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Passive magnetic shielded spin polarized electron source with optical electron polarimeter*

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A new GaAs(100) spin polarized electron source with an optical polarimeter, which is employed in the field of polarized electron and gas atom collision, is presented in detail. The apparatus is passive-magnetic-shielded by a box and a cylinder made of nickel–iron–molybdenum soft magnetic alloy without Helmholtz coil arrangement. And a uniformly distributed residual magnetic field of less than 5×10^{-7} T is obtained near the collision area. The spin polarized electron beam is transmitted and focused onto collision point from photocathode by a set of electron optics with more than 25% transmission 95 cm distance through an 1 mm diameter aperture. Construction and operation of the apparatus, such as vacuum and magnetic shielding system, photocathode, laser optics, electron optics and polarimeter are discussed. The polarization of the spin polarized electron beam is determined to be $30.8 \pm 3.5\%$ measured with a He optical polarimeter.

Keywords: spin polarized electron source, optical electron polarimeter, polarization

PACC: 0760F, 2925B, 2975

1. Introduction

In the last years of the 1970s, at the ETH-Zurich, the first spin polarized electron source based on photoemission from p-type GaAs with liquid nitrogen cooling was proposed, constructed and operated, and the source was used for polarized low-energy electron diffraction (PLEED) measurement of surfaces.[1,2] Subsequently, spin polarized electron beams, produced from such sources, have been used widely in many research fields, such as solid state physics, atomic and molecular physics, surface physics, and high energy physics.[3] In electron–atom collision, more information about spin-dependent effects and interactions can be obtained in detail using spin polarized electrons in stead of unpolarized electrons.[4−6]

In this article a new passive-magnetic-shielded and compact-designed spin polarized electron source with polarimeter is described, which is used for the measurement of Stokes parameters of emission photon after polarized electron and gas atom collision. The polarization direction of polarized electrons produced from photocathode can be modulated easily through controlling the voltage of the liquid crystal variable retarder (LCVR) by a personal computer, instead of the normal quarter wave plate. A set of electron optics is employed to transport and focus the electron beam onto the collision point, which is the intersection of the incident electron beam, effusive target gas beam and the photon detection direction. The optical electron polarimeter constructed based on He radiation $3^3P \rightarrow 2^3S_1$ (388.9 nm) is developed to determine the polarization of the incident spin polarized electron beam. This optical electron polarimeter can also be used as an integrated Stokes parameter P_i ($i = 1, 2, 3$) analyser by selecting an appropriate filter for a certain transition. In the present work, we do not intend to detect the scattered electrons.

2. Vacuum and magnetic shielding system

The schematic diagram of the apparatus including the vacuum and magnetic shielding systems is shown in Fig.1. Generally, an ultrahigh vacuum (UHV), in the low 10^{-8} Pa range, is required for cleaning, activating, and maintaining the GaAs photocathode.[2] On the other hand, the pressure in the collision cham-

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ber is in the high 10^{-4} Pa range as the target gas is admitted into the system. So a differential pumping chamber is needed to maintain the difference of the pressure between the source chamber and collision chamber. In the spin-polarized electrons and gas atoms collision experiment, the spin polarized electron source chamber, the differential pumping chamber and the collision chamber are aligned and connected by welded bellows. The chambers are fabricated from 304 or 316 L nonmagnetic stainless steel. All the inner and outer elements of the chambers employ nonmagnetic materials. Furthermore, standard UHV and nonmagnetic materials are employed for the elements inside the chambers. The spin polarized electron source is pumped by the combination of a sputtering ion pump and a titanium sublimation pump, which is preliminarily backed by the differential pumping chamber through a formed bellows, and shut off by a vacuum valve after baking the chamber, as shown in Fig.1. The differential pumping chamber is pumped by a turbo-molecular pump and a direct high-speed rotary vacuum pump. Three molybdenum apertures are used to obtain a good capability of differential pumping. Aperture 3 with 1 mm in diameter and aperture 2 with 2 mm in diameter and aperture 1 with 2 mm in diameter are used to restrict gas flow from the collision chamber and differential pump chamber to the source chamber, as shown in Figs.1 and 5. The collision chamber is pumped by a turbo-molecular pump and a direct high-speed rotary vacuum pump.

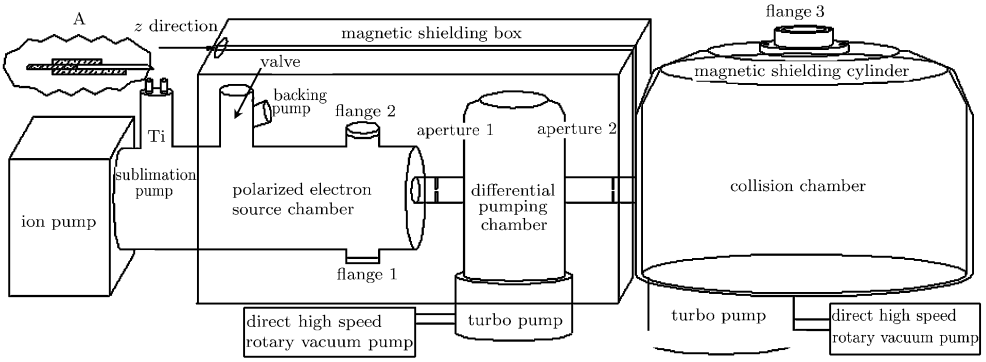


Fig.1. Schematic diagram of the vacuum and magnetic shielding systems of the apparatus. The vacuum system is comprised of spin-polarized electron source chamber, differential pumping chamber and collision chamber. The magnetic-shielding system is comprised of a box shielding the source chamber and differential pumping chamber, and a cylinder shielding the collision chamber.

All the vacuum system is backed by two sets of combinations of a turbo-molecular pump and a direct high-speed rotary vacuum pump. After backing up to a certain vacuum, the sputtering ion pump starts to work. The source chamber with sputtering ion pump and the differential pumping chamber with turbo-molecular pump are baked uniformly at 180 °C for four days. Furthermore, the system continues to be baked for one more day after shutting off the vacuum valve. Finally, the pressures in the three chambers, 4×10^{-8}, 6×10^{-7}, and 1×10^{-5} Pa, are obtained respectively after the chambers are cooled to room temperature. Each time the titanium sublimation pump is operated only before heating treatment of the GaAs crystal to prevent it from contamination.

Ideally the electron beam is transported and focused onto the collision point by an electron optic system, and its spin vector is maintained transverse to the momentum vector after the 90° deflector. Actually the momentum vector will be deflected and the spin vector will be rotated by the magnetic field for 95 cm transmission distance and low velocity near the crystal. In order to reduce the effect of the magnetic field, the normal treatment is to arrange Helmholtz coils around the apparatus.[7] In this paper, two steps are carried out instead of using Helmholtz coils. Firstly, the apparatus is aligned in the south–north direction which is parallel to the direction of geomagnetic field. Secondly, the source chamber and differential pumping chamber are covered by a magnetic shielding box, and the collision chamber is covered by a magnetic shielding cylinder. The magnetic shielding box is made of 1J85 nickel–iron–molybdenum (80% Ni, 5% Mo, and 15% Fe) soft magnetic alloy strip. The box has two parts which are overlapped with each other at the edges as shown by A in Fig.1, viewing from the z di-

rection. A technical schedule of the heat treatment of magnetic shielding box in vacuum is shown in Fig.2. The temperature is increased step by step, and maintained for four hours at 1200 °C while the pressure is kept at 1×10^{-3} Pa, after decreasing to 300 °C in the controlling system, a natural cooling to room temperature is followed. The intensity of the magnetic field, which is measured with a magnetometer, is uniformly lowered to 1×10^{-6} T in the box, and as low as 5×10^{-7} T in the cylinder. Uniformity of the residual magnetic field is the most important advantage of using passive-magnetic-shielding box as compared with that using Helmholtz coils.

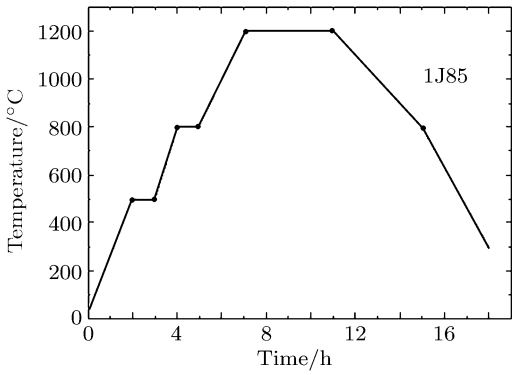


Fig.2. Technical schedule of heat treatment of the magnetic-shielding system made of 1J85 nickel–iron–molybdenum soft magnetic alloy strip.

3. GaAs spin polarized electron source

The general theoretical and experimental considerations of a GaAs spin polarized electron source are given by Pierce in detail.[2] Spin-polarized electrons are obtained by means of photoemission from GaAs crystal excited by the circularly polarized light with photon energy slightly higher than the band gap of GaAs.

3.1. The GaAs photocathode with activation treatment

In our spin-polarized electron source, a p-type GaAs(100) crystal with a dimension of 4×4 mm is employed as the photocathode. The rectangular piece is cut from a GaAs wafer with a thickness of 0.6 mm, which is doped with Zn to a carrier concentration of 2.4×10^{18} cm^{-3}. The assembly of the GaAs photocathode with activation treatment equipment is shown in Fig.3. The GaAs crystal is placed in a Mo heater block and clamped by means of a Mo disc attached to the block by screws. In the experiment, in order to obtain a superclean surface in UHV, the crystal is first heated up to ∼400 °C for several hours by a tungsten filament that is placed closely under the heater block and in the centre of the ceramic holder of the heater block. Then the crystal is heated up to 610 °C for 2 hours by means of electron bombardment, that is, the thermal electrons emitted from the tungsten filament are accelerated to bombard the heater block by setting a high voltage of +800 V to the heater block. In this course, the temperature is monitored by a thermocouple touching the side of the crystal through a groove in the heater block, and is shown by a digital meter. An infrared thermometer is also used to check the temperature. Before installing the GaAs crystal in the source, it is chemically cleaned by the following procedure: (a) ammonia solution for 2 minutes; (b)deionized water for half minute twice; (c) anhydrous methanol for half minute three times; (d) dried by nitrogen gas.

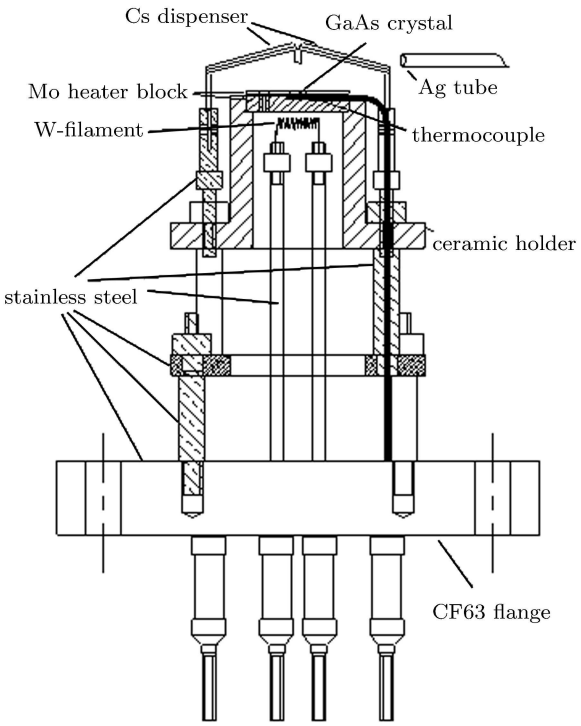


Fig.3. The mechanism of GaAs photocathode with activation treatment equipment including GaAs crystal, ceramic holder, Mo heater block, W filament, thermocouple, Cs dispensers, Ag tube, and CF63 flange.

After heat treatment, the crystal is left to cool down naturally. Once the crystal is cooled down to ≤55 °C, the activation procedure can be carried out.

The surface of GaAs crystal is then activated with alternating layers of caesium and oxygen to obtain a negative electron affinity (NEA) surface.[8,9] Then the spin polarized electron beam is emitted from the crystal excited by circularly polarized laser light. During the activation, the 820 nm laser is used to irradiate the crystal directly without a lamp firstly. The photocurrent from the NEA crystal is typically between 2 and 10 μA with the laser power at 2 mW. This corresponds to a quantum efficiency (QE) of 0.15%–0.76%. The lifetime of our photocathode is more than 250 hours. Two Cs dispensers are screwed in three rod clamps that are screwed on the ceramic holder. The ceramic holder is fixed on a 316 L nonmagnetic stainless steel flange which is mounted on the source chamber with flange 1 (Fig.1), and a 316 L nonmagnetic stainless steel hollow disc is placed between the ceramic holder and the flange via two sets of three-rods to adjust the height of the photocathode. The Cs dispensers are located at a distance of ∼16 mm with the slits facing to the GaAs surface, and the distance can be adjusted. When a current is passed through the dispenser, caesium will be emitted through the slit into the source chamber and deposited onto the GaAs surface. Caesium vapour can be controlled easily by the Cs dispenser current to provide a stable electron emission, depending on the rate of deposition required. High purity oxygen is leaked into the electron source chamber by permeation through a heated thin walled silver tube attached to a flange. The oxygen gas flux can be controlled by the temperature of silver tube, and the purity of oxygen admitted through the silver tube is ∼99.99%.[7]

3.2. Laser optics with LCVR

The laser optics of the spin polarized electron source is shown in Fig.4, which is composed of laser diode, linear polarizer, and LCVR. Approximately linear polarized 820 nm light from a laser diode becomes linearly polarized light after transmitting through the linear polarizer. The circularly polarized light is obtained using LCVR,[10] and focused through a quartz vacuum window which is mounted on flange 2 (see Fig.1) onto the surface of GaAs crystal to photon-emit spin polarized electrons. The LCVR used here can play the roles of quarter-, half-, three-quarter- or whole-wave plates for 820 nm light with special voltages by calibration, setting its fast axis oriented at 45° to the polarizer. In order to calibrate the LCVR and determine the incident photon polarization, a spinning polarimeter is developed. As shown in Fig.4, the intensity of incident polarized light travelling through a spinning polarizer driven by a stepping motor is detected by silicon photocathode and transferred to voltage signal that is monitored by an oscillograph. Changing the voltage of LCVR, circularly polarized light is obtained when the peak–peak value reaches a minimum, and a linear polarized light is obtained when the peak–peak value reaches a maximum.[11] By calibration, ac rms voltages of 3.120, 2.240, 1.830 and 1.535 V correspond to $\lambda/4$, $\lambda/2$, $3\lambda/4$ and 1λ, respectively. The polarization direction of spin-polarized electrons can be modulated easily by switching the helicity of incident circularly polarized light which is changed by the supplied voltage of LCVR.

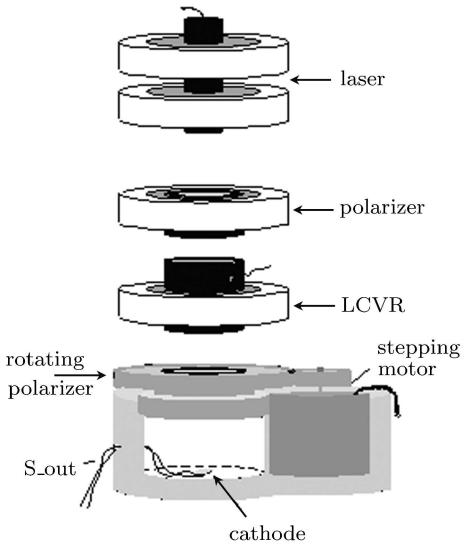


Fig.4. Optical system of the spin-polarized electron source with rotating optical polarimeter. The optical system is comprised of laser diode, linear polarizer, and LCVR. The rotating optical polarimeter is comprised of rotating polarizer, stepping motor, and silicon photocathode.

4. Beam transport and electron optics

The longitudinally spin-polarized electrons emit from the GaAs crystal by irradiation of circularly polarized light. The emitted electrons are accelerated and focused, by three apertures, to the entrance of a 90° electrostatic deflector that is employed together with compensators to rotate the electron moving direction, but the spin direction of the electrons keeps unchanged. Then the electrons are transported and focused, by a set of electron transport lenses, onto the collision point to interact with the helium atom target.

Figure 5 shows the scale diagram of the electron optics system. It is comprised of photocathode, three focusing apertures, 90° deflector with compensator, transport and focusing lenses, two X–Y deflectors, three Mo apertures, and double Faraday cup.

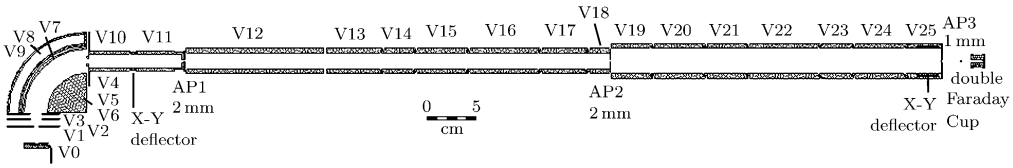


Fig.5. Scale diagram of the electron optics system comprising photocathode V_0, three-focusing apertures V_1–V_3, 90° deflector with compensator V_4–V_9, transport and focusing lenses V_{10}–V_{25}, two X–Y deflectors, three Mo apertures, and a double Faraday cup. The 90° deflector is comprised of inner element V_4, side plates V_5 and V_6, outer element V_8, side compensator V_7, and outer compensator V_9. The electron travelling length is 95 cm.

First of the three-focusing apertures with 6 mm diameter is at a distance of 10 mm to the cathode. A narrow section cut out of a half-hemispherical structure is used as the 90° deflector. To reduce the edge effects between inner and outer elements of the 90° deflector, side plates and side compensators are added on both sides, and the outer compensator is added outside the outer element. The X–Y deflector is employed to shift the moment vector in x or y direction. First Mo aperture with 2 mm diameter is placed between the source chamber and differential pumping chamber, the second one with 2 mm diameter is placed between the differential pumping chamber and collision chamber, and the third one with 1 mm diameter is placed at the exit of the electron beam on the collision chamber. The three Mo apertures are employed here to maintain the pressure of the source chamber and collimate the electron beam. A gap of 4 mm is made between lens V_{12} and lens V_{13} for pumping. The current intensity of the electron beam arriving at the collision point is monitored by the double Faraday cup which is placed close to the collision point. In the present experiment, the potentials of elements V_1–V_{25} are "floated" on the potential of cathode V_0, the potentials of X–Y deflector 1 are "floated" on the potential of lens V_{10}, and the potentials of X–Y deflector 2 are "floated" on the potential of lens V_{25}. The energy of incident electron is determined and scanned by the potential of photocathode. The potentials of elements $V_0 - V_{25}$ are shown in Table 1, with 30 eV energy of incident electron. And the transmission ratio from the photocathode to the double Faraday cup is higher than 25% along a distance of 95 cm.

Table 1. Potentials of the elements (V_0–V_{25}) of electron optics system (in voltage). The electron optics system is shown in Fig.5.

V_0	V_1	V_2	$V_{3,10}$	V_4	V_5	V_6	V_7	V_8	V_9
−30.0	93.0	−30.0	77.8	170.1	108.0	122.3	108.8	48.4	−21.3
V_{11}	$V_{12,13,14}$	V_{15}	V_{16}	V_{17}	V_{18}	$V_{19,20}$	$V_{21,22}$	$V_{23,24}$	V_{25}
292.6	967.6	383.4	555.9	164.3	554.0	265.9	1.0	81.7	0

5. Electron polarization measurement by using optical polarimeter

In order to perform the experiments in the field of spin-polarized electron–atom collision, the polarization of incident electron beam must be precisely measured. The Mott scattering is a standard technique for electron polarimetry, but its systematic uncertainties are rather large.[12] An alternative method is to measure the circular polarization of the impact radiation produced by spin-polarized electrons colliding with atoms.[13]

In this work, the electron polarization is measured by helium optical electron polarimeter based on the He $3^3P \rightarrow 2^3S_1$ (388.9 nm) transition, which was first proposed by Gay.[14] The spin-polarized electron beam, emitting from the GaAs photocathode by irradiation of circularly polarized photons, is transported and focused onto the collision point by means of electron optics. Then its polarization is determined by helium optical electron polarimeter composed of helium gas jet, focusing lens, quartz vacuum window which

is mounted on the flange 3 (see Fig.1), retarder, polarizer, refocusing lens, interference filter, and photomultiplier tube, as shown in Fig.6. The helium target atoms from a gas jet are excited by the incident electrons collision. The radiations, treated as a point source, become 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 refocusing lens. Here an interference filter with narrow-band is placed before the photocathode of PMT to select 388.9 nm radiations from excited helium atoms. Each optical element above the vacuum chamber is placed in a light-shielding holder. And the holders for retarder and polarizer can be rotated easily for different angles, separately. The Stokes parameters P_i ($i = 1, 2, 3$) is determined by the intensities and polarizations of the radiation after a series of measurements.[15]

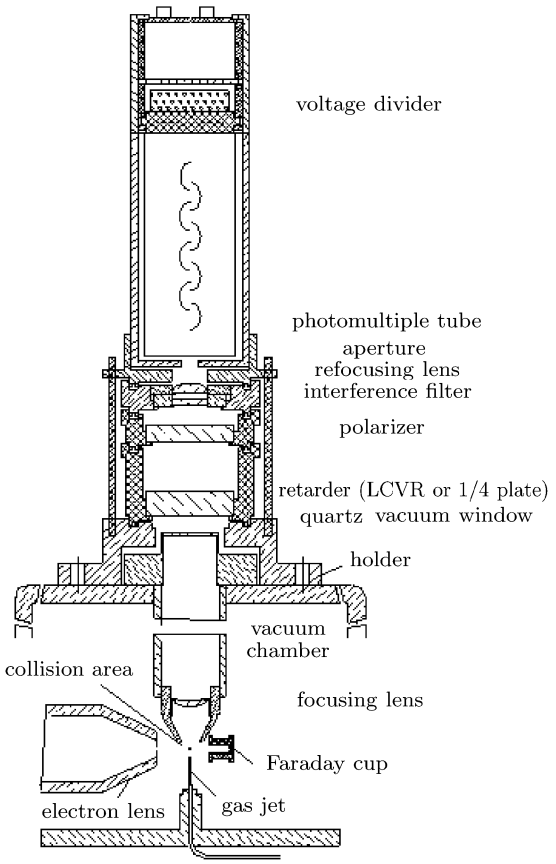


Fig.6. Diagram of the helium optical electron polarimeter comprising helium gas jet, focusing lens, quartz vacuum window, retarder, polarizer, refocusing lens, interference filter and photomultiplier.

According to the relation between incident electron polarization P_e and Stokes parameters,[14] $P_e = 6P_3/(3 - P_1)$, the electron polarization is determined by Stokes parameters P_1 and P_3. In such a relation, the Stokes parameter P_3, which is related closely to the electron spin polarization, is the main contribution to P_e. The measured P_3 approximates a constant value $P_3 = 14.8\% \pm 1.7\%$ in the incident energy region free from cascade effects, as shown in Fig.7. The polarization of electrons produced from our GaAs(100) spin polarized electron source is determined to be $30.8\% \pm 3.5\%$.[15]

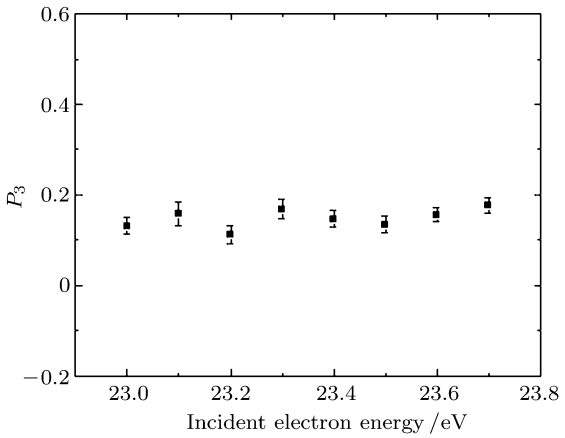


Fig.7. The integrated Stokes parameter P_3 for the He $3^3P \rightarrow 2^3S_1$ (388.9 nm) radiation versus incident electron energy from 23.0 to 23.7 eV.

6. Summary

In this work, we have set up a new GaAs(100) spin polarized electron source with an optical polarimeter. A pressure, 4×10^{-8} Pa, is obtained in the source chamber with the vacuum system. A uniformly distributed residual magnetic field, less than 5×10^{-7} T, is obtained in the collision chamber which is passive-shielded by a cylinder made of nickel–iron–molybdenum soft magnetic alloy without using Helmholtz coil. A transmission ratio, higher than 25%, is obtained with the electron optics system. And the polarization of electrons produced from our source is determined to be $30.8\% \pm 3.5\%$ with our He optical polarimeter.[15] In the future work, the apparatus will be more employed in the research field of polarized electron and gas atom collision to investigate the spin-dependent effects and interactions.

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