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Study on optical electron polarimeter and measurement of the relative Stokes parameters of weak light*

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In this paper, we present the research on an optical electron polarimeter, which is used to determine the polarization of an incident electron beam by measuring the relative Stokes parameters of the fluorescence emitted from the He gas following the impact excitation with the electron beam. The fundamental theory of the optical electron polarimeter is discussed with the $3^3P \rightarrow 2^3S$ transition of He. The structure and performance of the instrument are described, which are different in some aspects from previous works. The arrangement of the experiment for measuring the relative Stokes parameters of linearly polarized weak light is also investigated, which actually involves the same processes as the polarization measurement with the incident electron beam. The results obtained are in agreement with the theoretical prediction.

Keywords: impact excitation, polarization, optical electron polarimeter, relative Stokes parameters
PACC: 3480D, 2970, 2975, 0760F

1. Introduction

In recent years, considerable progress has been achieved in producing polarized electron beams based on photoemission from GaAs.[1] Such a polarized electron source may have applications in solid-state physics, atomic and molecular physics, nuclear physics,[2] and chemical and biological physics. To study the spin-dependent effects and interactions in these fields, the polarization of the electron beam must be measured with considerable accuracy.

The conventional method of measuring the polarization of the electron beam is by means of a Mott polarimeter, which has several disadvantages.[3] In 1969, Farago and Wykes[4] proposed an optical method to detect the polarization of the electron beam. The proposed scheme involved the exchange excitation of Hg from the ground state to the 6^3P_1 state by polarized electrons followed by $6^3P_1 \rightarrow 6^1S_0$ resonant radiation of circular polarized photons. The incident electron polarization P can be related to the relative Stokes parameter P_3 of the radiation. In 1971, Wykes[5] suggested an alternative method in which the $ns^2\ ^1S_0$ ground state of Hg, Cd or Zn is excited to the $ns(n+1)s\,^3S_1$ level and the resulting $ns(n+1)s\,^3S_1 \rightarrow nsnp\,^3P_J$ radiation can be detected. P_3 and P have a simple relationship that holds at all incident electron energies.

In 1983, Gay[6] suggested that He gas be used to replace Zn, Cd or Hg vapour as the target for the optical polarimeter, using the $3^3P \rightarrow 2^3S$ transition with more advantages. The corresponding experiments were carried out in 1991 by Gay *et al.*,[7] in 1995 by Fischer and Kessler[8] and in 1996 by Hayes.[9] After that, a comprehensive study was carried out on the noble gases and it was found that Ne, Ar, Kr and Xe can also be used as the target atoms to determine the polarization of electrons with the help of $np^5(n+1)p\,^3D_3 \rightarrow np^5(n+1)s\,^3P_2$ transitions. These have the same advantages of He over Hg, Cd and Zn. In 1996, Gay *et al.*[10] finished the optical polarimeter study of all noble gases except for He.

In this paper we present our optical electron polarimeter, which is used to determine the polarization of the electron beam produced by the GaAs polarized electron source. Our design considerations are somewhat different from those mentioned above, especially in the optical detection and data processing systems. The fundamental theory of the optical electron polarimeter with the $3^3P \rightarrow 2^3S$ transition of He is described in section II. In section III, the structure and

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performance of the instrument are introduced. The arrangement of the experiment is discussed in section IV and the relative Stokes parameters of the linearly polarized weak light are also measured. There is good agreement with the corresponding theory.

2. Theoretical basis of the optical electron polarimeter

The optical electron polarimeter is based on the collision between the incident polarized electron beam and the target atoms.[11] As an example, He gas can be used as the target atom here. The ground state of He can be excited to the high-energy level of 3^3P, and the resonant fluorescence radiation of 388.9nm can be produced by the $3^3\mathrm{P}\rightarrow 2^3\mathrm{S}$ transition. Then a set of polarization light analysers is introduced to determine the relative Stokes parameters P_1, P_2 and P_3. In the excitation process, the strong electron–electron exchange effects enable the transfer of the spin component of the incident polarized electron to the excited state of He. Due to the spin selection rule of the $3^3\mathrm{P}\rightarrow 2^3\mathrm{S}$ transition, the radiation carries the spin information of the incident polarized electron. So it is feasible to determine the polarization of the incident electron by detecting the relative Stokes parameters of the resonance radiation. The relationship between the polarization of the incident electron P and the relative Stokes parameters of radiation in this system is[6]

$$P = 6P_3/(3 - P_1), \tag{1}$$

where P_1 and P_3 are the first and third relative Stokes parameters of the decay light, corresponding respectively to the linear and circular polarization of the 388.9nm radiation in the He system.

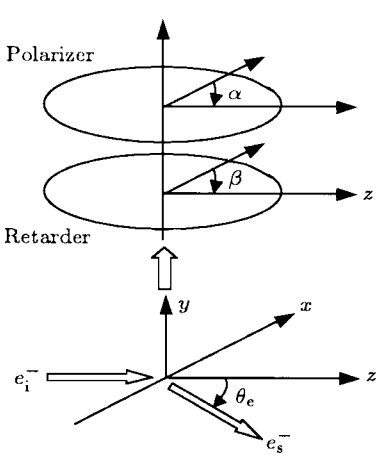


Fig.1. Collision geometry of optical electron polarimeter and its detection system for the relative Stokes parameters of the decay light.

The scattering geometry of the optical electron polarimeter is shown in Fig.1. The direction of incident electron beam is along the z-axis and the electron spin polarization direction is either parallel or anti-parallel to the y-axis. The scattering plane is defined by the momentum of incident (e_i^-) and scattered (e_s^-) electrons. The measurement system of the relative Stokes parameters of the radiation is arranged along the y-direction, i.e. the direction for detecting the decay light must be parallel or anti-parallel to the direction of spin polarization of the incident electron. The decay light detection system consists of a phase retarding plate and a linear polarizer with their reference axes aligned to the incident electron beam direction z. The retarder produces a relative phase difference δ between the orthogonal ordinary and extraordinary components of the transmitted wave. If we set the transmission axis of the polarizer and the fast axis of the retarder at angles α and β relative to the z-axis, the intensity of the light transmitted through this system is given by[12]

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

where the relative Stokes parameters, P_1, P_2 and P_3, and the intensity, I, completely describe the state of polarization of the decay light. The individual measurements of the intensity of the light transmitted can be realized with different values of angles α and β, and the retarder phase δ can also be changed during the experiment. It is obvious from Eq.(2) that the intensity I of decay light and the relative Stokes parameters, P_1, P_2 and P_3, have the linear relationship expressed by $I(\alpha,\beta,\delta)$, so they can be determined by the linear fit method using the experimental data.[13]

3. Structures of the optical electron polarimeter

The schematic diagram of our polarimeter is shown in Fig.2. It consists of four main parts: the vacuum chamber, polarization analyser system, data acquisition system and the control system. The vacuum in the chamber can be better than 5×10^{-7}Pa without any He effused in it. When He gas is introduced the pressure will be 5×10^{-5}Pa. A dual Fara-

day cup can be put behind the scattering point along the z-axis to detect the real time current of the incident polarized electron beam. The polarization analyser system consists of a phase retarder, a polarizer, an interference filter for 388.9nm light and two focusing lenses. The acceptance solid angle of this system is about 0.47sr. The filter is used to transmit the 388.9nm radiation with a bandwidth of about ±5nm. The data acquisition system includes a GBD52a photomultiplier tube (PMT), a main amplifier, a constant fraction discriminator (CFD), a 8253 counter and a microcomputer. The output of the amplifier should be enough for the CFD to produce the standard TTL pulses for input to the counter. The number of pulses per unit time, which is proportional to the intensity of the radiation, is sent to the microcomputer through the I/O card. The data acquisition program performs the functions of data collection, data processing and linear fit to calculate the relative Stokes parameters and determine the polarization of the incident polarized electron beam in real time. The spectrum display function is also incorporated into the program. In the course of the experiment, the angles α and β in Eq.(2) can be adjusted from 0° to 360° via the microcomputer. The adjustment of angles α and β can be as fine as 0.01°, which is precise enough for the measurement of the relative Stokes parameters.

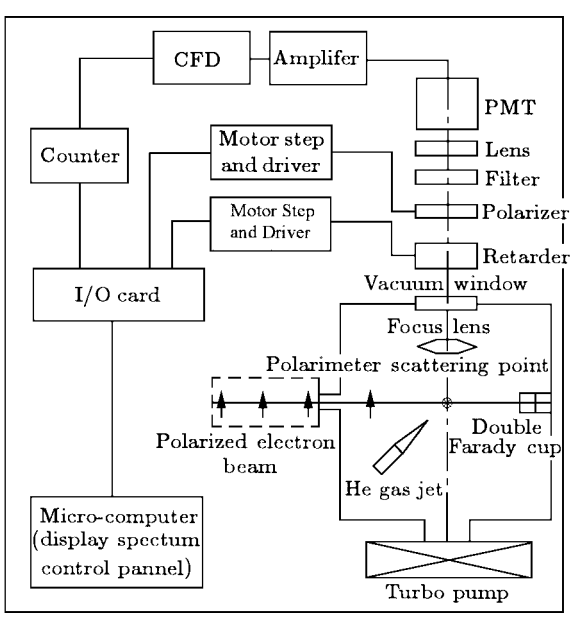


Fig.2. Configuration of the optical electron polarimeter.

Our polarimeter design has some differences compared with those of previous works, especially in the relative Stokes parameters analyser system and data processing system. Instead of employing the liquid crystal variable retarder (LCVR) used by almost all of the foreign research groups, a conventional phase retarder is used in our instrument, which is much cheaper. Furthermore, a linear fitting method can be introduced to make it much easier to estimate the experimental error. The disadvantage is that much longer data acquisition times (about several days) are needed so that the instrumental stability becomes very important. Finally, besides the polarization measurement, our instrument can serve as a highly precise relative Stokes parameters detection system to be used in corresponding research fields.

4. Measurement of relative Stokes parameters with linearly polarized weak light

In order to test the performance of our design of optical electron polarimeter, a linearly polarized weak light is used to replace the fluorescence radiation produced by excited target He for its relative Stokes parameters measurement. The theoretical values for a completely linearly polarized light are P_1=1 and P_2=P_3=0.[12] If the measured relative Stokes parameters of the linearly polarized weak light are consistent with the theoretical values, our instrument can be safely used to determine the polarization of the incident electron beam. The linearly polarized weak light is collimated to the polarimeter scattering point in Fig.2 and its intensity can be adjusted. The polarization direction of the weak light is along the z-axis, which is the momentum direction of the incident electron beam. The experimental procedure consists of the following three steps.

4.1. Calibration of the transmission axis of polarizer (zeroing of angle α)

Though the transmission axis of a commercial polarizer is usually marked on the product, it is still very difficult to align the transmission axis of the polarizer along the z-direction correctly in installation. It is prerequisite to find a way to determine the transmission axis experimentally.

In Eq.(2), if an unpolarized electron beam is used to excite He and produce resonant fluorescence radiation of 388.9nm, the cylindrical symmetry of the collision requires that only P_1 is non-zero (as is the linearly

polarized weak light).[14] Therefore, Eq.(2) becomes

$$I(\alpha,\beta,\delta) = \frac{I}{2}\{1 + P_1[\cos 2(\alpha-\beta)\cos 2\beta - \sin 2(\alpha-\beta)\sin 2\beta\cos\delta]\}. \quad (3)$$

If the retarder is taken away from the system in Fig.1, δ and β also become zero. Then Eq.(3) reduces to

$$I(\alpha,0,0) = \frac{I}{2}(1 + P_1\cos 2\alpha). \quad (4)$$

If there is a difference α_0 between the transmission axis and the direction of the incident electron beam z-axis when mounting the polarizer in the polarization analyser system for the first time, Eq.(4) can be modified to

$$I(\alpha,0,0) = \frac{I}{2}[1 + P_1\cos 2(\alpha-\alpha_0)]. \quad (5)$$

Here α is the initial transmission angle of the polarizer. We rewrite Eq.(5) in the more obvious form

$$I(\alpha,0,0) = \frac{I}{2}(1+P_1\cos 2\alpha_0\cos 2\alpha + P_1\sin 2\alpha_0\sin 2\alpha). \quad (6)$$

Because α_0 is constant during the experiment, it is very easy to acquire the data of Eq.(6) with discrete values of angle α varying from 0° to 360°. Then a linear fitting method is used to obtain the parameter α_0. Finally an extra rotation of α_0 can be given to the polarizer so that the transmission axis is aligned to the z-axis, which is the precise physical zero angle for the polarizer (α=0).

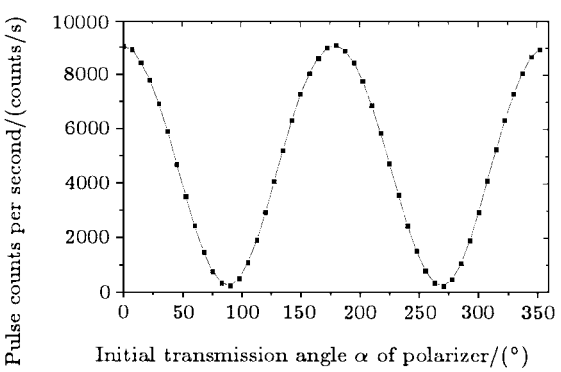


Fig.3. Pulse counts per second as a function of the initial transmission angle α of the polarizer when it is first mounted in the system.

Using the linearly polarized weak light and removing the retarder from the system of Fig.2, the transmission axis of the polarizer can be calibrated. Thirty groups of data taken under the same condition are averaged to improve the statistical accuracy. One group of data is presented in Fig.3 to show the relation between the counting rate of pulses and the initial transmission angle α of the polarizer. When all groups of data are averaged, we obtain the result α_0=–1.50°±0.09°. Finally, we rotate the polarizer by α_0 to align the transmission axis to the z-axis exactly.

4.2. Calibration of the fast axis (zeroing of angle α) and phase difference δ of the retarder

The fast axis and the phase difference δ of the commercial retarder are also unreliable, particularly the phase difference δ, which changes with the wavelength of the transmission light. So it is necessary to find an experimental method to determine the physical zero angle of the fast axis (β=0) and δ accurately.

Either the radiation produced by unpolarized electron excitation or the linearly polarized weak light can be used to do the calibration. After step A is finished, the retarder is put to the right position as shown in Fig.2. Because of the cylindrical symmetry of the collision, both P_2 and P_3 are zero in Eq.(2). Thus Eq.(3) is again valid. If the deviation of the fast axis is β_0, the transmitted intensity of light is given by

$$I(\alpha,\beta,\delta) = \frac{I}{2}\{1 + P_1[\cos 2(\alpha-(\beta-\beta_0))\cos 2(\beta-\beta_0) - \sin 2(\alpha-(\beta-\beta_0))\sin 2(\beta-\beta_0)\cos\delta]\}. \quad (7)$$

Further transformation of Eq.(7) gives

$$I(\alpha,\beta,\delta) = \frac{I}{2}\left[1 + \frac{1}{2}P_1(1+\cos\delta)\cos 2\alpha + \frac{1}{2}P_1(1-\cos\delta)\cos 4\beta_0\cos 2(2\beta-\alpha) + \frac{1}{2}P_1(1-\cos\delta)\sin 4\beta_0\sin 2(2\beta-\alpha)\right], \quad (8)$$

where δ is constant because the wavelength of the transmission light is fixed. Equation (8) is again linear. The experimental data of the individual measurements for angle α and β varying from 0° to 360° can be obtained and linear fitting is used again to find the parameters β_0 and δ accurately. We use the linearly polarized weak light and mount the retarder in the system as shown in Fig.2. Thirty groups of data taken under the same conditions are acquired as in step A. One group of data is given in Fig.4 to show the relation between the counting rate of pulses and the initial fast axis angle of the retarder β when it

is first mounted in the system. α can be set to 0° and 90° to minimize the experimental error.[12] We averaged all groups of data statistically and obtained the results β_0=23.25°±0.06° and δ=88.13°±0.34° in Eq.(8). Finally, we rotated the retarder by an angle β_0 to align its fast axis to the z-axis exactly. δ can be used as a constant parameter in future experiments.

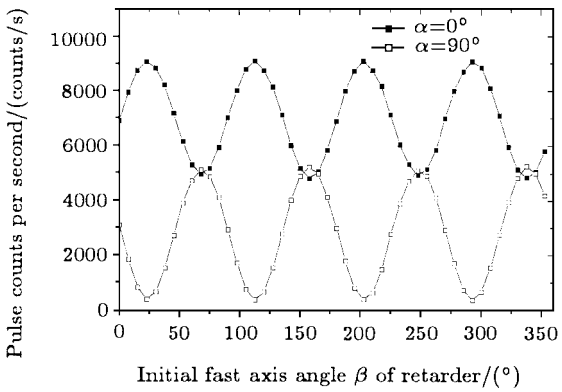


Fig.4. Pulse counts per second as a function of the initial fast axis angle β of the retarder when it is first mounted in the system. The experimental data of α=0° and α=90° are plotted side by side.

4.3. Measurement of the relative Stokes parameters and the polarization of electrons beam

Having determined the accurate angles α and β and the phase difference δ, we can change the incident electron beam to a polarized one to determine the relative Stoke parameters of the radiation using the linear fitting method (here linearly polarized weak light can be applied). Finally the polarization of the incident electron beam can be obtained from Eq.(1).

In the experiment, thirty groups of experimental data are collected again for good statistics. For each group of data the angle β was changed from 0° to 360° with the step size of 7.5°, while the angles α of 0°, 30°, 60° and 90° were selected, as shown in Fig.5. All thirty groups of data are averaged to get the relative Stokes parameters of linearly polarized weak light: P_1=0.920±0.010, P_2=–0.020±0.016 and P_3=–0.012±0.010. Comparing these results with the theoretical values P_1=1, P_2=P_3=0, we conclude that P_2 and P_3 are in fairly good agreement with the theoretical expectation, while P_1 has a small deviation. This can be due to the fact that weak light may not be strictly linearly polarized. In other words, when the transmission axis of the polarizer is orthogonal with the polarization direction of the weak light, there may still be pulse counts. Certainly we can use these data to make corrections to obtain good experimental results.

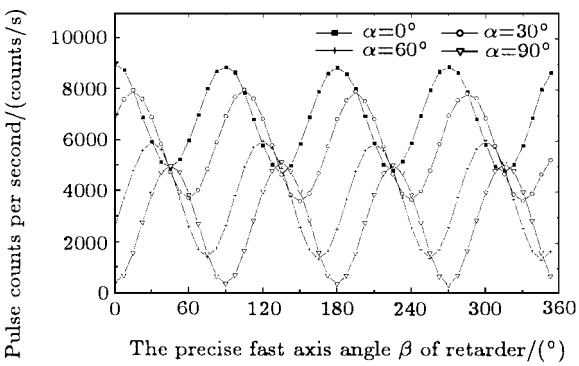


Fig.5. Pulse counts per second as a function of the fast axis angle β of the retarder. The experimental data at α=0°, α=30°, α=60° and α=90° are plotted side by side.

5. Conclusion

We have developed the complete system of the optical electron polarimeter, including the four parts of the instrument described above and the program for the data acquisition and control. As an offline test, linearly polarized weak light has been used to simulate the radiation emitted from the excited He atom to measure its relative Stokes parameters. The experimental method here is similar to that with the electron beam. The polarization axis of the weak light is aligned to the direction of the incident electron beam. We obtained the results α_0=–1.50°±0.09°, β_0=23.25°±0.06° and δ=88.13°±0.34° in steps A and B described above. In step C, we found that the relative Stokes parameters, P_1=0.920±0.010, P_2=–0.020±0.016 and P_3=–0.012±0.010, are in agreement with the theoretical expectation within the experimental error. The match between the software and the instrument was also faultless.

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