higher $S_{\rm eff}$ can not only improve the figure of merit of a spin detector, but also lessen its sensitivity to instrumental asymmetries. Comparison is also made with preliminary theoretical results. Good agreement between theory and experiment is seen in the thorium Sherman function relative to that of gold.

INTRODUCTION

Spin-polarized electrons are playing an ever increasing role in studies of electron scattering from atoms, molecules, and surfaces. One of the more significant stimuli for the development of the field has been the emergence of a wide variety of analyzers for electron spin. Although the various analyzers now in use may differ in configuration, efficiency, and suitable application, all still depend on the spin-orbit effect to detect the spin polarization of an electron beam: in scattering elastically from a target, electrons with spin "up" relative to the scattering plane have a different cross section from those with spin "down" because of the interaction between the spin of the electron and its orbital motion around the scattering center. The size of the spin-orbit interaction determines the amount by which the scattering cross sections for spin-"up" and spin-"down" electrons differ, and hence is central in determining the efficiency of a spin analyzer. Generally speaking, large spin-orbit effects are seen in targets with large atomic charge Z, and with high incident electron energy.

Traditionally, electron-spin analyzers have used gold ($Z=79$) as a scattering target and incident beam energies as high as 120 keV. These high-energy analyzers are often referred to as Mott analyzers.[1] Typically, the electron beam to be analyzed is accelerated to the highest energy possible and then made incident on as thin a gold foil as possible. Scattered electrons are detected with two detectors located at $\pm 120°$ with respect to the incident electron beam, and the polarization P_e of the electron beam is derived from the left-right asymmetry $A_{\rm LR}$:

$$P_e = S_{\rm eff}^{-1} A_{\rm LR}. \qquad (1)$$

The asymmetry $A_{\rm LR}$ is defined as the normalized difference between the left detector signal N_L and the right detector signal N_R, i.e.,

$$A_{\rm LR} = (N_L - N_R)/(N_L + N_R). \qquad (2)$$

$S_{\rm eff}$, the effective Sherman function, is the asymmetry that would be observed with a 100% polarized electron beam. To obtain an absolute measure of the electron-beam polarization, $S_{\rm eff}$ must be supplied either by reliable theory or an independent measurement.

In the first generation of Mott analyzers,[2] the electron detectors are usually of the solid-state type and generally must be floated at the high voltage used to accelerate the electrons to the desired scattering energy. With this type of detector, $S_{\rm eff}$ depends strongly on foil thickness. This is mainly due to the broad (~ 10 keV) energy resolution of these electron detectors, which allows inelastic multiple scattering in thicker foils to be included in the detector signal, causing a loss of spin information. If an absolute measure of P_e is desired, measurements must be made at several foil thicknesses and extrapolation to zero thickness must be carried out. The extrapolated value can then be compared with elastic calculations or double scattering results to obtain P_e.

A more recent Mott analyzer design[3,4] has the electron detectors at ground potential. This offers several advantages, including simplicity of the associated detection electronics and control over the rejection of inelastically scattered electrons. Various forms of this type of analyzer exist, consisting of concentric cylinders or hemispheres. The inner electrode, at high voltage, surrounds the gold foil, while the outer electrode is held close to ground potential. The electron beam is incident through apertures and is accelerated to high voltage as it reaches the foil. Electrons scattered at $\pm 120°$ exit the inner electrode through apertures and are decelerated on their way through the outer electrode to the detectors. This deceleration field forms an energy filter which makes it impossible for electrons that have lost more than a certain amount of energy to reach the detectors. Additional electrodes in front of the detectors allow one to select any energy filtering window desired.

In this type of analyzer, which is known as a retarding Mott analyzer, the degree to which $S_{\rm eff}$ depends on foil thickness is a function of the size of the inelastic energy window used in detecting the scattered electrons. The dependence of $S_{\rm eff}$ on the foil thickness becomes negligible for small energy windows, below about 75 eV,[5] which indicates that the degradation of $S_{\rm eff}$ by multiple scattering can be attributed almost entirely to inelastic effects. Extrapolation to zero foil thickness can then be replaced by extrapolation to zero energy loss.[3,4,6,7]

This, together with the fact that the retarding Mott analyzer has a smaller solid angle of detection, makes this type of analyzer useful for measurements that can be compared directly to theory. The extrapolation to zero energy loss can usually be done with more accuracy than an extrapolation to zero foil thickness, because of the inherent inaccuracy in measuring foil thicknesses.[8] A smaller solid angle of detection means S_{eff} is not averaged over a range of scattered angles. Thus one has more confidence that the measurement is carried out in accordance with the assumptions of the theory, i.e., pure elastic, single atomic scattering into an infinitesimal solid angle.

Although the absolute calibration of spin analyzers is important, most experiments involving electron spin tend to concentrate on relative measurements of P_e. If one has a spin analyzer whose S_{eff} has been calibrated (and is known to be constant from experiment to experiment), the main concern becomes signal-to-noise in the spin measurement. This is governed by the so-called figure of merit $\mathscr{F} = S_{eff}^2 I/I_0$, where I/I_0 is the fraction of the incident intensity reaching the detectors after scattering from the target.[2] Higher figures of merit can often be obtained by sacrificing S_{eff} somewhat for an increased I/I_0. Retarding Mott analyzers are often used with an inelastic window of several hundred volts for this reason. A good illustration of this principle is also seen in the low-energy diffuse scattering spin-polarization detector,[9] in which the scattering occurs at 150 eV. S_{eff} is reduced to ~ 0.1, but detection over large solid angles increases I/I_0, more than compensating for this. As a result, this device has one of the highest figures of merit of any spin-polarization detector.

Almost all of the improvements in figure of merit realized so far in various designs of Mott detectors have been through increasing I/I_0 at the expense of reducing S_{eff}. Actually, since S_{eff} goes into $\mathscr{F}$ quadratically, an improvement in S_{eff} could be much more significant. Furthermore, increasing S_{eff} can help combat another potential problem in spin-polarization analyzers, i.e., instrumental asymmetries resulting from beam or electrode misalignments, or imbalance in detection electronics. The effects of these artificial asymmetris can be minimized by increasing S_{eff}. Thus it was considered worthwhile to explore various possibilities for increasing S_{eff}.

Since S_{eff} is known to increase with the atomic charge Z of the target in an analyzer based on spin-orbit scattering, it seems logical to use the highest Z material available. At the end of the periodic table, one finds uranium at $Z = 92$, which is unsuitable because of its chemical reactivity in pure form, protactinium ($Z = 91$), which is far too rare to be practical, and thorium, which at, $Z = 90$, is in many ways ideally suited for use as a target in Mott detectors. Its Z is not significantly different from uranium, but it is less chemically reactive; it is only mildly radioactive, being a weak α emitter; and it is a soft, ductile metal in pure form.

I. EXPERIMENT

To evaluate thorium as a target in electron-spin analyzers, a series of measurements comparing the effective Sherman functions of a thorium and a gold foil were carried out using a 100-keV cylindrical retarding Mott analyzer based on a Rice University design.[3] A sketch of the analyzer is shown in Fig. 1. The incident electron beam, with polarization 28%, current ~ 5 nA, and nominal energy 100 eV, was generated by a GaAs source normally used for scattering experiements with polarized electrons and polarized atoms.[10] The thorium and gold targets were mounted on a moveable sample holder at the center of the high-voltage inner cylinder. The gold target consisted of a 1250-Å film evaporated onto formvar.

The thorium sample was a disk of diameter 12.7 mm and thickness 0.09 mm. Because of the thickness of the sample, the thorium target must be considered as a bulk target, rather than a thin foil. Nevertheless, based on investigations with thick gold targets,[6,7] it can be expected that the measured zero-energy-loss value of S_{eff} will be very close to the pure elastic, single scattering value.

When pure thorium is exposed to air for a long period of time, it develops a thick black oxide layer. This was removed before installation in the vacuum system by etching in concentrated sulfuric acid at 230 °C for 2 h, followed by passivation for 30 s in a $\sim 30\%$ solution of nitric acid at room temperature. After this treatment the sample attained a shiny, metallic appearance which did not visibly deteriorate after several days of exposure to air.

Effective Sherman functions were measured for both the gold and thorium as a function of scattering energy and maximum inelastic energy loss V_{inel}, which was varied by adjusting the bias on apertures in front of the channel electron multipliers. The front cones of the multipliers were maintained at the same voltage as the apertures, as this was found

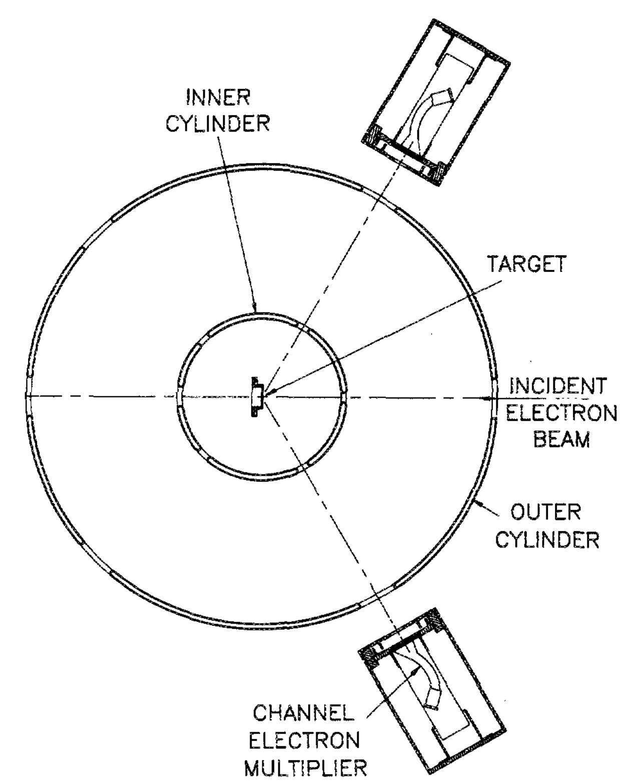

FIG. 1. Sketch of the retarding Mott analyzer.

empirically to give the best inelastic rejection.

For each measurement of S_{eff}, the incident electron spin was reversed at 1 s intervals and the signals from both detectors were collected. This resulted in four count rates, ranging from about 3 to 40 kHz, which were accumulated over a period of about 80–100 s. A background signal of about 1 kHz for thorium and 400 Hz for gold was also measured by biasing the detector apertures at -400 V with respect to ground. Since this background was proportional to the incident electron-beam current, it is thought to have been largely due to ions desorbed by the incident beam. It probably could have been reduced significantly by biasing the target a few hundred volts positive with respect to the inner cylinder, had provision been made for this. The background signal was subtracted from each count rate before further data processing.

Since the electron spin was reversible in this experiment, the four count rates could be used to calculate "spin up minus spin down" rather than "left minus right" asymmetries. These two types of asymmetry are formally equivalent because of the symmetry properties of the spin-orbit interaction. However, the "up-down" asymmetry is generally less sensitive to apparatus asymmetries. The effective Sherman function was derived from the expression

$$S_{eff} = P_e^{-1}(N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow). \qquad (3)$$

The quantity $N_\uparrow$ was taken as the average value of the signal in the left detector with incident spin up and the signal in the right detector with incident spin down. $N_\downarrow$ was calculated in a corresponding manner. In forming this average, we have made use of the fact that, as far as the spin-orbit interaction is concerned, spin-up (or down) scattering to the left is equivalent to spin-down (or up) scattering to the right. In addition, "up-down" asymmetries were calculated for each detector independently and displayed in real time as counts were accumulated. These asymmetries were always equal in magnitude within counting statistical uncertainty, which was taken as a good indication that instrumental false asymmetries were negligible for these measurements.

In order to put the measured effective Sherman functions on an absolute scale, it was also necessary to determine the polarization of the electron beam, P_e. This was obtained from the 100-keV gold data. The assumption was made that at $V_{inel} = 0$, S_{eff} is equal to 0.394, the theoretical value for 100-keV pure elastic single scattering at an angle of 120°.[11] This value of S_{eff} is consistent with the value ~ 0.39, which is generally accepted in the literature. The direct experimental evidence supporting this acceptance, however, is somewhat sparse.[8] Our assumption of a theoretical value thus introduces a necessary, but difficult to quantify, uncertainty into the measurements presented here. Since this uncertainty enters as a scale factor, however, we can safely ignore it for present purposes, with the understanding that the data may have to be rescaled if the theoretical value for S_{eff} is revised in the future.

The value of the raw experimental asymmetry at $V_{inel} = 0$, which is to be divided by 0.394 to give P_e, should in principle be determined by an extrapolation of the data. However, the true functional form of the dependence of S_{eff} on V_{inel} is unknown. The choice of extrapolation function is hence somewhat arbitrary, and any function that yields a good fit to the data is as good as any other. Good fits were obtained with a quadratic function over the whole data range and a linear function out to $V_{inel} = 425$ V. The $V_{inel} = 0$ intercepts from these two fits were slightly different, but in fact, both agreed with the measurement of the asymmetry at $V_{inel} = 25$ V within its statistical error bar. Thus it was considered sufficient to take the measurement at $V_{inel} = 25$ V as a good approximation of the value of the asymmetry at $V_{inel} = 0$. The resulting electron-beam polarization was 0.282 ± 0.004. The uncertainty estimate in P_e was arrived at by combining in quadrature the statistical (one standard deviation) uncertainty of the measurement at $V_{inel} = 25$ V with half the difference between the linearly and quadratically extrapolated intercepts. This latter contribution to the uncertainty was added as a rough approximation to the uncertainty introduced through the lack of knowledge of the functional form for extrapolation. Provided there are no drastic changes in S_{eff} between $V_{inel} = 0$ and 25 V, this should be a good estimate of the uncertainty. We note that this uncertainty value does not include the uncertainty arising from the reliance on theory necessary for establishing the absolute scale.

Although it would not affect our measurements because of the background subtraction, it was considered possible that the emission of α particles from the thorium sample might cause background problems in some experiments. Measurements were made with the incident beam and high voltage off, comparing count rates when the thorium and gold foils were in place. In each case the count rate was 0.1 Hz or less, indicating that α emission in totally negligible.

II. RESULTS AND DISCUSSION

The result of the measurements are shown in Figs. 2 and 3. Figure 2 shows S_{eff} vs V_{inel} for thorium and gold at 100 and 20-keV incident beam energies. Figure 3 shows the dependence of S_{eff} on scattering energy. The error bars shown in the figures represent one-standard-deviation errors derived from counting statistics. They do not include scale factor contributions from either the experimental error in P_e or the use of theory for absolute calibration. These additional errors should be kept in mind if these data are compared with other measurements or calculations.

The behavior of S_{eff} as a function of V_{inel} for thorium is essentially similar to that of gold. The magnitude of S_{eff} is about 25%-30% higher at small values of V_{inel}, and is about 15%–20% higher at large values of V_{inel}. The larger Sherman function can be attributed to the higher Z of thorium, which, interestingly, is about 14% higher than the Z of gold, suggesting a Z^2 dependence in S_{eff}. The faster fall of of S_{eff} with V_{inel} is most likely attributable to the thickness of the thorium target. One should expect that multipile scattering is much more significant with a thick target, and hence the degradation of S_{eff} should be more drastic as V_{inel} is increased.

We have not shown the scattering intensity as a function

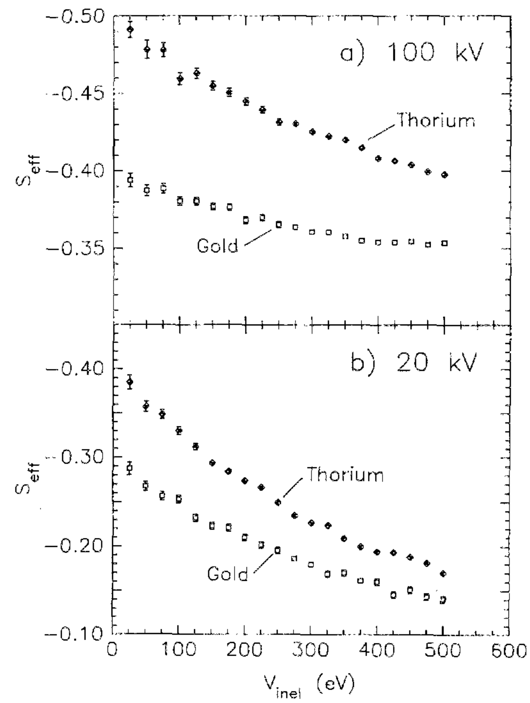

FIG. 2. Effective Sherman function S_{eff} for gold and thorium vs maximum energy loss V_{inel} accepted by the detectors. (a) 100-keV scattering energy; (b) 20-keV scattering energy. Error bars are one standard deviation from counting statistics and are shown only when larger than the plotting symbol. They do not include possible scale factor errors due to either the experimental error in determining P_e or the reliance on theory for absolute scale determination.

of V_{inel} because its behavior is essentially identical in all cases. For gold or thorium, 100 or 20 keV, the intensity increases in an almost exactly linear fashion, starting near zero when $V_{inel} \simeq 0$. The absolute intensities are of course different in each case; at 20 keV they are generally larger than at 100 keV, and at each energy the thorium intensity is about 15% higher than the gold intensity. A quantitative measurement of intensity versus scattering energy was not possible because of systematic effects due to the strong focusing involved in the acceleration and deceleration between the cylinders.

Figure 3 shows S_{eff}, measured with $V_{inel} = 25$ V, as a

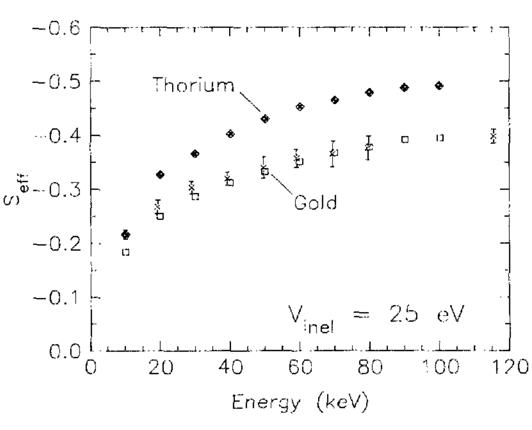

FIG. 3. Effective Sherman S_{eff} for gold and thorium vs scattering energy, measured with $V_{inel} = 25$ eV. Crosses represent data of Gray *et al.* (Ref. 4). Error bars are as in Fig. 2.

function of scattering energy. As was indicated by the extrapolation of the 100-keV gold data, these measurements give results that are most likely very close to the $V_{inel} = 0$ values. Hence they should be comparable with theory. Again, the thorium and gold targets exhibit similar qualitative behavior: S_{eff} decreases as the energy goes down, as expected. As in the V_{inel} studies, the thorium results are 20%–30% higher. The largest difference is at 20 keV.

Also shown in Fig. 3 for comparison are results from Gray *et al.*[4] The agreement with the present results for gold is excellent. Furthermore, the disagreement with the theory of Holzwarth and Meister[12] at lower energies found by Gray *et al.* is confirmed by our measurements.

At present, there are no published calculations of the Sherman function of thorium for comparison with our measurements. We have received by private communication from Ross and Fink[11] preliminary results at 100 keV, obtained from the same theoretical approach as that used to predict the gold Sherman function of -0.394. They predict a Sherman function of -0.485, which is in good agreement with our measurement of -0.491 ± 0.009 (this error estimate includes both the statistical error and the error from the P_e measurement, combined in quadrature).

III. DISCUSSION

We have shown that thorium can be useful as a target in electron-spin analyzers which utilize the spin-orbit effect to measure the spin of the incident electrons. The effective Sherman function for a retarding Mott analyzer employing a thick thorium target can be as much as 30% greater than for gold, which can significantly improve the figure of merit of the analyzer. For example, in the retarding Mott analyzer, a 30% higher S_{eff} together with the 15% higher I/I_0 leads to nearly a factor of 2 increase in $\mathscr{F}$. The fact that the figure of merit is enhanced mainly by increasing S_{eff} rather than I/I_0 makes this improvement even more significant, because it can be done while actually decreasing the importance of systematic instrumental asymmetries, rather than increasing them.

In addition, we have confirmed some earlier results. We have shown that thick targets work quite adequately in place of thin foils in a retarding Mott analyzer.[7] We have also confirmed earlier measurements of the energy dependence of S_{eff} for gold at $V_{inel} \approx 0$.[4]

Our measurements of the energy dependence of S_{eff} for thorium provide new data for comparison with calculations. The agreement with preliminary results of Ross and Fink[11] at 100 keV is encouraging, although it must be remembered that the same theory provided the calibration of the electron-beam polarization via the gold measurements.

Strictly speaking, our measurements can therefore only be considered as a confirmation of the relative values of the gold and thorium Sherman functions. As more true absolute measurements on gold or thorium become available, however, the absolute scale of the current results may well prove accurate.

In the future, it will be most interesting to investigate the energy dependence of the Sherman function for thorium at lower energies, particularly in the regime of a few hundred volts, where the diffuse, back scattering-type detectors operate.[9] If the Z^2 scaling of S_{eff} still holds, one might well expect a significantly higher Sherman function, which would then dramatically improve the figure of merit of these already very efficient detectors. The lessened significance of instrumental asymmetries would be especially useful in these detectors. It remains to be seen, however, whether the surface properties of a thorium target are such that a stable Sherman function for low-energy electrons is possible without stringent UHV requirements.

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