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A low-voltage retarding-field Mott polarimeter for photocathode characterization

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ABSTRACT

Nuclear physics experiments at Thomas Jefferson National Accelerator Facility's CEBAF rely on high polarization electron beams. We describe a recently commissioned system for prequalifying and studying photocathodes for CEBAF with a load-locked, low-voltage polarized electron source coupled to a compact retarding-field Mott polarimeter. The polarimeter uses simplified electrode structures and operates from 5 to 30 kV. The effective Sherman function for this device has been calibrated by comparison with the CEBAF 5 MeV Mott polarimeter. For elastic scattering from a thick gold target at 20 keV, the effective Sherman function is 0.201(5). Its maximum efficiency at 20 keV, defined as the detected count rate divided by the incident particle current, is $5.4(2)\times10^{-4}$, yielding a figure-of-merit, or analyzing power squared times efficiency, of $1.0(1)\times10^{-5}$. The operating parameters of this new polarimeter design are compared to previously published data for other compact Mott polarimeters of the retarding-field type.

1. Introduction

Nuclear physics experiments have come to rely on high polarization electron beams, and place stringent demands on the electron source. In particular, beam requirements at Thomas Jefferson National Accelerator Facility's CEBAF (Continuous Electron Beam Accelerator Facility) include polarization over 80% and average current capability of at least 100 μA. Access to the CEBAF polarimeters for photocathode research is constrained by the experimental schedule. Previous offline photocathode polarization research at Jefferson Lab was performed using a 100 kV vertical electron gun and conventional Mott polarimeter, which required extensive radiation shielding and a personal safety system. We describe here a simple, load-locked, low-voltage polarized electron source used in conjunction with a newly designed compact, retarding-field Mott polarimeter which enables photocathode pre-qualification for the CEBAF injector as well as polarization characterization of novel photocathode materials.

2. Polarized electron source

The polarized electron source is an ultra-high vacuum system where GaAs photocathodes are heated and then activated to a negative electron affinity state using cesium and an oxidant. When illuminated with circularly polarized light at energies just over the band gap, activated GaAs emits longitudinally polarized electrons [1,2]. Fig. 1 shows a SIMION [3] model of the beam trajectory through the source with typical bias voltages for each electrostatic element noted. The photocathode (element a in Fig. 1) is biased at -268 V with respect to the Mott polarimeter target using a battery bias box, and photocurrent is monitored with a picoammeter. Since Mott scattering detects an asymmetry for transversely polarized electrons, the spin direction of the initially longitudinally polarized electron beam direction must be bent 90°. This is accomplished using an electrostatic bend (elements b and c) of the design developed by Al-Khateeb et al. [4]. The beam is then focused and steered using one split lens (elements f and g) and two cylindrical lenses [5] (elements e and h) to the Mott polarimeter for polarization analysis.

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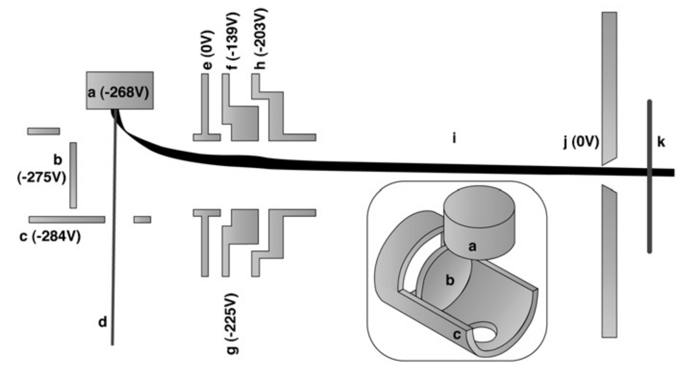

Fig. 1. SIMION model of beam transport through the polarized electron source showing lenses and typical voltages in cross-section, with the three-dimensional inset showing detail of the photocathode and "pusher" electrostatic bend. The incident laser beam path and the SIMION modeled electron trajectories are labeled d and i, respectively. The beam limiting aperture is labeled j, and k indicates the insertable planar electrode for current monitoring.

For photoemission, we use a fixed (773 or 840 nm) or variable (~770–780 nm) wavelength laser, or a monochromator which produces un-collimated light at wavelengths from 650 to 850 nm. An x–y translational stage allows movement of the laser beam while maintaining normal incidence to the photocathode, and an optical attenuator system varies laser power and subsequent photocurrent. The final optical element is a quarter-wave plate to circularly polarize the light. The computerized data acquisition program controls a laser shutter and an insertable half-wave plate which is used to change the helicity of the circularly polarized laser light and to help cancel instrumental asymmetries.

New photocathodes are introduced into the source using a load-lock system, and a bake of the load-locked bellows at 250 °C for 12 h allows samples to be changed within a day. The photocathode is mounted on a hollow stainless steel "stalk" where the GaAs is heated to a surface temperature of ~550 °C for 2 h using an external heater prior to chemical activation with Cs and the oxidant NF_3 (though O_2 could be used instead). An 8″ diameter stainless steel chamber houses the polarized source and is pumped with a combination of ion and non-evaporable getter pumps [6]. To achieve pressure in the low UHV regime, the polarimeter was initially baked in a hot air oven for 30 h at 200 °C, which is the limit for the Teflon insulators in the lens transport system and the CEM support structure. During the bake, a sheet metal wall separates the hot air oven into two sections so that the source chamber can be heated to nearly 250 °C to further reduce the water vapor pressure and activate the NEG pumps to approximately 60% of their maximum pump speed. The combination of NEG and ion pumps typically achieves pressure in the low 10^{-11} Torr range, leading to a very long photocathode lifetime, with reactivations necessary every few months.

The polarized source is coupled to the Mott polarimeter through a 3.2 mm diameter aperture on centerline to define the beam. The source lens system is separated from the Mott lens transport system by 15 cm, and an isolated planar electrode can be inserted after the aperture before the Mott transport system to monitor the current that enters the lens transport system.

3. Mott polarimetry

Our Mott polarimeter has a particularly simple design, shown in Fig. 2, with no electrode structures except the inner high-voltage hemisphere and the grounded outer hemisphere, which in turn supports simplified retarding-field grids. Its hemispherical structure is similar to a "mini-Mott" design reported earlier [7], but is smaller and simpler, eliminating guard rings and other ancillary electrodes. It is also similar to a micro-Mott design discussed briefly by Ciccacci et al. [8] that is somewhat larger. The electrode structure supports voltages at least as high as our 30 kV power supply maximum.

Many parameters have historically been used to characterize Mott polarimeters. Because incident electron currents are often low, the polarimeter's detection efficiency, defined as the electron detection rate divided by the incident electron current, I/I_o, is important. In addition, experiments requiring spin analysis of scattered electrons often place severe spatial constraints on the size of the polarimeters that can be used [9,10]. So-called "micro-Mott polarimeters", developed largely at Rice University by Dunning and co-workers [11–14] over the last two decades, solve these two issues simultaneously by reducing polarimeter size; as a rule of thumb, the detection efficiencies of Mott polarimeters vary inversely with their size, since the chief factor in determining efficiency is the effective solid angle subtended by the electron detectors at the Mott scattering target. The figure of merit, η, for a Mott polarimeter is inversely proportional to the square of the time required to measure polarization to a given statistical accuracy [9,15] and is defined as

$$\eta \equiv (S_{\text{eff}})^2 \times I/I_o, \tag{1}$$

where S_{eff} is the effective Sherman function or polarimetric analyzing power given by

$$S_{\text{eff}} = A/P_e, \tag{2}$$

P_e is the electron polarization, and

$$A = \frac{R-L}{R+L} \tag{3}$$

is the scattering asymmetry, with the values of R and L corresponding to the count rates in the "left" and "right" electron detectors of the Mott polarimeter. Generally speaking, as the detection solid angle, and thus the ratio I/I_o, increases, S_{eff} decreases.

3.1. Polarimeter design

Electrons that enter the polarimeter are accelerated to energies from 5 to 30 keV between two hemispherical stainless steel electrodes supported on a ceramic insulator (see Fig. 2). Electrons scatter from a gold target (5 μm of gold plated on a copper cylinder) inside the inner hemisphere. In principle, the target could be biased negatively relative to the inner hemisphere to suppress noise due to ions accelerated into the detectors [16]. This was not done, as no ion-related noise was observed. The vacuum chamber serves as adequate radiation shielding at 30 kV for typical operating currents up to 100 nA on target. Scattered electrons are decelerated in the gap between the inner and outer hemispheres and detected with channel electron multipliers (CEMs) [17], each subtending 0.27 sr, centered at 120°. To reduce the chance of electrical discharge, the outer surface of the inner hemisphere was highly polished (mirror finish with 5 micro-inch rms surface roughness), and the aperture holes in both hemispheres were rounded and polished. Two gold mesh [18] grids in front of each CEM, separated by 3.5 mm, establish a spatially well-defined retarding potential volume and reject inelastically scattered electrons. The grids are affixed to aluminum support rings using Aerodag [20] and isolated by ruby balls. As the retarding potential is increased negatively from ground, electrons that have lost energy through inelastic scattering are increasingly excluded from the measurement; when the retarding potential energy approaches that of the incident beam kinetic energy, only the elastically scattered electrons are detected. In this paper, we