An investigation of high fractions of metastable helium atoms

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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 \(3.5 \times 10^{10}\) cm\(^{-3}\) was observed at a static gas pressure of 0.5 Torr. The highest fraction of metastables \((N_{2s}/N_{He})\) 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.

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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 \(1 \times 10^{10}\) cm\(^{-3}\) is needed in order to detect the electric field. Using a cylindrical hollow cathode discharge\(^{[5]}\) with a supplied gas density of \(1 \times 10^{10}\) 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 \(z\)-axis the anode has a hole with a big cross section of \(10\times36\) mm\(^2\) so that we have a good diagnostic access to the plasma source. Two holes with \(\phi 12\) 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 \(20\times38\) 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 \(z\)-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 gas.

![Fig. 1. Structure of PD to excite the He beam. Cathode: 36 \times 36 \text{ mm}^2; anode: 54 \times 18 \times 74 \text{ mm}^3; hole along \(z\)-axis: 10 \times 36 \text{ mm}^2; along \(y\)-axis: 20 \times 38 \text{ mm}^2 and along \(z\)-axis: \(\phi 12\) mm. Magnetic field at the origin: \(B = 0.08\) G.](http://www.col.org.cn)
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 ~ 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[6-9]. 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 \( N_{2S}/N_{He} \) are plotted as a function of the static gas pressure for different discharge currents. The highest fraction of metastables \( N_{2S}/N_{He} \) 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 \( 3.5 \times 10^{10} \text{ cm}^{-3} \) for discharge current of 190 mA and \( 1.47 \times 10^{10} \text{ cm}^{-3} \) 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 \( 0.8 \times 10^{10} \text{ cm}^{-3} \). This is a big difference from the hollow cathode case.

![Fig. 2. The fractions of metastable \( N_{2S}/N_{He} \) versus the discharge current for different static gas pressures.](image)

![Fig. 3. The fractions of metastable \( N_{2S}/N_{He} \) versus the static gas pressure for different discharge currents.](image)

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 \( 2S - n^1D \) 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 \( n^1S > 1 \times 10^{10} \text{ cm}^{-3} \) for the technique to be effective[9]. 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: \( 3.22 \times 10^{13}, 3.22 \times 10^{14}, \text{and } 3.22 \times 10^{15} \text{ cm}^{-3} \)), the metastable densities obtained are \( 0.6 \times 10^{10}, 1.3 \times 10^{10}, \text{and } 1.8 \times 10^{10} \text{ cm}^{-3} \), respectively. Correspondingly, the fractions of metastables \( N_{2S}/N_{He} \) are \( 2 \times 10^{-4}, 4 \times 10^{-5} \) and \( 5.4 \times 10^{-6} \).

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 satis-
filled. 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 $2 \times 10^{-6}$ cm$^{-3}$. This is a typi-
cal value for the DC glow discharge plasma whose tem-
perature 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 characteris-
tic feature in the PD (the PD operates at a typical pressure
of about 0.1 mTorr$^6$). The highest fraction of meta-
stables 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 cur-
rent. This is an indication that a higher density of meta-
stable atoms can be created if we increase discharge
current or choose a smaller ballast resistor in circuit un-
der 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 produc-
ing high-density metastable atoms in PD. Because of the
field of the permanent magnets located behind the cath-
odes, the electrons are confined to their radial starting
position, and are reflected between the two cathodes
through the anode many times, causing multiple colli-
sions with neutral atoms to create metastables. This all-
ows the PD to operate at lower pressures than the hollow
cathode. An interesting fact is that variation of the mag-
netic 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 ap-
proximate 10% error in data processing.

Penning type discharge was adopted to generate high
fractions of metastables in a low density He beam. Meta-
stable density produced 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 dis-
charge 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.

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