PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3527
UC-70

PPPL-3527

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by

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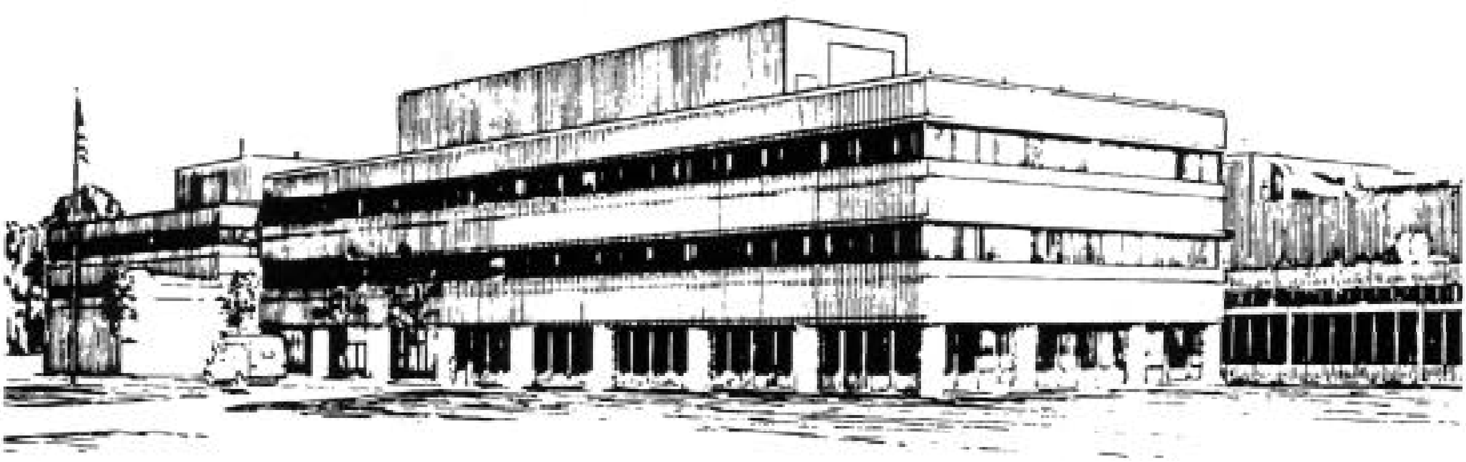
December 2000



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Multiple electron stripping of 3.4MeV/μ Kr^{7+} and Xe^{11+} in nitrogen

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Use of heavy ions beams with ~10 MeV/μ, mass ~ 200 and average charge state of 1+ has been proposed as a driver for heavy ion fusion. Stripping of the ion beam by background gas results in an increase in the space charge density of the beam, which may make focusing the intense ion beam onto small targets more complex. Knowledge of the electron-loss-cross-sections is essential to understand and address the problem. Currently, there are no 10 MeV/μ, mass = 200, charge state = 1 beams available, and the theories that calculate electron-loss-cross-sections can be experimentally tested only by using available beams of somewhat lower energy and higher initial charge state. The charge state distribution of ions produced in single collisions of 3.4 MeV/μ Kr^{7+} and 3.4 MeV/μ Xe^{11+} in N_2 have been measured at the Texas A&M Cyclotron Institute using a windowless gas cell. The charge states of the outgoing ions are determined by magnetic analysis using a position-sensitive microchannel-plate detector. The cross-sections for single and multiple electron loss are determined, and the results indicate that substantial multiple-electron loss occurs. The relative cross-section for loss of i +1 electrons is 0.3 to 0.7 times that for i electron loss. The average number of electrons removed per one collision (sum of the electron-weighted cross-sections normalized to the total cross-section) is 1.86 for Kr and 1.97 for Xe.

I. INTRODUCTION

One of the approaches presently being explored as a route to practical fusion energy uses heavy ion beams focused upon a metallic target to produce X-rays, which then drive the compression of a deuterium-tritium pellet.[1] Some of the more prominent baseline designs currently being proposed for such reactors envision propagating a beam of singly-charged positive ions of a relatively heavy element, such as xenon or krypton, across a distance of several meters between the final focus magnet system and the target in the center of the target chamber. The target chamber gas density would probably be composed primarily of the vapor from a liquid wall such as FLIBE, a salt of fluorine, lithium, and berylium. The density of beryllium difluoride vapor in one such reference design, HYLIFE-II is 5 x 10^{13} cm^{-3}.[2] Ionization of this medium would supply space-charge-neutralizing electrons to compensate partially the space-charge force of the positive ion beam, which would otherwise cause the beam spot size to expand, decreasing the focusability. This medium would also remove additional electrons from the ion beam through impact ionization, thus raising the average charge state of the beam. This can increase the beam spot size, since the deflection of ions in the residual space-charge fields is proportional to their charge state.

It is thus important in planning possible operating regimes for heavy-ion-driven fusion reactors to assess the rate at which the charge state of an incident beam evolves while passing through a background gas. It is important in particular, to assess whether multi-electron-loss events, events in which a beam ion loses more than one electron in a single ionization event, are major contributors to the charge state evolution and dispersion of the beam. Experiments carried out in the early 1980's to assess the atomic neutralization efficiency of beams of negative ions ranging in mass from lithium to silicon found that a substantial fraction of the time more than one electron was lost in a single collision[3] at beam energies in the range of 2 – 7 MeV. It has been suggested[4] that this might be a ubiquitous phenomenon that would be prominent in the regimes of interest to heavy ion fusion. At the beam energies of 20 – 40 MeV/μ[2] planned for heavy ion driver beams, many of the electrons carried by the beam ions will have translational kinetic energies greater than their binding energies, with the result that electrons from shells other than the outermost can be removed, leading to Auger cascades.

The experiments described in this paper are intended to appraise the magnitude of multi-electron loss events in regimes approaching, although not exactly duplicating, those anticipated for heavy ion fusion drivers. The gas used to simulate the medium in the fusion target chamber is molecular nitrogen, whose average atomic number is reasonably close to that of beryllium difluoride. Ideally, one would like to use beams of singly charged xenon and krypton at energies of 20 MeV/μ. Such beams are not presently available from accelerators. The experiments reported here have instead used Kr^{7+} and

Xe^{11+} at 3.4 MeV/μ. If multi-electron loss events play a prominent role for these beams, in which the electron cloud is held more tightly than would be the case with the singly charged incident beam actually planned for a heavy ion driver, then it can be inferred that multi-electron loss events will also be significant for the actual driver beams. This information will be useful in the design of heavy ion fusion reactor options, since it will provide a guide to how much emphasis needs to be placed upon the implementation of approaches to improve the space-charge neutralization of the beam.

II. EXPERIMENTAL METHOD

Beams of 3.4 MeV/μ Kr^{7+} and Xe^{11+}, extracted from the Texas A&M K500 superconducting cyclotron were directed through a 22 degree deflection magnet located 10 m in front of the target chamber. The beam was collimated by three 1-mm diameter apertures followed by a 2-mm diameter collimator before entering a differentially-pumped gas cell. The gas cell of effective length 0.019m was filled with N_2 to pressures from 1 to 96 mTorr, as measured by a capacitance manometer, and maintained by an automatic fill valve to about ±0.3 mTorr accuracy. The background pressure in the beam line and target chamber were monitored with ion gauges and ranged between 1.5 and 5.0 $\times\ 10^{-6}$ Torr, depending upon target cell pressure and vacuum history. After exiting the gas cell, the beam passed through another magnet to disperse the charge states and on to a position-sensitive microchannel plate detector (PSD). Data was taken with no flow in the gas cell to take into account stripping of the beam in the background gas. In order to avoid rate-dependent gain changes and extraneous peaks due to pulse pile-up, the beam intensity was keep below 1500 counts/s. The charge distributions were counted until the statistics in the 4-electron loss peaks were better than 2%.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the charge state distributions for incident beams of 3.4 MeV/μ Kr^{7+} and Xe^{11+} taken with gas cell pressures of 4 mTorr. It is clear from inspecting these plots that multiple electron loss collisions are important. In the case of Kr, 3.6 % of the initial beam is stripped of only one electron, and 1.3% is stripped of two electrons. For Xe, the corresponding numbers are 2.6% and 0.8%. These high rates of two-electron loss relative to one-electron loss cannot be explained by multiple, single-electron-loss collisions.

The data has been analyzed to determine the cross sections for multiple electron loss collisions in a thin target approximation (that is assuming no second collisions). The intensity of the incident beam having charge n (I_0) is taken as the sum of all the observed charge states. Since the higher charge states (> n+7 for Kr and > n+11 for Xe) were outside the spatial limits of the position-sensitive detector, this procedure slightly underestimates the total incident intensity, by less than about 1%. The intensity of charge state n falls linearly along the length of the stripping cell so that the average intensity of charge state n across the stripping cell is the average of the initial intensity and the observed intensity of charge state n at the detector.

The intensity (I_{n+i}) of charge state n+i is related to the cross-section (σ_i) in m^2/atom for stripping i electrons from charge state n, the cell pressure (P) in mTorr, and the beam intensity I_0 by the equation:

$$I_{n+i} = 6.43 \times 10^{19} Pl\sigma_i (I_0 + I_n)/2 \quad (1)$$

where l is the effective stripping cell length in m. The measured intensity of I_{n+i} for each pressure was corrected for stripping in the beam line by treating the no-flow case as a background level and subtracting the no-gas-flow value of I_{n+i} weighted by the ratio I_0 at pressure P divided by I_0 with no gas flow. This subtraction is justified since the target chamber pressure changes less than ± 10 % for cell pressures below 8 mTorr and the beam line pressure does not change at all. Table I gives σ_i for Kr^{7+}. The uncertainty in σ_i of 15% is due mainly to the uncertainty in l, the relative error in σ_i is ~ 2%.

Figures 2 and 3 show the electron loss cross sections for Kr and Xe obtained using the data for pressures ≤ 8 mTorr. The Kr cross-sections for 2 through 7 electron loss derived from the data at a single pressure are shown versus pressure in Figure 4. If electron loss due to multiple collisions were important, the effective cross section would increase as P^2 for double collisions and as P^3 for triple collisions. The data show that this is clearly not the case for pressures below about 10 mTorr. Therefore, the thin cell approximation is justified.

IV. THEORETICAL CALCULATIONS

Two methods traditionally have been employed for calculations of ionization cross sections of collisions between high-energy atoms and ions. The classical trajectory method originated from classical works of Bohr[5] and is based on a classical description of electron motion and interaction with the projectile. The second approach is based on quantum mechanical calculations in the Born approximation of scattering amplitude. This method is based on Bethe's classic article[6]. A third method using a model by Gryzinski[7] can also be compared. The application of the first two methods depends on the magnitude of the potential acting on the electron by the field of the projectile atom or ion. If the change in action $S(\rho) = \int_{-\infty}^{\infty} V(\rho,t)dt$ after the interaction with the electron is large compared with Planck's constant $\hbar$, the quasi-classical approach may be used. In the opposite case the Born approximation may be valid.[8] For an atom of nuclear charge Z, moving with velocity v, and zero impact parameter ($\rho = 0$) $S(0) \sim \frac{2Z\,a_z}{v}$, where a_z is the screening radius of the atom. For the parameters of this experiment $S(0) \sim \hbar$, so neither of the approximations discussed above is strictly valid. To assess the cross-sections we performed the calculations in both of the limiting cases. Details of the calculations will be presented in a separate paper.[9]

The quantum mechanical calculations are carried out using a plane wave Born approximation (PWBA)[10]. The cross-section for ionization of an electron on orbital nl is given by [11]

$$\sigma_{nl} = \frac{8\pi\, e^4}{v^2\hbar^2} \int_0^{\infty} \int_{q_{\min}}^{q_{\max}} P(\varepsilon,q)(Z - F(q))dq\, d\varepsilon \qquad (2)$$

where $F(q)$ is the projectile's atomic form factor, and $P(\varepsilon,q) = |<\psi(\varepsilon)\,|\exp\left(i\vec{q}\vec{r}\right)|\,\psi_{nl}>|^2$ is the ionization form factor of the target ion. The form factors are calculated using the Thomas-Fermi-Dirac (TFD) method described in Ref. 12., and the ionization potentials of the ion are taken from Ref. 13. They are well reproduced with the TFD method, so the ion structure is calculated by use of the TFD method as well.

The cross-sections in the classical approach are calculated by integrating over all impact parameters where electron removal is possible. Because the cross sections for ionization of individual electrons in each orbital are calculated, the multiple-electron events can be calculated statistically assuming that the ionization of different electrons is independent.[9] The results for the Kr case are collected in Table 1. The same data are plotted in Figure 2, where the data point at 0 corresponds to the gross cross-section.

The cross-sections characterizing the ionization of an incident projectile in a collision with a target atom can be performed using the binary encounter model of Gryzinski.[7] Excellent descriptions of this model can be found in Refs. 14 and 15. The ability of this model to reproduce empirical ionization cross-sections for beam-target interactions similar to those examined here has been demonstrated.[16] The cross-section σ_{nl} for the ionization of electron nl in an incident ion can be expressed as

$$\sigma_{nl} = 4\pi a_o^2 \frac{Ry^2}{I_{nl}^2}(\overline{Z}_t^2 + Z_t)G[V]. \tag{3}$$

In this expression, $Ry = 13.6\ eV$, $a_o = 0.53\ 10^{-10}\ m$, $\overline{Z}_t$ is the effective screened nuclear charge of the target atom as experienced by electron nl, I_{nl} is its ionization potential, and $G[V]$ is a velocity-matching function of the scaled velocity $V \equiv v / v_{nl}$, where v is the projectile velocity and v_{nl} is the orbital velocity of the electron to be ionized. The total ionization cross-section for the incident ion is the sum of the cross-sections for the ionization of the individual electrons.

Probabilities for multiple ionization can be formulated by extending the treatment of Kessel[17] to more complex ions such as those considered here in the Gryzinski method. In general, the probability P of an ionization event is related to the cross section σ characterizing the ionization and the impact parameter b of the collision producing the ionization by

$$P \approx \frac{\sigma}{\pi b^2}. \tag{4}$$

This expression can be used to estimate a gross ionization probability that can be used to approximate multiple ionization probabilities and cross-sections. While single ionization would occur with the above probability P, ionization of m electrons in a single collision can be considered to occur with probability of P^m.

As evident from Table I and Figs. 2 and 3, the predicted cross-sections reproduce the main trends in behavior of the experimental results, but they differ from each other and the experimental results by factor of two or more. Moreover, the PWBA agrees best with experiment among these models. For better agreement more refined calculations are needed, as well as data with different energies and charge states to check the scaling of the models over a wider range.

V. CONCLUSIONS

These experiments have shown that, for beams with parameters approaching those likely to be used for heavy ion fusion drivers, multi-electron loss events are very important factors in the charge state evolution of the beam. This suggests that it will be important to ensure that an adequate means of space-charge neutralization is provided.

These measurements have also provided benchmarking validation of modeling techniques, which should allow the modeling to be refined and used with greater confidence to model the charge state evolution of actual heavy ion driver beams.

ACKNOWLEDGEMENTS

We gratefully acknowledge the staff at the Texas A&M Cyclotron Institute, especially Don May and George Kim who proved invaluable in providing the desired ion beam species. This work was supported by US. DOE Contract No. DE-AC0276CH03073 and the Robert A. Welch Foundation.

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TABLE I Cross-sections for 1 through 7 electron loss for 3.4 Mev/μ Kr^{7+} in N_2.

Electrons Lost	Experimental σ 10^{-20} m^2	PWBA σ	Classical σ	Gryzinski σ
1	0.44	0.41	0.72	0.54
2	0.17	0.18	0.19	0.249
3	0.090	0.16	0.11	0.114
4	0.046	0.093	0.045	0.0521
5	0.022	0.040	0.013	0.0239
6	0.012	0.013	0.003	0.0109
7	0.0058	0.0040	0.00061	0.0050
Gross $\sum_i i\sigma_i$	1.47	1.9	1.7	1.8
Average charge	1.86	2.1	1.6	1.8

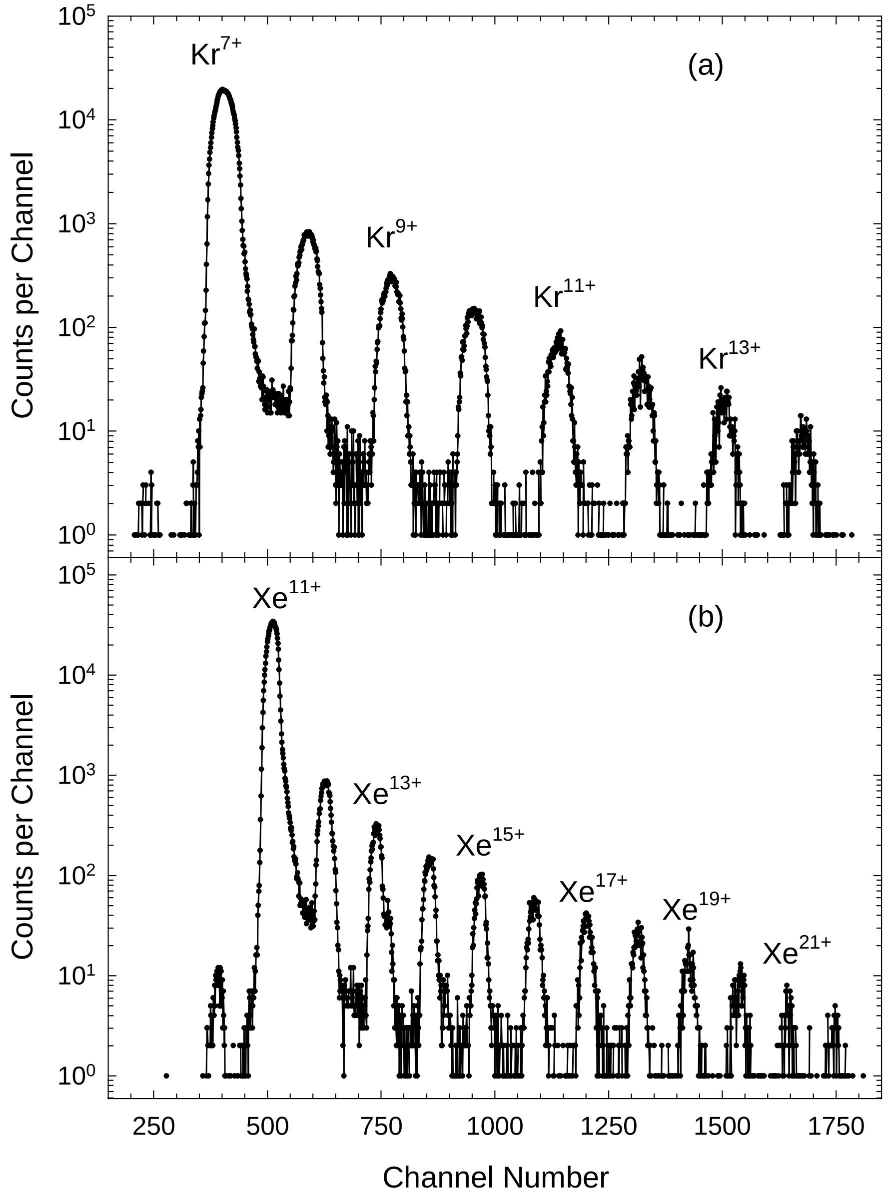
Figure Captions

Figure 1. Charge distributions for 3.4 MeV/u beams of (a) Kr^{7+} and (b) Xe^{11+} showing the number of detected ions as a function of position along the detector with a N_2 pressure of 4 mTorr in the gas cell.

Figure 2. Average cross-sections for electron loss from 3.4 MeV/μ Kr^{7+} in N_2 per one nitrogen atom determined from the data taken at cell pressures ≤ 8 mTorr.

Figure 3. Average cross-sections for electron loss from 3.4 MeV/μ Xe^{11+} in N_2 per one nitrogen atom determined from the data taken at cell pressures ≤ 8 mTorr.

Figure 4. Cross-sections determined for the loss of 2 through 7 electrons as a function of pressure for Kr^{7+}. Note that below about 10 mTorr, the data is insensitive to pressure, the thin-cell approximation is justified and single collisions are the dominant process.



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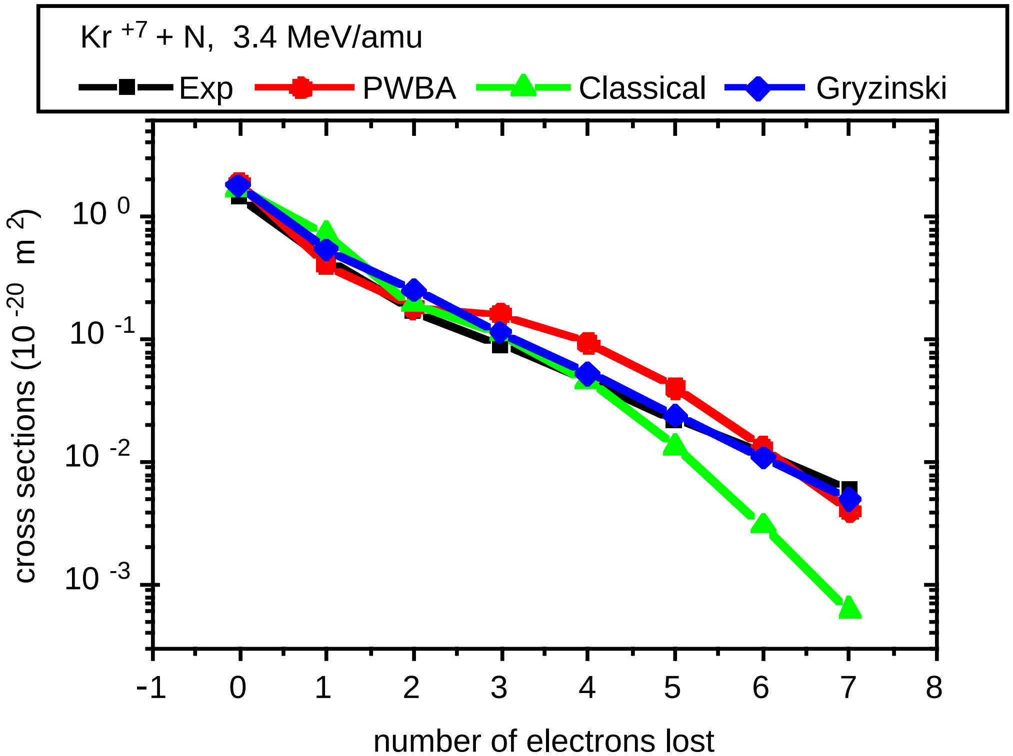
[1] Fig.1 D. Mueller



[2]

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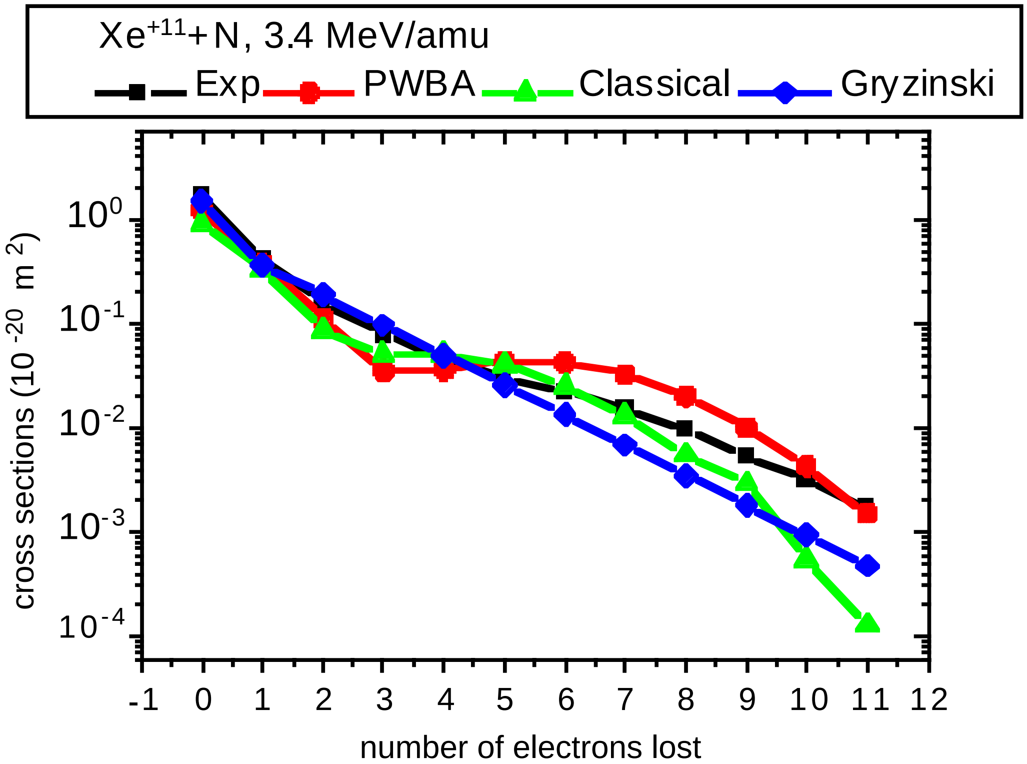
[2] Fig.2 D. Mueller



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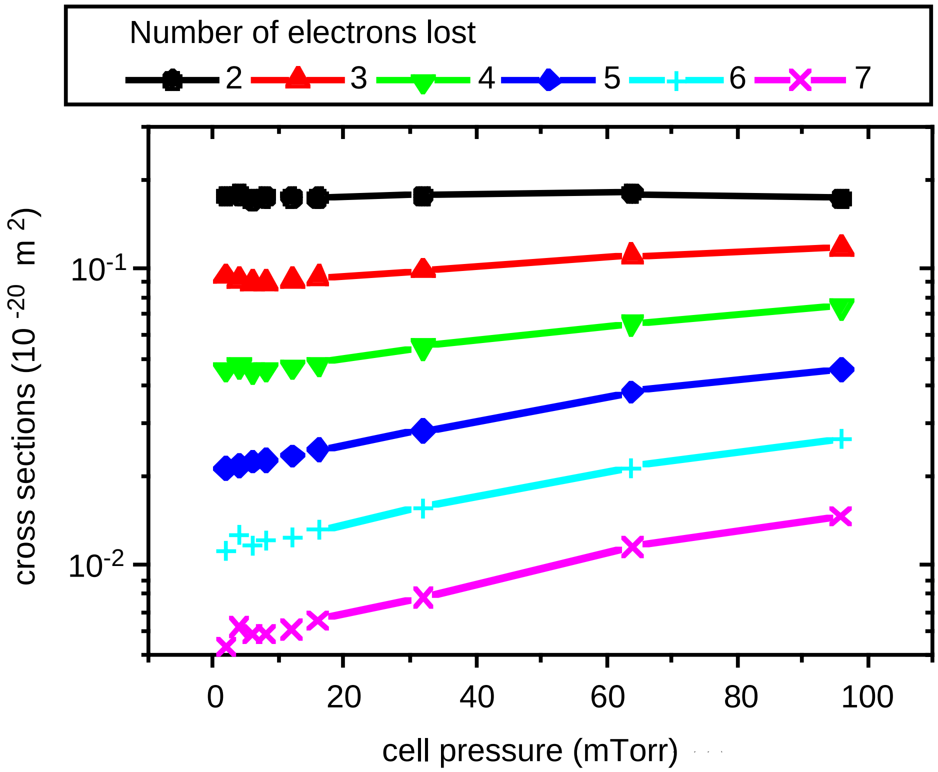
[3] Fig.3 D. Mueller



[4]

[4] Fig.4 D. Mueller

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