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Precision determination of electron scattering angle by differential nuclear recoil energy method

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ABSTRACT

The accurate determination of the scattered electron angle is crucial to electron scattering experiments, both with open-geometry large-acceptance spectrometers and ones with dipole-type magnetic spectrometers for electron detection. In particular, for small central-angle experiments using dipole-type magnetic spectrometers, in which surveys are used to measure the spectrometer angle with respect to the primary electron beam, the importance of the scattering angle determination is emphasized. However, given the complexities of large experiments and spectrometers, the accuracy of such surveys is limited and insufficient to meet demands of some experiments. In this paper, we present a new technique for determination of the electron scattering angle based on an accurate measurement of the primary beam energy and the principle of differential nuclear recoil. This technique was used to determine the scattering angle for several experiments carried out at the Experimental Hall A, Jefferson Lab. Results have shown that the new technique greatly improved the accuracy of the angle determination compared to surveys.

1. Introduction

The accurate determination of the scattered electron angle (θ) is crucial to most of electron scattering experiments, which rely heavily on the accuracy of the four-momentum transfer squared (Q^2) measurement. Since Q^2 is related to θ by

$$Q^2 = 2EE'(1 - \cos(\theta)) \tag{1}$$

the θ measurement plays a key role in elastic scattering experiments where both cross-section (σ) and the form factors strongly depend on Q^2. The two other factors of Q^2 measurement are the energies of the incoming and scattered electrons. Until about three to four decades ago, the uncertainties in Q^2 were dominated by the uncertainties in these energy measurements and not by the uncertainties in the scattering angle determination. In fact, the differential nuclear recoil method was used in some cases to extract the scattered electron energy given the incoming electron energy and the scattering angle [1]. Because of the improvement in present electron scattering experiments, the scattered and incoming electron energies are determined with high precision using high resolution magnetic spectrometers and many independent beam energy measurement techniques. As a result, the accuracy of the scattering angle measurement becomes the limiting factor in the accuracy of Q^2. This is especially the case for forward-angle electron scattering experiments, where the scattering angles are small (up to about 10°).

The scattering angle (θ) of an electron is defined as the angle between the direction of the scattered electron and the direction of the primary electron beam. In the case of dipole-based magnetic spectrometers, the scattering angle is calculated using a combination of

- the angle of the spectrometer axis with respect to the ideal beam line (θ_0), and
- the horizontal and vertical angles of the scattered electron (ϕ_{tg} and θ_{tg}) with respect to the spectrometer axis.

An illustration and a relation between θ, θ_{tg}, ϕ_{tg} are shown in Fig. 1 and in the following equation

$$\theta = \arccos\left(\frac{\cos(\theta_0) - \phi_{tg}\sin(\theta_0)}{\sqrt{1 + \theta_{tg}^2 + \phi_{tg}^2}}\right) \tag{2}$$

Generally, surveys are used to determine θ_0 by measuring the angle between two imaginary lines: the first line along the ideal spectrometer axis and the second line along the ideal beam direction.

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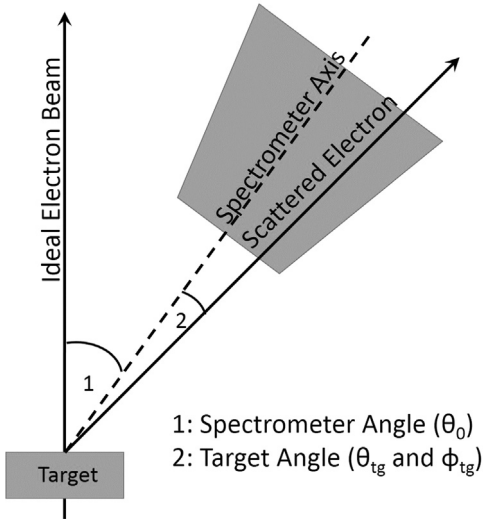

Fig. 1. The figure shows the conventional definitions of the spectrometer central angle (θ_0) and the target angles (θ_{tg} and ϕ_{tg}). The scattering angle for each event is calculated using θ_0, θ_{tg}, and ϕ_{tg}. The figure is shown as viewed from above.

This angle measurement was performed using special equipment from the Stanford Industrial Measurement System (SIMS) [2,3] and later was updated to an advanced system of optical, laser, and touch probe [4,5] to locate positions of the target center and the ideal spectrometer center and generally has an angular uncertainty of approximately 0.5 mrad (0.03°). However, multiple corrections required to relate the ideal spectrometer angle to the actual spectrometer angle including target position, and the position of the sieve-slit center with respect to the nominal central ray, increase the uncertainty of θ_0 to close to 1.0 mrad (0.06°). Such an uncertainty is unacceptably high for some forward angle experiments where the scattering angle itself is in the range of 10° or smaller. The obvious example is PREX [6], where the central angle was very small (~87 mrad). The angle uncertainty of 1 mrad would lead to uncertainties of up to < 1% in angle determination and up to < 2% in Q^2 determination. These values of uncertainties were twice larger than the experiment requirements.

In this paper, we present a novel technique to determine the electron scattering angle. This technique called the nuclear recoil technique is based on the idea of differential nuclear recoil for elastic electron scattering off target nuclei. This technique has already been used to determine the scattering angle for many experiments carried out in Experimental Hall A at Jefferson lab including HAPPEX-III [7], PVDIS [8,9], PREX, and G2p [10]. These experiments used the Jefferson Lab Hall A High Resolution Spectrometer (HRS) pair to detect the scattered electrons at forward angles with high precision.

The Jefferson Lab Hall A High Resolution Spectrometers (HRS) are a pair of identical vertically bending spectrometers called L-HRS and R-HRS, each with a combination of three quadrupoles (Q1, Q2, and Q3) and a dipole magnet to focus and to bend the scattered electrons. As described in [11], the θ_{tg} and ϕ_{tg} angle calibration for each HRS is done using a sieve-slit collimator mounted at the entrance of the spectrometer and data from electrons elastically scattered off a set of thin foil targets. In this case, the calibrated angles are referenced with respect to the line that connects the central sieve slit hole to the center of the target foil. However, in order to combine the calibrated θ_{tg} and ϕ_{tg} with θ_0 measured using surveys, corrections for the following offsets need to be applied:

- the vertical and horizontal offsets of central sieve-slit hole with respect to the spectrometer axis,
- the offset (or the mis-pointing) of the spectrometer axis with respect to the hall center,
- the offset of the central target foil with respect to the hall center.

Each of these offsets needs to be measured when performing surveys, which carries an uncertainty of approximately 0.5 mm. These correction terms consequently increase the overall uncertainty of the scattering angle measurement. Furthermore, the required surveys cost many hours of downtime for the experiment following each spectrometer angle change. On the other hand, the nuclear recoil technique does not require any of the corrections mentioned above, and thus, can significantly improve the accuracy of the measurement.

2. Nuclear recoil technique by differential nuclear recoil energy in electron scattering

In order to perform the nuclear recoil technique, the ability to determine scattered electron energy with high accuracy must be achieved. For experiments in Jefferson Lab Experimental Hall A, the scattered electron energy is measured using two identical HRSs. The standard HRS has an absolute energy accuracy in the range of $\sim 3 \times 10^{-4}$ for the energy of 0.3–4.0 GeV. However, two of the forward-angle experiments listed above, PREX and G2p, required an additional dipole magnet in front of each HRS to bend scattered electron from 5° to 12.5°. This modification required a recalibration of both HRS. The recalibration procedures are described in [12]. The final accuracy of the scattered electron energy measurement for PREX was found to be better than 0.1%. Given that the HRS dipole magnetic field has an accuracy at the 10^{-5} level, energy differences between energy spectrum peaks could be determined to a few times 10^{-5} level of accuracy. This was tested during HAPPEX-III and PREX calibrations by measuring the differences in the energy of elastically scattered electrons off ^{12}C nucleus and energies of scattered electrons that excited ^{12}C to first excited state (ΔE_C), which is well measured and known to be 4.433 ± 0.005 MeV. The accuracy of measuring ΔE_C was within 40 keV for both HAPPEX-III and PREX, better than the required accuracy of the experiment.

Consider the equation for an electron scattering off a target of mass M_t

$$E' = \frac{(E - E_{loss1}) - E_x\left(1 + \frac{E_x}{2M_t}\right)}{1 + \frac{2(E - E_{loss1})\sin^2\left(\frac{\theta}{2}\right)}{M_t}} - E_{loss2} \tag{3}$$

where E, E', θ, E_{loss1}, E_{loss2}, and E_x, are the beam energy, the energy of the scattered electron, the scattering angle, the energy loss occurred before the scattering, the energy loss occurred after the scattering, and the energy required to excite the target nucleus, respectively. In the case of elastic electron scattering, the E_x term vanishes and the equation becomes

$$E' = \frac{E - E_{loss1}}{1 + \frac{2(E - E_{loss1})\sin^2\left(\frac{\theta}{2}\right)}{M_t}} - E_{loss2} \tag{4}$$

For the kinematics of Jefferson Lab forward angle experiments ($E \geq$ 1 GeV and $\theta \leq$ 10°) and for scattering off thin foil targets, the above equation could be simplified to

$$E' = \frac{E}{1 + \frac{2(E)\sin^2\left(\frac{\theta}{2}\right)}{M_t}} - E_{loss} + \text{correction}(M_t, \theta, E, E_{loss1}) \tag{5}$$