An investigation of high fractions of metastable helium atoms

X. P. Feng (冯贤平)[1] and B. W. James[2]

[1]Physics Department, East China University, Shanghai 200051

[2]School of Physics, The University of Sydney, NSW 2006, Australia

Received November 18, 2002

Penning type discharge was adopted to excite helium atoms. It is suitable for generating high density metastables at a range from 0.1 mTorr to 0.5 Torr. The highest metastable density of 3.5×10^{10} cm^{-3} was observed at a static gas pressure of 0.5 Torr. The highest fraction of metastables ($N^1_{2\text{S}}/N_{\text{He}}$) of 10^{-3} in a low gas pressure was obtained. The variation of the magnetic field strength on the discharge does not result in a significant density change of the metastable helium atoms. When no magnetic field was applied, no discharge took place.

OCIS codes: 020.0020, 020.2070, 020.6580.

An ideal technique for the measurement of the electric fields inside plasma is the laser induced fluorescence (LIF) on a pulsed, supersonic He metastable beam[1,2]. This technique is closely related to the density of the metastable He beam and a tunable dye laser used for exciting the forbidden transitions from the metastable helium atoms[3,4]. Preliminary study indicates that a metastable density of 1×10^{10} cm^{-3} is needed in order to detect the electric field. Using a cylindrical hollow cathode discharge[5] with a supplied gas density of 1×10^{10} cm^{-3}, we have produced a supersonic beam with high-density 2^1S atoms of -10^{10} cm^{-3} but with a low fraction (10^{-6}) of metastables. A problem is that a high-pressure gas beam might have a great influence on the plasma operated with a low gas pressure. In order to obtain higher fractions of the metastables in a low density of He beam, a penning discharge (PD) is used since it is able to operate at very low gas pressures. In 1994, Heise reported his study of radiometric characterization of a PD in the vacuum ultraviolet at low gas pressure condition[6]. In 2001, we studied the spectral emissions of the plasma from a PD source[5].

In this letter we report the study on a high density metastable helium atoms produced using a PD. The purpose of this work is to develop the low-pressure supersonic helium beam with a very high density of 2^1S atoms for the electric field measurements in the plasmas operating under a low gas pressure.

A PD is supported by a magnetic field that is parallel to the electric field of the cathode falls. The two cathodes face each other, and emitted electrons oscillated between the cathodes fall through the center anode ring. Because of the field of the permanent magnets located behind the cathodes, the electrons are confined to their radial starting position. Radial diffusion is induced by collision.

The structure of PD is shown in Fig. 1. A pair of parallel disk-cathodes with a gap of 26 mm is set with surfaces perpendicular to the axis (y) of the discharge. To apply magnetic field in the y-direction between the gap we place permanent magnet disks behind the cathodes. Magnetic field is about 0.08 T at the origin. The cathode and anode bodies are made of stainless steel. A PD source designed and fabricated in our laboratory is mainly based on the work of Heise[5,6]. The length of the discharge region is 38 mm along z-axis. Along x-axis the anode has a hole with a big cross section of 10×36 mm^2 so that we have a good diagnostic access to the plasma source. Two holes with $\phi12$ mm aligned on the z-axis in the anode are inlet and outlet for the helium beam or absorption measurement. The anode has another rectangular hole along the y-axis with cross section 20×38 mm^2 and a length of 18 mm. Discharge plasma is produced in this hole. Emission and LIF spectra from the plasma can be observed through two holes on the x-axis. The density of metastable atoms is detected using atomic absorption spectroscopy based on a monochromator together with a lock-in amplifier, and plasma emission spectra are recorded using a multi-channel spectrograph.

The PD can operate at very low helium gas pressures. A possible reason is that during discharge, electrons are trapped by the magnetic field and are reflected between the two cathodes through the anode many times, causing multiple collisions with neutral

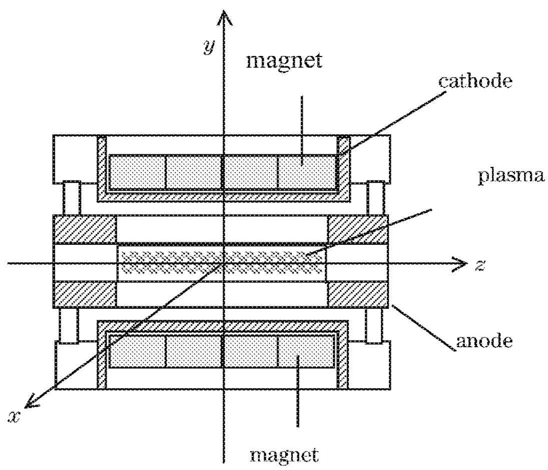

Fig. 1. Structure of PD to excite the He beam. Cathode: 36×56 mm^2; anode: $54 \times 18 \times 74$ mm^3; hole along x-axis: 10×36 mm^2; along y-axis: 20×38 mm^2 and along z−axis: $\phi12$ mm. Magnetic field at the origin: $B = 0.08$ G.

atoms to create metastable atoms with high density. The percentages of the spectral absorption for a wavelength of 501.6 nm (line of $3p-2s$ emission) have been detected at the different discharge currents and the static gas pressures. For example, at a discharge current of $\sim$ 190 mA, the absorption percentages of 20.2%, 16.3% and 13.5% are observed for 10, 100, and 500 mTorr gas discharges, respectively. The relationship between the spectral absorption and the metastable density is obtained based on a simple quantum mechanic formula[7−9]. Considering the length of the plasma source of 38 mm and assuming a uniform plasma source, the fractions of metastables as a function of discharge current for the static gas pressures of 10, 100, and 500 mTorr are shown in Fig. 2.

The fraction of the metastable helium atoms decreases with the increase of the static helium gas pressure but it does increase with discharge current. It should be mentioned that for the variation of the magnetic field strength from 0.07 to 0.11 T, no obvious density variations of the metastable helium atoms were observed. When no magnetic field was applied, no discharge took place. Therefore, in the following experiments, we place a fixed strength magnet (0.08 T) in the back of the cathodes.

In Fig. 3(a) variations of the fractions of metastables ($N^1_{2S}/N_{\rm He}$) are plotted as a function of the static gas pressure for different discharge currents. The highest fraction of metastables ($N^1_{2S}/N_{\rm He}$) about 10^{-3} in 0.5 mTorr static pressure is observed. After then, the fractions of metastables exponentially decrease with the increase of the gas pressure between 0.1 to 100 mTorr. The density of the metastable atoms is almost independent of the pressure up to 100 mTorr. With further increasing static helium gas pressure, the fraction of metastables is approximately unchanged as shown in Fig. 3(b). Correspondingly, the density of the metastable atoms nearly linearly increases with the increase of the static gas pressure and discharge current. The highest density of metastable helium atoms is 3.5×10^{10} cm^{-3} for discharge current of 190 mA and 1.47×10^{10} cm^{-3} for 30 mA discharge at the static gas pressure of 500 mTorr. The metastable densities obtained are high enough to be used in LIF for an electric field measurement at the edge of a plasma source. Even if a static gas pressure remains at 0.5 mTorr for plasma discharge, we still achieve a metastable density up to 0.8×10^{10} cm^{-3}. This is a big difference from the hollow cathode case.

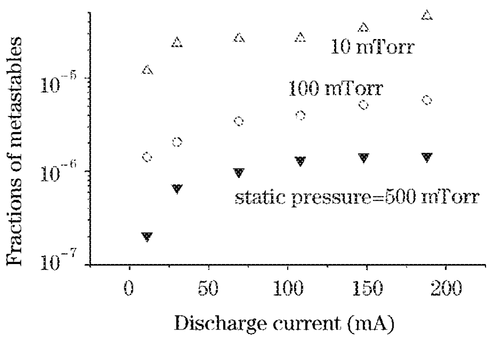

Fig. 2. The fractions of metastable ($N^1_{2S}/N_{\rm He}$) versus the discharge current for different static gas pressures.

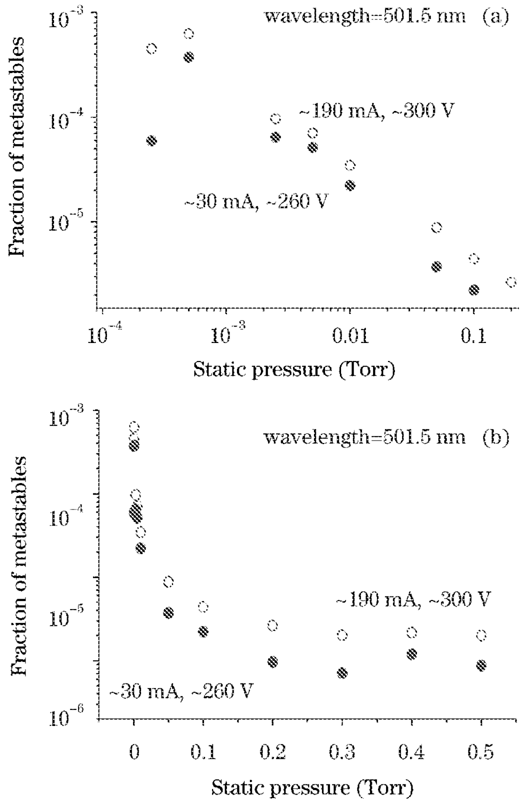

Fig. 3. The fractions of metastable ($N^1_{2S}/N_{\rm He}$) versus the static gas pressure for different discharge currents.

An increase of metastable density is obtained from plasma discharge at static gas pressures from 100 to 500 mTorr, probably indicating that a higher density of metastable helium atoms can be obtained at a higher gas pressure. However, we are not able to verify it because discharge occurs between the penning anode and the vessel. Further experiments are needed for examining above predication.

The LIF technique mainly uses the forbidden transition-excitation of the 2^1S-n^1D by a laser and the Stark mixing between the n^1P and n^1D levels to measure the electric field[9]. The technique is dependant on whether or not enough metastable atoms can be produced in the pulsed beam, and it has been quoted that $n2^1S>1\times10^{10}$ cm^{-3} for the technique to be effective[5,6]. However, the pulsed neutral helium beam needs to have a lower density so as not to disturb the main plasma being studied.

The experimental data have demonstrated that PD would produce high fractions of the metastables in a low density of He beams. For example, remaining static helium gas pressures at 1, 10, and 100 mTorr (densities: 3.22×10^{13}, 3.22×10^{14}, and 3.22×10^{15} cm^{-3}), the metastable densities obtained are $0.6\times10^{10}, 1.3\times10^{10}$, and 1.8×10^{10} cm^{-3}, respectively. Correspondingly, the fractions of metastables ($N^1_{2S}/N_{\rm He}$) are $2\times10^{-4}, 4\times10^{-5}$ and 5.4×10^{-6}.

We have found that the glow discharge occurrence between the anode and the vessel for several-hundred mTorr of helium gas pressure discharge. These gas pressures may be too high for generating plasma by the PD. Under such high-pressure condition, hollow cathode glow discharge takes place rather than the PD because DC voltage glow discharge condition (gas pressure times gap distance between anode and cathode is nearly 1) is satisfied. Evidence is that the metastable atom density is approximately proportional to the He gas density in the range from 0.2 to 0.5 Torr gas pressure. The fraction of metastables is about 2×10^{-6} cm^{-3}. This is a typical value for the DC glow discharge plasma whose temperature is 2 eV, at most case which is very close to the value of 2.2 eV we obtained from diagnosing plasma. As a comparison, the fractions of metastables decrease with increasing gas density, as shown in Fig. 3(a), means that a flat dependence of metastable density between 2.5 mTorr and 0.1 Torr. The peak fraction is observed to be at the gas pressure of 0.5 mTorr, which is a characteristic feature in the PD (the PD operates at a typical pressure of about 0.1 mTorr[6]). The highest fraction of metastables is up to 10^{-3} which is much higher than that by the hollow cathode.

From the relationship between the fractions and the metastable density, we can conclude that the metastable density almost linearly increases with the discharge current. This is an indication that a higher density of metastable atoms can be created if we increase discharge current or choose a smaller ballast resistor in circuit under relatively low voltage. Currently, we are not able to verify above expectation because of the limitation of power supply.

Magnetic field plays a very important role in producing high-density metastable atoms in PD. Because of the field of the permanent magnets located behind the cathodes, the electrons are confined to their radial starting position, and are reflected between the two cathodes through the anode many times, causing multiple collisions with neutral atoms to create metastables. This allows the PD to operate at lower pressures than the hollow cathode. An interesting fact is that variation of the magnetic field strength in the discharge does not result in a significant change of the density of the metastable atoms. A probable reason is that the size of the plasma source is much larger than Lamour radius under above magnetic field strength. The magnets always remain on the PD during the plasma discharge. When no magnetic field was applied, no discharge took place.

Finally, it should be mentioned that appearance of some slightly unstable plasma source has been observed which results in an approximate 10% relative error in measurement of metastable density. We also have approximate 10% error in data processing.

Penning type discharge was adopted to generate high fractions of metastables in a low density He beam. Metastable density producted by PD increase with an increase of helium gas pressure at ranges of 0.1 – 500 mTorr, but the highest fraction of metastables of 10^{-3} is obtained in a low density He beam. The result indicates that a higher density of metastable helium atoms can be achieved if a higher discharge current is used. Magnetic field plays a very important role in producing plasma discharge. When no magnetic field was applied, no discharge took place. However, variation of the magnetic field strength during the discharge does not result in a significant change of the density of metastable helium atoms.

We thank Prof. K. Takiyama of Hiroshima University for many help and useful suggestions. Parts of this work have been supported by Sydney University, Dong Hua University and the Shanghai Science and Technological Research Council (contract No. 0252nm110). X. P. Feng's e-mail address is xpfeng@dhu.edu.cn.

References

1. B. W. James, D. Andruczyk, X. P. Feng, J. Howard, K. Takiyama, and T. Oda, in *Proceedings of Laser Aided Plasma Diagnostics Conference* (2001).
2. J. Amorim, G. Baravian, and J. Jolly, J. Phys. D: Appl. Phys. **33,** R51 (2000).
3. J. Harris and the H-1 team, J. Plasma Fusion Res. **1,** 37 (1998).
4. T. Katsuta, K. Takiyama, T. Oda, K. Mizuno, and T. Ogawa, Fusion Engineering and Design, **34-35,** 769 (1997).
5. X. P. Feng, D. Andrutzyk, B. W. James, and K. Takiyama, in *Proceedings of The Second International Workshop on Plasma Processing* (2002).
6. C. Haise, J. Hollandt, R. Kling, M. Koch, and M. Kühne, Appl. Opt. **33,** 5111 (1994).
7. M. Otsuka, R. Ikee, and K. Ishii, J. Quant. Spectrosc. Radiat. Transfer. **21,** 699 (1989).
8. S. Sasaki, NIFS Data 49 (National Institute for Fusion Science, Nagoya, Japan).
9. M. Goto and T. Fujimoto, NIFS Data 43 (National Institite for Fusion Science, Nagoya, Japan).