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Citation: Review of Scientific Instruments **86**, 046103 (2015); doi: 10.1063/1.4916953
View online: http://dx.doi.org/10.1063/1.4916953
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REVIEW OF SCIENTIFIC INSTRUMENTS **86**, 046103 (2015)

Note: Determining the detection efficiency of excited neutral atoms by a microchannel plate detector

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(Received 13 January 2015; accepted 24 March 2015; published online 3 April 2015)

We present a method for determining the detection efficiency of neutral atoms relative to keV ions. Excited D* atoms are produced by D_2 fragmentation in a strong laser field. The fragments are detected by a micro-channel plate detector either directly as neutrals or as keV ions following field ionization and acceleration by a static electric field. Moreover, we propose a new mechanism by which neutrals are detected. We show that the ratio of the yield of neutrals and ions can be related to the relative detection efficiency of these species. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4916953]

Measurements involving excited neutral atoms are typically achieved through field ionization and detection of the resulting ions or by detection of fluorescence from the decay of excited states.[1] Field ionization only provides access to highly excited Rydberg states, while fluorescence studies are restricted to allowed atomic transitions. Directly measuring metastable excited neutrals can provide some advantages over other methods, such as gaining access to all excited states, and it has been shown that these measurements are possible using micro-channel plate (MCP) detectors.[2–5]

Particle detection by MCP detectors relies on electron emission and multiplication in the micron-size channels.[6] For light ions, the detection efficiency saturates at around 2-3 keV impact energy, typically at a value equal to the active open area of the detector.[7] In the detection of excited neutral atoms, electron emission and amplification are possible if the internal potential energy of the atom is greater than the work function of the MCP surface (a few eV). Some basic ideas describing this phenomenon exist;[8] however, quantitatively describing the electron emission rate from the MCP surface (i.e., the detection efficiency) has proven difficult.

In addition to detection via the potential energy of the atom, we propose another mechanism. In normal operating conditions, the electric field due to the bias voltage of the MCP is strong enough to field ionize atoms in highly excited Rydberg states. This process always results in the emission of one electron that begins the charge-amplification process.

In this work, we present a method for determining the detection efficiencies of each of these mechanisms, relative to the detection of keV ions (ε_{ion}). This simple scheme allows one to determine the relative efficiencies of both the "potential energy" detection (ε_{PE}) and field ionization within the MCP channel (ε_{FI}) independently. This information may be used to characterize a detector and optimize it for detection of neutrals. To evaluate the efficiencies, we use D* (excited atomic deuterium fragments) formation by laser-induced fragmentation of D_2. The D* potential energy (10.2-13.6 eV) is much greater than the work function of the MCP. The method presented here applies to other species, though they may have different detection efficiencies.

Laser pulses of central wavelength near 800 nm and duration of 30 fs at 10 kHz (corresponding to a peak intensity $I_0 \sim 3\times 10^{13}$ W/cm^2) are focused on an effusive D_2 gas jet by a spherical mirror (f = 75 mm).[9] The laser polarization is oriented along the axis of the setup shown in Fig. 1, directing fragments emitted in the polarization direction toward either of two MCP detectors where the time of flight is measured.

Each detector is preceded by two high-transmission copper electroformed meshes (88% transmission, 90 lines/in.). For detecting only D* fragments, +150 V is applied to the front mesh to repel any positive ions. A voltage on the second mesh creates an electric field that field ionizes atoms in highly excited states. The direction of the field dictates whether these ions are repelled or detected. The electric field strength is adjustable, which allows control over the range of excited states that are measured and the mechanism by which they are detected. The threshold static electric field strength for field ionization follows the scaling law[11] $E_{th} = \frac{1}{5.783n^4}$. The front MCP is operated at −200 V when detecting neutrals only, and at −1800 V when field ionizing D* between the meshes and accelerating the ions to keV kinetic energy. These negative voltages ensure no electrons are detected. Timing signals are picked off from the back of the MCP stack, and the count rate is kept low enough, much less than one event per laser shot, to avoid saturation.

Determining the detection efficiencies by internal potential energy (ε_{PE}) and field ionization within the channel (ε_{FI}), relative to keV ions (ε_{ion}), requires a series of related measurements.

The electric field inside the MCP channels field ionizes excited states with n quantum number n_{MCP} and above. We estimate the field strength as the MCP voltage divided by its thickness, a good approximation based on SIMION simulations of the electric field near the MCP surface. Setting a repelling field between the meshes (E_{FI}) equal in strength to the MCP field results in the measurement of D* by the potential energy mechanism alone. In hydrogen, n = 2 has sufficient excitation to be detected, so D* in states $2 \le n \le n_{MCP}$ are

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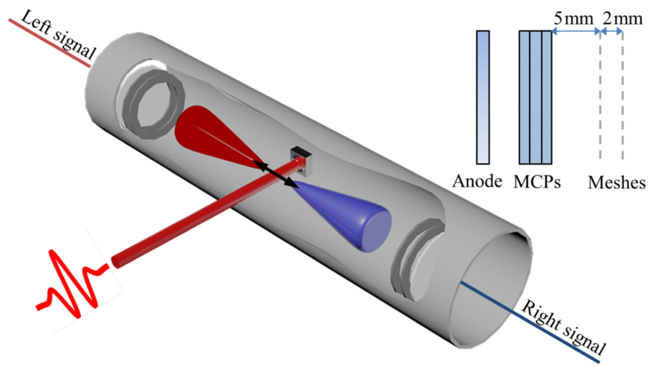

FIG. 1. Schematic of double-sided time-of-flight spectrometer used to measure D* fragments from D_2, along with a diagram of the z-stack MCP detector.[10]

measured (Fig. 2)

$$M_1 = \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE}, \tag{1}$$

where M_1 is the number of measured D* and N_n is the number produced by the laser in state n. We assume that ε_{PE} is independent of n, as all excited states are much higher in energy than the work function of the MCP, and occupy a narrow energy range (10.2-13.6 eV).

Repeating this measurement with the same E_{FI}, but switching the field direction so that field-ionized D* are detected as D^+ results in

$$M_2 = \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE} + \sum_{n=n_{MCP}}^{\infty} N_n\, \varepsilon_{ion}\,. \tag{2}$$

In a second pair of measurements, E_{FI} is increased above the MCP field. The mesh field ionizes D* with $n \geq n_L$, where $n_L < n_{MCP}$. Again, in one measurement the field ionized D* are repelled and in the other they are detected

$$M_3 = \sum_{n=2}^{n_L} N_n\, \varepsilon_{PE}, \tag{3}$$

$$M_4 = \sum_{n=2}^{n_L} N_n\, \varepsilon_{PE} + \sum_{n=n_L}^{\infty} N_n\, \varepsilon_{ion}\,. \tag{4}$$

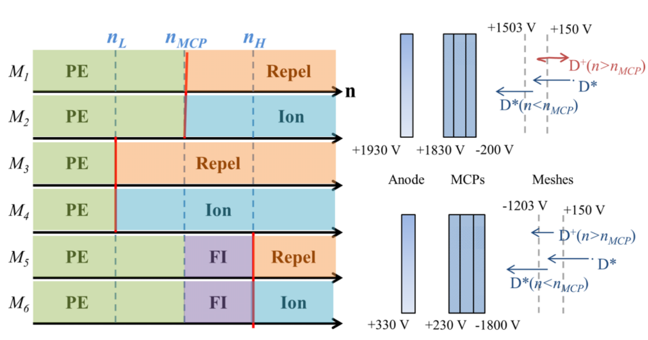

FIG. 2. Left: schematic diagram of the three pairs of measurements involved in determining the relative detection efficiencies, corresponding to measurements $M_1 - M_6$ listed in the text. Right: example detector configurations for repelling (top) and detecting (bottom) field ionized D*.

The difference between M_1 and M_3 is the yield of D* with $n_L \leq n \leq n_{MCP}$ measured as neutrals by the potential energy mechanism.

$$[M_1 - M_3] = \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE} - \sum_{n=2}^{n_L} N_n\, \varepsilon_{PE} = \sum_{n=n_L}^{n_{MCP}} N_n\, \varepsilon_{PE} = \varepsilon_{PE} \sum_{n=n_L}^{n_{MCP}} N_n\,.$$

Similarly, the yield of D* in the same range of n detected as ions is given by

$$[M_4 - M_3] - [M_2 - M_1] = \sum_{n=n_L}^{\infty} N_n\, \varepsilon_{ion} - \sum_{n=n_{MCP}}^{\infty} N_n\, \varepsilon_{ion} = \varepsilon_{ion} \sum_{n=n_L}^{n_{MCP}} N_n\,.$$

As the number of D* in each excited state, N_n, produced by the laser field is unknown, the absolute detection efficiencies cannot be determined, but the relative efficiency $\varepsilon_{PE}/\varepsilon_{ion}$ is given by dividing the two expressions above

$$\frac{[M_1 - M_3]}{[M_4 - M_3] - [M_2 - M_1]} = \frac{\varepsilon_{PE} \sum_{n=n_L}^{n_{MCP}} N_n}{\varepsilon_{ion} \sum_{n=n_L}^{n_{MCP}} N_n} = \frac{\varepsilon_{PE}}{\varepsilon_{ion}}\,. \tag{5}$$

In a similar fashion, we can determine the relative detection efficiency of D* by field ionization inside the MCP channel, $\varepsilon_{FI}/\varepsilon_{ion}$, by performing an additional pair of measurements. Now, E_{FI} is set to be weaker than the field inside the MCP, field ionizing $n \geq n_H$, where $n_H > n_{MCP}$. D* in the states between n_{MCP} and n_H are detected by field ionization in the MCP while all states below n_{MCP} are still detected because of their potential energy. Once more, measurements are performed repelling and detecting the ions from all the higher excited states ionized between the meshes

$$M_5 = \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE} + \sum_{n=n_{MCP}}^{n_H} N_n\, \varepsilon_{FI}, \tag{6}$$

$$M_6 = \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE} + \sum_{n=n_{MCP}}^{n_H} N_n\, \varepsilon_{FI} + \sum_{n=n_H}^{\infty} N_n\, \varepsilon_{ion}\,. \tag{7}$$

Computing the differences between the measured yields as before gives the yield in states $n_{MCP} \leq n \leq n_H$ detected by field ionization in the MCP,

$$[M_5 - M_1] = \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE} + \sum_{n=n_{MCP}}^{n_H} N_n\, \varepsilon_{FI} - \sum_{n=2}^{n_{MCP}} N_n\, \varepsilon_{PE} = \sum_{n=n_{MCP}}^{n_H} N_n\, \varepsilon_{FI} = \varepsilon_{FI} \sum_{n=n_{MCP}}^{n_H} N_n\,,$$

and as field-ionized keV ions,

$$[M_2 - M_1] - [M_6 - M_5] = \sum_{n=n_{MCP}}^{\infty} N_n\, \varepsilon_{ion} - \sum_{n=n_H}^{\infty} N_n\, \varepsilon_{ion} = \sum_{n=n_{MCP}}^{n_H} N_n\, \varepsilon_{ion} = \varepsilon_{ion} \sum_{n=n_{MCP}}^{n_H} N_n\,.$$

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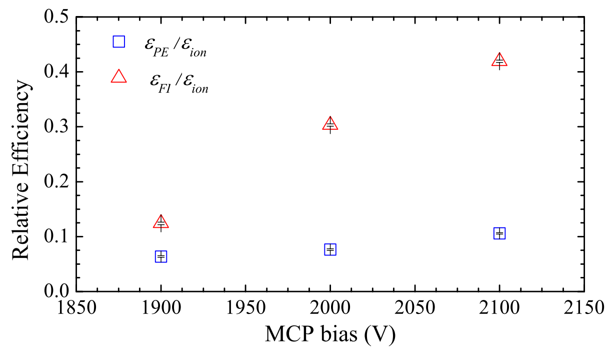

FIG. 3. Measured relative efficiencies $\varepsilon_{PE}/\varepsilon_{ion}$ (blue squares) and $\varepsilon_{FI}/\varepsilon_{ion}$ (red triangles) as functions of MCP bias voltage.

Finally, dividing these expressions results in the relative efficiency for $\varepsilon_{FI}/\varepsilon_{ion}$,

$$\frac{[M_5 - M_1]}{[M_2 - M_1] - [M_6 - M_5]} = \frac{\varepsilon_{FI} \sum_{n=n_{MCP}}^{n_H} N_n}{\varepsilon_{ion} \sum_{n=n_{MCP}}^{n_H} N_n} = \frac{\varepsilon_{FI}}{\varepsilon_{ion}} . \qquad (8)$$

If the absolute efficiencies are needed, the ion detection efficiency can be determined using the method described by Gaire *et al.*[12] In Fig. 3, we show the relative efficiencies evaluated using Eqs. (5) and (8). We observe that as the MCP bias voltage is increased (i.e., the MCP gain is increased), both relative efficiencies also increase. At these MCP voltages, the ion detection efficiency is saturated (likely to the open area). This was determined by directing D^+ created in the laser interaction toward the detector with a weak electric field and detecting ions with 2 keV impact energy. At the MCP voltages mentioned above, the D^+ rate was constant, indicating that the ion detection efficiency was saturated. Therefore, the increase with detector gain is mainly due to increases in the neutral detection efficiency.

Furthermore, we observe that ε_{FI} is significantly greater than ε_{PE}, which is not unexpected. While field ionization within the MCP channel always results in the release of an electron that can start the charge-amplification process, these results suggest that transferring internal energy to the surface does not. Previous studies[2] have found that, depending on the species and detector conditions, the efficiency of "potential energy" detection can range from 10^{-4} to 0.5. We were limited to a maximum bias of 2100 V due to technical issues; however, we expect the efficiency would improve with increased voltage.

It should be noted that while these efficiency measurements only require one detector, we made use of the two detectors in our experimental setup by operating one at constant settings while evaluating the efficiency on the other. This allowed us to correct for fluctuations in target density and laser power that change the number of D* produced in the interaction, by using the yield on the detector held constant for normalization.

In summary, we have presented a simple technique for determining the relative detection efficiency of a MCP detector for neutral particles. In addition to the well-known "potential energy" detection mechanism for excited neutrals, we suggest that highly excited neutrals can be detected by field ionization inside the MCP. The relative detection efficiencies of each of these mechanisms is measured using the experimental scheme described herein.

This work was supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy, Grant No. DE-FG02-86ER1349. The PULSAR laser was provided by Grant No. DE-FG02-09ER16115 from the same funding agency. B.J. is supported by the Department of Energy Office of Science Graduate Fellowship Program (DOE SCGF), made possible in part by the American Recovery and Reinvestment Act of 2009, administered by ORISE-ORAU under contract no. DE-AC05-06OR23100.

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