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Experimental study on helium optical electron polarimetry*

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Optical electron polarimetry is suitable for calibration of a spin-polarized electron source, especially for measurement of polarization of spin-polarized electron beam. In this paper, a new optical electron polarimeter is described, which is based on the circularly polarized He radiation induced by the bombarding of He atoms with spin-polarized electrons. The theoretical basis of the optical electron polarimetry and the structure of the optical electron polarimeter are discussed. The measurement of polarization of spin-polarized electrons produced from a new GaAs (100) spin-polarized electron source is carried out. The result of polarization of 30.8% for our spin-polarized electron source is obtained using the He optical electron polarimeter.

Keywords: optical electron polarimeter, spin-polarized electrons, polarization
PACC: 0760F, 2925B, 2975

1. Introduction

Since the GaAs spin-polarized electron source was proposed three decades ago,[1] spin-polarized electron beam has been used widely in the electron-atom collision field.[2−5] As the rapid growth of such experiments, a precise electron polarimetry is needed for the spin-polarized electron beam. Mott-scattering polarimetry is a standard technique, but its systematic uncertainties, which are mainly caused by multiple and plural scattering, are rather large. The absolute uncertainty is certainly larger than ±5%.[6] The measurement of the circular polarization of radiation of atoms excited by spin-polarized electrons impact is an alternative method, which was first proposed by Farago and Wykes[7] in 1969. The incident electron polarization can be related to the circular polarization of the radiation.

Compared with the transitions of some heavy atoms, such as Hg$6^3P_1 \rightarrow 6^1S_0$, and Hg, Cd, Zn $ns(n+1)s^3S_1 \rightarrow nsnp^3P_J$ transitions,[8] which have strong energy dependence of polarization, the transition $3^3P \rightarrow 2^3S_1$ of helium, suggested by Gay[9] in 1983, has been demonstrated to be a very good candidate for optical electron polarimetry.[10] Through further studies, Gay has found that Ne, Ar, Kr and Xe atoms can also be used as the targets to determine the polarization of electron beam.[11]

In this article, we report the experimental study of helium optical electron polarimetry. The measurement of the polarization of incident spin-polarized electron beam was performed at PPL (Polarization Physics Laboratory) at Tsinghua University by optical electron polarimetry. The spin-polarized electron beam is produced from our new p-type GaAs (100) spin-polarized electron source. And a new optical electron polarimeter, using He $3^3P \rightarrow 2^3S_1$ (388.9nm) transition, is developed to determine the polarization of electron beam.

2. Basis of the helium optical electron polarimetry

The incident spin-polarized electron polarization P_e can be related to the relative Stokes parameters P_3 and P_1 of the radiation $3^3P \rightarrow 2^3S_1$ after exchange excitation from the ground state to the 3^3P_J manifold. Immediately following the excitation, only the electron spin coordinate is oriented. Thus the time-averaged value of P_3, i.e. circular polarization, is non-

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zero.

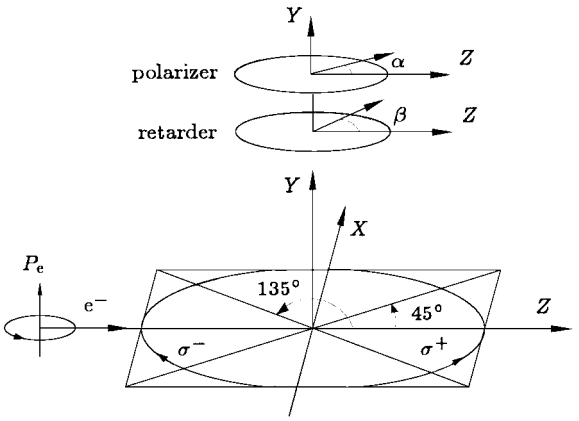


Fig.1. Collision geometry of optical electron polarimetry. The electron beam is incident along the Z axis with its polarization along the Y axis, and the optical electron polarimeter is arranged along the Y direction.

For the collision geometry of the optical electron polarimeter shown in Fig.1, the incident electron beam's direction determines the Z axis and the electron spin polarization direction is parallel or antiparallel to the Y direction along which the optical electron polarimeter is aligned. The initial density matrix is written in the LS direct product space:[9]

$$\rho(3^3P, t=0) = \rho_{\rm L} \otimes \rho_{\rm S}, \tag{1}$$

where, in the m_z basis,

$$\rho_{\rm L} = \frac{1}{3}\begin{pmatrix} 1+A_0^{\rm col} & 0 & 0 \\ 0 & 1-2A_0^{\rm col} & 0 \\ 0 & 0 & 1+A_0^{\rm col} \end{pmatrix}, \tag{2}$$

$$\rho_S = \frac{1}{6}\begin{pmatrix} 2 & \sqrt{2}P_{\rm e} & 2 \\ \sqrt{2}P_{\rm e} & 2 & \sqrt{2}P_{\rm e} \\ 2 & \sqrt{2}P_{\rm e} & 2 \end{pmatrix}. \tag{3}$$

Here $A_0^{\rm col}$ is the Fano–Macek alignment parameter.[12] The Stokes parameters P_1 and P_3 are defined as

$$P_1 = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp}, \quad P_3 = \frac{I_{\sigma-} - I_{\sigma+}}{I_{\sigma-} + I_{\sigma+}}, \tag{4}$$

where, as shown in Fig.1, $I_\parallel$ and $I_\perp$ refer to the intensities of radiation light with electric field direction parallel and perpendicular to the incident electron beam axis, respectively. $I_{\sigma+}$ and $I_{\sigma-}$ refer to the left-handed and right-handed circularly polarized light, respectively. $I_\parallel$, $I_\perp$, and $I_{\sigma+}$, $I_{\sigma-}$ can be written as

$$I_{\sigma^\pm,\parallel,\perp} = \sum_{J,k,q} \langle J|\,|L^k|\,|J\rangle\, \rho^k_{-q} l^k_q(\pm,\parallel,\perp), \tag{5}$$

$$\rho^k_{-q} = \sum_{MM'} (-1)^{M+J} \begin{pmatrix} J & k & J \\ -M & q & M' \end{pmatrix} \langle JM|\,\rho(t=0)\,|JM'\rangle, \tag{6}$$

$$l^k_q(\pm,\parallel,\perp) = \sum_{q_1 q_2} (-1)^{q_2} \varepsilon^*_{q_1}(\pm,\parallel,\perp)\varepsilon_{q_2}(\pm,\parallel,\perp) \begin{pmatrix} 1 & k & 1 \\ -q_2 & q & q_1 \end{pmatrix}, \tag{7}$$

$$\widehat{\varepsilon}(\pm) = \frac{\sqrt{2}}{2}(\widehat{z} \pm {\rm i}\widehat{y}),$$

and,

$$\widehat{\varepsilon}(\parallel) = \widehat{z}, \quad \widehat{\varepsilon}(\perp) = \widehat{y}. \tag{8}$$

Transforming Eqs.(1)–(3) into Eq.(6), and Eqs.(5)–(8) into Eq.(4), we can obtain

$$P_1 = \frac{-15A_0^{\rm col}}{36-5A_0^{\rm col}}, \quad P_3 = \frac{18P_{\rm e}}{36-5A_0^{\rm col}}. \tag{9}$$

So the relationship between the polarization of the incident electron beam $P_{\rm e}$ and the Stokes parameters of He radiation $3^3{\rm P} \rightarrow 2^3{\rm S}_1$ is expressed as

$$P_{\rm e} = 6P_3/(3-P_1). \tag{10}$$

3. Experimental set-up for He optical electron polarimetry

Figure 2 shows the diagram of the helium optical electron polarimeter. This version is a new design with significant improvement as compared with the earlier version.[13] The optical electron polarimeter is composed of electronic optical lens, helium gas jet, Faraday cup, two focusing lenses, quartz vacuum window, retarder, polarizer, interference filter, and photomultiplier tube. The spin-polarized electron beam, activated from a GaAs photocathode,[14] is transported and focused onto the collision point through a 1mm diameter aperture. The electron beam can be monitored

by a double-cylindrical Faraday cup. The helium target atoms, injected from a gas jet, are excited by incident electrons collision. The radiation, treated as a point source, becomes a parallel photon beam after passing through the first focusing lens, of which the focus is overlapped with the point source. Photons with different polarization directions will pass through the combination of retarder and polarizer with different arrangement. Then the photon beam is refocused onto the photocathode of the photomultiplier by the second focusing lens. Here an interference filter with narrow-band is placed before the photocathode of the photomultiplier tube to select the 388.9nm radiation from excited helium atoms. Each optical element above the vacuum chamber is placed in a separate light-shielding holder. And the holders for retarder and polarizer can be rotated easily for different angles, separately. The Stokes parameters P_1 and P_3 are determined by intensities and polarizations of the radiation after a series of measurements. And the polarization of the incident electrons can be obtained using Eq.(10).

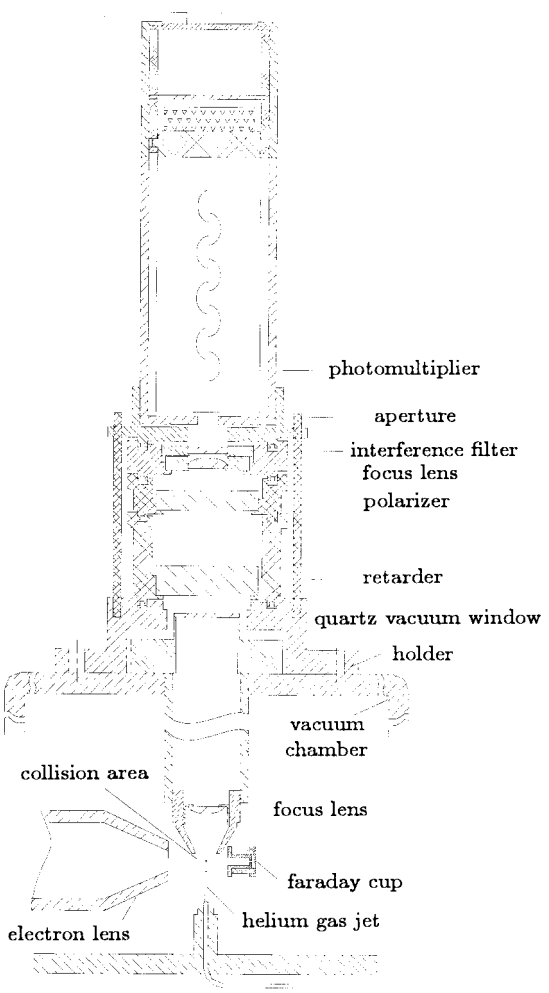


Fig.2. Schematic diagram of the helium optical electron polarimeter. It comprises electronic optical lens, helium gas jet, Faraday cup, two focusing lenses, quartz vacuum window, retarder, polarizer, interference filter, and photomultiplier.

4. Polarization of spin-polarized electrons

According to Fig.1, if the transmission axis of the polarizer and the fast axis of the retarder are set at angles α and β respectively relative to the Z-axis, the intensity of the light, with initial intensity I, transmitted through the combination of polarizer and retarder is given by[15]

$$\begin{aligned} I(\alpha,\beta,\delta) =& I/2\{1 + P_1[\cos 2(\alpha-\beta)\cos 2\beta \\ & - \sin 2(\alpha-\beta)\sin 2\beta\cos\delta] \\ & + P_2[\cos 2(\alpha-\beta)\sin 2\beta \\ & + \sin 2(\alpha-\beta)\cos 2\beta\cos\delta] \\ & + P_3[\sin 2(\alpha-\beta)\sin\delta]\}. \end{aligned} \tag{11}$$

The Stokes parameters P_1 and P_3 can be determined by setting appropriate values of α and β but with a constant $\delta = \pi/2$. So the polarization of incident electron beam is obtained by the measurements of P_1 and P_3.

The polarization direction of the incident spin-polarized electron beam can be modulated easily by changing the helicity of the laser light,[16] which irradiates the GaAs cathode to produce spin-polarized electrons by photoemission of the cathode. In the energy region free from cascade effects, the result of polarization averaged over the polarization directions of

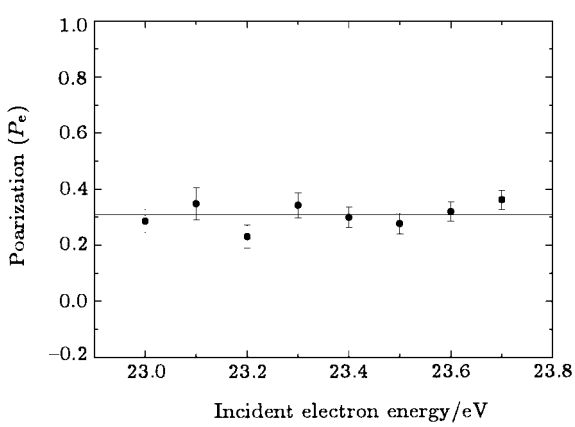


Fig.3. The electron polarization P_e as a function of incident electron energy. By averaging over the polarizations of spin-up and spin-down electron beams, the weighted averaged electron polarization of 30.8% is obtained in the incident energy region.

spin-up and spin-down is shown in Fig.3, with the incident energy ranging from 23.0 to 23.7eV in 0.1eV increment. The threshold energy for this transition is 23.0eV. The weighted averaged value of polarization is 30.8%±3.5%.

5. Conclusion

Optical electron polarimetry is an alternative method for the measurement of polarization of electron beam. Among the radiation available for different polarimetry discussed above, the He optical electron polarimeter, utilizing helium $3^3P \rightarrow 2^3S_1$ transition, is the most convenient selection for its weak energy dependence of electron polarization. It is also more suitable for polarization measurement than Mott-scattering polarimeter for its smaller systematic uncertainties. The helium optical electron polarimeter has been developed for measuring the polarization of spin-polarized electron beam, which is produced from a GaAs (100) photocathode. The polarization of 30.8% is obtained using this polarimeter. It is a satisfactory result, as compared with the other measurements in the world. It can also be regarded as an excellent result for the maximum theoretical polarization for the new spin-polarized electron source is given to be 50%.[1]

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