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Publication Date

1980-09-01



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Submitted to Physical Review Letters

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September 1980

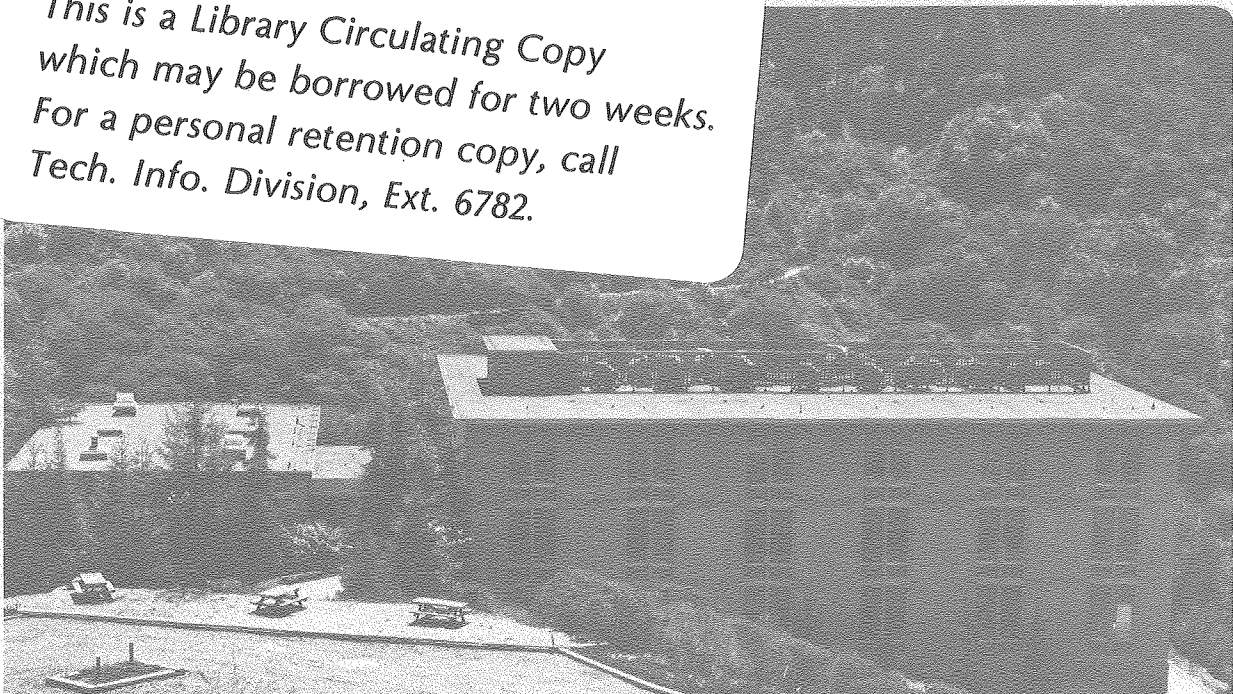
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LBL-11552 c.2

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LBL-11552

To be submitted to Physical Review Letters

Electron capture by trapped Ne^{10+} at very low energies

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(Received

Abstract. An electrostatic ion trap has been used to trap Ne^{q+} ($1 \leq q \leq 10$) ions created by a fast xenon beam passing through neon gas. Exponential decay in time of the Ne^{10+} fraction due to electron capture from neon gas was observed and the decay rates measured. For mean kinetic energies between 7-45 eV, the total electron capture cross section ($\sigma_{e.c.}$) is found to be velocity independent. For this energy range we obtain $\sigma_{e.c.}(\text{Ne}^{10+}) = 2.4 \times 10^{-15} \text{ cm}^2$, with an estimated uncertainty of 30 percent.

Electron capture by low-energy multiply charged ions on neutral gases has been a subject of considerable recent interest in connection with fusion research¹ and astrophysical problems.² A considerable number of calculations have resulted based on a variety of models.³ Experimental progress has been achieved mainly using beam-gas techniques,⁴ but for multicharged heavy ions has been almost entirely confined to the kinetic energy range above ~ 1 keV and charge states less than fully stripped.

In this letter, a new technique is described that uses the low-energy multicharged recoil ions produced in a gas traversed by a fast heavy-ion beam.⁵ These ions are then trapped in an electrostatic trap where they undergo electron capture from the atoms in the residual gas. By sampling the ion population in time after their creation, the decay rates associated with electron capture are directly measured. Varying the trap potential allows determination of these rates as a function of ion kinetic energy. From this information, it is possible to infer values for the total cross section for electron capture and the velocity dependence. As a demonstration, a measurement of the total capture cross section of Ne^{10+} (fully-stripped) on neutral neon gas in the range of mean kinetic energies 7 eV – 45 eV is described. However, the method has application to very low-energy, high-charge states of a wide variety of ions and target gases.

Pulsed 3.5 MeV/u Xe²⁷⁺ beams from the LBL Super-HILAC were collimated to ~1.25 cm diameter and passed through an ultra-high vacuum target chamber isolated from the ~10⁻⁶ Torr vacuum of the beam line by thin carbon foils. The base chamber pressure was typically 1 x 10⁻⁸ Torr. The mean charge state of the foil transmitted beam in the target chamber was ~Xe⁺³⁸. The ion beam was collected in a deep, well-shielded Faraday cup several meters downstream of the chamber. The collected charge was used for data normalization, and a beam arrival pulse was generated for timing synchronization. An electrostatic ion trap⁶ was constructed as shown schematically in Fig. 1. It consists of a ~15 cm diameter copper cylinder ~18 cm in length coaxially mounted with an electrically isolated thin tungsten wire (dia = 0.08 mm). A potential difference (ΔV) maintained between these elements produced a nearly logarithmic potential well in which slow positive ions were radially confined. Isolated end caps held at an appropriate potential with respect to the central wire restricted ion motion parallel to the axis so that a three-dimensional trapping configuration could be achieved without seriously disturbing the logarithmic potential near trap center. The ion trap was mounted in the target chamber so that the projectile beam was transmitted axially through the trap parallel with the central wire at a separation of 1.25 cm.

^{22}Ne target gas was admitted into the trap region from a clean glass reservoir through a variable leak valve. The reservoir contained target gas at a pressure of a few Torr to allow smooth control of low ($1-6 \times 10^{+10}/\text{cm}^3$) target densities. The pressure in the trap region was measured with a nude Bayard-Alpert ion gauge calibrated for neon by comparison (over two orders of magnitude) with a capacitance manometer.

Target ions created during the 3.3 msec Xe^{38+} beam pulse recoil at nearly 90° with respect to the incident beam; i.e., in a plane perpendicular to the trap axis. The recoil energies of these ions may be estimated from measured production cross sections.⁵ The large effective impact parameters and short collision times result in energies of only a few eV even for the most highly stripped recoil ions. Therefore, trap well depths produced by potential differences of only tens of volts across the elements are much greater than initial ion recoil energies. The ion trap was insensitive to the mass or charge of the bound ion. Hence, essentially all Ne^{q+} formed in the trap with nonzero angular momentum about the central wire are confined and are found to have average kinetic energies in the well which depend only on the trap parameters.

The trapped Ne^{q+} ions interact with neutrals in the thin background gas while orbiting the central wire. Both elastic and inelastic collisions can occur, but impact energies are usually too

low for ionization of neutrals except through electron capture, and for the trap geometry chosen very few elastic collisions can lead to loss of the ions from the trap (only those which reduce the ion angular momentum to essentially zero). Therefore, decay of a Ne^{q+} population through interactions with neutral target gas is due primarily to electron capture collisions.

The bare ion decay rate was measured by emptying the ion trap at progressive delay times after detection of the projectile beam pulse and by storing the number of Ne^{10+} ions released into the detection system as a function of time. Ions were dumped from the trap by switching the central wire potential from its negative trapping value to the positive potential of the outer cylinder. A geometric fraction of the released ions passed through a grid-covered hole in the trap outer cylinder. Transmitted ions were filtered according to their mass-to-charge ratio (m/q) by a commercial quadrupole residual gas analyzer (RGA) and detected by a channel electron multiplier, as shown in Fig. 1. Isotopically pure ^{22}Ne target gas was used in these experiments. The RGA resolution is sufficient to separate all charge states of $^{22}\text{Ne}^{q+}$ and in particular to fully resolve $m/q = 2.20$ ($^{22}\text{Ne}^{10+}$) ions from $m/q = 2.00$ ions (e.g., H_2^+). The RGA can be remotely scanned at fixed decay times to provide m/q spectra for calibration and to ensure negligible background signal from other gases. To preclude the possibility of substantial levels of contaminants being

introduced with the target gas, m/q scans were taken at widely varied target densities and the spectra searched for pressure dependent non- $^{22}\text{Ne}^{q+}$ peaks. None were found.

In measurements of the decay rates of Ne^{10+} , the RGA was programmed to transmit only $m/q = 2.20$ ions. The time interval from production to release of the ions from the trap (trapping time t_i) was then scanned in a stepwise fashion. The trapping time was held fixed at each value t_i for many beam pulses until a prescribed beam charge had been accumulated at the Faraday cup. The trapping time was then incremented and the process repeated until the period between beam pulses had been scanned. The analyzed ion count data was collected by a minicomputer in multichannel scaling mode, each channel corresponding to a particular t_i .

The resulting decay curves are well described by a single exponential, $N = N_0 e^{-\gamma t}$, as shown by the semilog plots of Fig. 2. The decay rate, γ , can be expressed as $\gamma = \langle\sigma v\rangle n + \gamma_0$, where γ_0 is the net decay rate associated with trap leakage and collisions with background gases other than neon; $\langle\sigma v\rangle n$ is the decay rate of $^{22}\text{Ne}^{10+}$ due to electron capture to all lower charge states from neutral ^{22}Ne at density n . The rates γ vs n were obtained from least-squares fits to series of data such as shown in Fig. 2. Plots of γ vs n for several trap potentials are shown in Fig. 3. The slopes of straight line fits to these data

provide $\langle \sigma v \rangle$, the capture collision rate constant averaged over the Ne^{10+} velocities at each trap potential. The extrapolated decay rate for Ne^{10+} ions at zero neon density was approximately 3 sec^{-1} , consistent with ion loss due to electron capture from the N_2 and H_2O dominated background density of about $6 \times 10^8 \text{ cm}^{-3}$.

By switching off the trap in a time significantly shorter than a trapped ion "orbital" period ($>$ several μsec), the Ne^{10+} are released unperturbed. This "fast dump" technique was employed in time-of-flight (TOF) and retardation measurements (using the accel/decel grids shown in Fig. 1) to study the velocity distribution of Ne^{10+} ions in the trap. The results are consistent with ion motion calculated in a model assuming a purely logarithmic radial potential; not unexpected, as the ions observed are restricted to those near mid-length of the trap. TOF data was acquired at several trapping times in an attempt to observe any time evolution of the velocity and spatial distributions of the bound ions. No significant variation was observed, which is strong evidence that loss of Ne^{10+} by mechanisms other than electron capture is negligible.

The virial theorem applied to ion motion in the plane perpendicular to the trap axis near trap mid-length shows that the rms ion velocity v_{rms} is independent of initial conditions and depends only on the trapping potential as $v_{\text{rms}} = C(q\Delta V)^{1/2}$,

where $C = 7.6 \times 10^4 \text{ cm/sec} \cdot (\text{eV})^{1/2}$ is determined by the geometry of the trap and ion mass. This has been compared with the mean ion velocities found from the TOF and retardation data, and found to be consistent with those results to within 10 percent. To study the velocity dependence of the capture cross section, the trap potential was varied from 10 V to 70.7 V. The Ne^{10+} capture rate constants were measured as described above for each trap potential with results shown in Table 1. Assuming a power dependence of $\langle \sigma v \rangle$ on the trap potential $\langle \sigma v \rangle = A(q\Delta V)^p$, a least-squares fit to the data yields $p = 0.54 \pm 0.05$. Figure 4 demonstrates the constancy of $\langle \sigma v \rangle / (\Delta V)^{1/2}$ with $(\Delta V)^{1/2}$, implying that in the range of impact energies studied here, the cross section is velocity independent. A forced fit of $\langle \sigma v \rangle = \sigma_{e.c} v_{\text{rms}}$ to the data yields $\sigma_{e.c} = 2.4(0.2) \times 10^{-15} \text{ cm}^2$. This error is the statistical error in the least-squares fit. The absolute error is estimated to be 30 percent primarily due to uncertainty in the neon density.

A simple semiclassical model to describe the electron capture process in the low-energy regime has recently been proposed.⁷ A prediction of this model is that charge capture takes place into high n -states where n is determined by two conditions. First, the energy of the level into which the electron is captured must be equal to the perturbed binding energy in the target atom. Second, the target and projectile must approach

sufficiently close so that electron transfer is classically possible. Studies conducted at GSI in Darmstadt⁸ are in good agreement with the predicted states. A further prediction of the model is that the cross sections are velocity independent. This is in accord with our observations. Moreover, our value for the total cross section is in reasonable agreement with the simple semiclassical model for one-electron capture.

Acknowledgment

We wish to acknowledge the invaluable assistance of Dr. Harvey Gould, Mr. Douglas MacDonald, and the operators and staff of the LBL Super-HILAC. This work was supported by the Fundamental Interactions Branch, Division of Chemical Sciences, Office of Basic Energy Sciences, U.S. Department of Energy, under Contract No. W-7405-Eng-48.

Footnotes

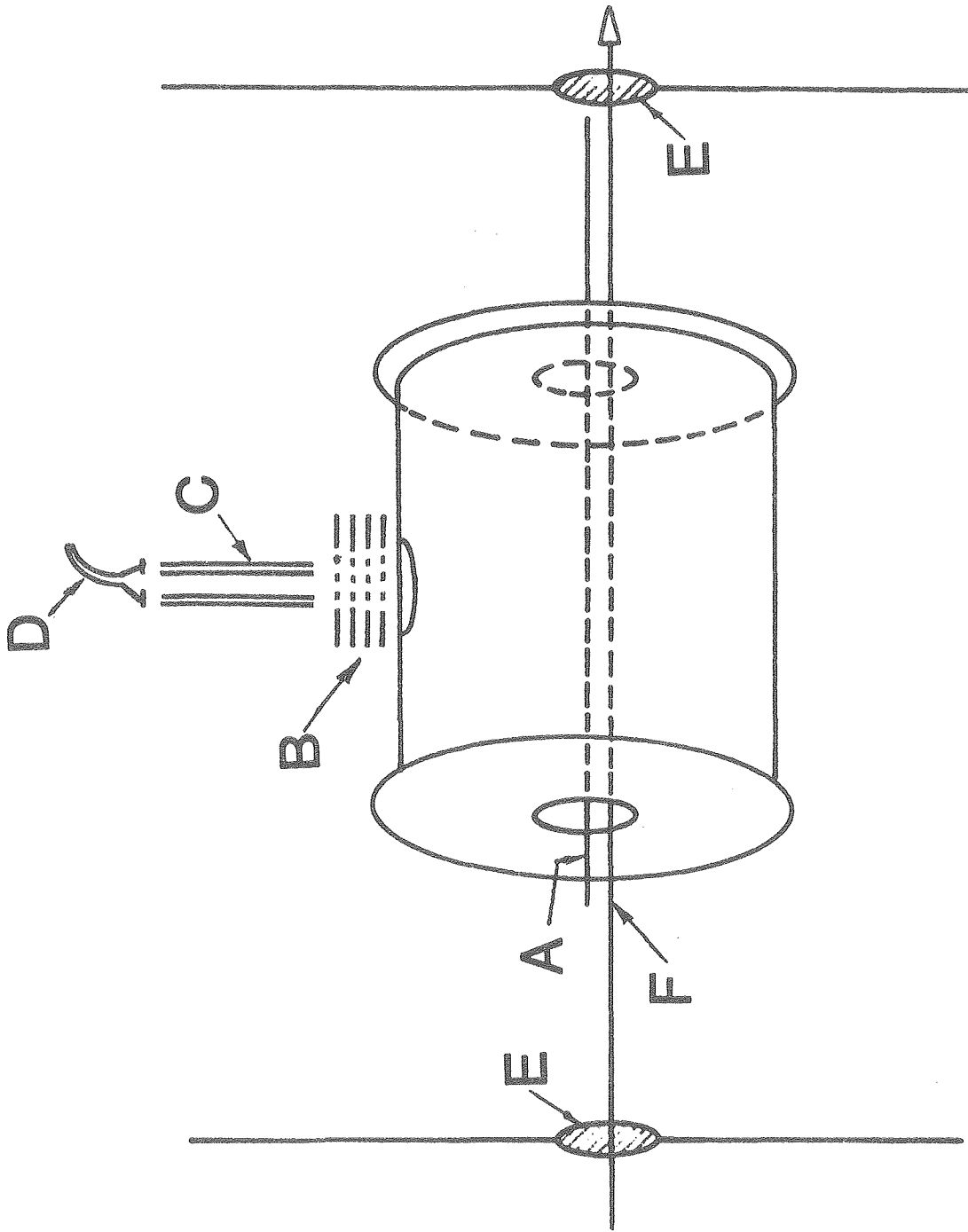
1. H.B. Gilbody, in Advances in Atomic and Mol. Physics (vol. 15), D.R. Bates, ed. (Academic Press, New York, 1979) p. 293.
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Table 1. Variation of capture rate constant $\langle\sigma v\rangle$ with trap potential ΔV .

ΔV (Volts)	v_{rms} (10^6 cm/sec)	$\langle\sigma v\rangle$ (10^{-9} cm ³ /sec)
70.7	2.02	5.1 ± 0.2
40.7	1.53	3.6 ± 0.3
20.7	1.09	2.8 ± 0.1
10.0	0.76	1.7 ± 0.1

Figure Captions

- Figure 1. Electrostatic ion trap. A - central wire, B - accel/decel grids, C - quadrupole m/q analyzer, D - channel electron multiplier, E - vacuum isolation foils, F - beam axis.
- Figure 2. Decay of trapped Ne^{10+} at trap potential of 20.7 V for various neon densities. Each curve has been normalized at $t = 0$, corresponding to the trailing edge of the beam pulse. Error bars indicate statistical uncertainties of the data.
- Figure 3. Ne^{10+} decay rates as a function of target density for trap potentials shown. Slopes give $\langle\sigma v\rangle$ for electron capture from neon.
- Figure 4. Decay rate constant $\langle\sigma v\rangle$ scaled by $(\Delta V)^{-1/2}$ versus $(\Delta V)^{1/2}$. Units of vertical and horizontal axes are $10^{-9} \text{ cm}^3/\text{sec-V}^{1/2}$ and $\text{V}^{1/2}$, respectively. Error bars indicate only the statistical errors in least-squares fits to the data.



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Fig. 1

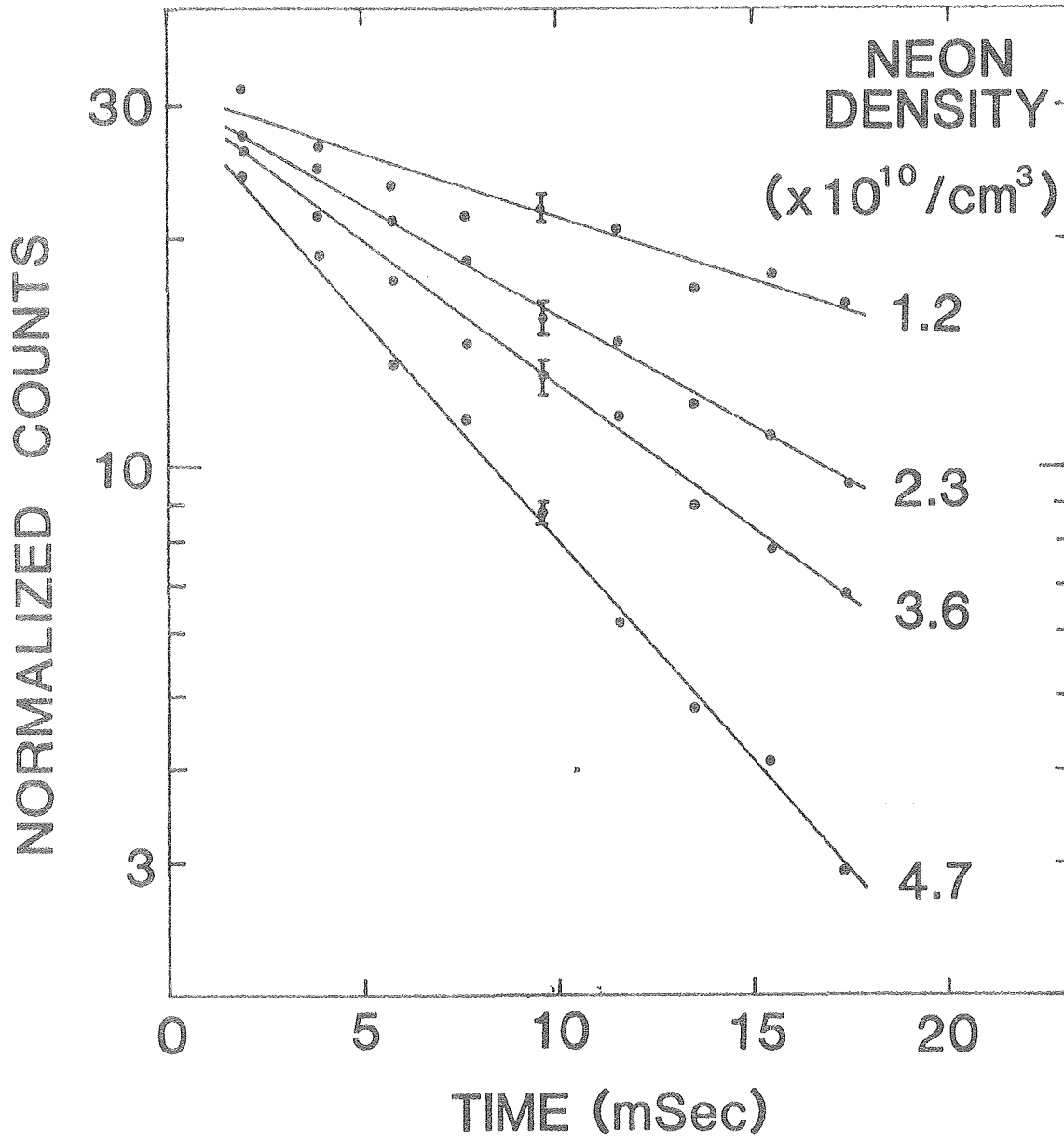


Fig. 2

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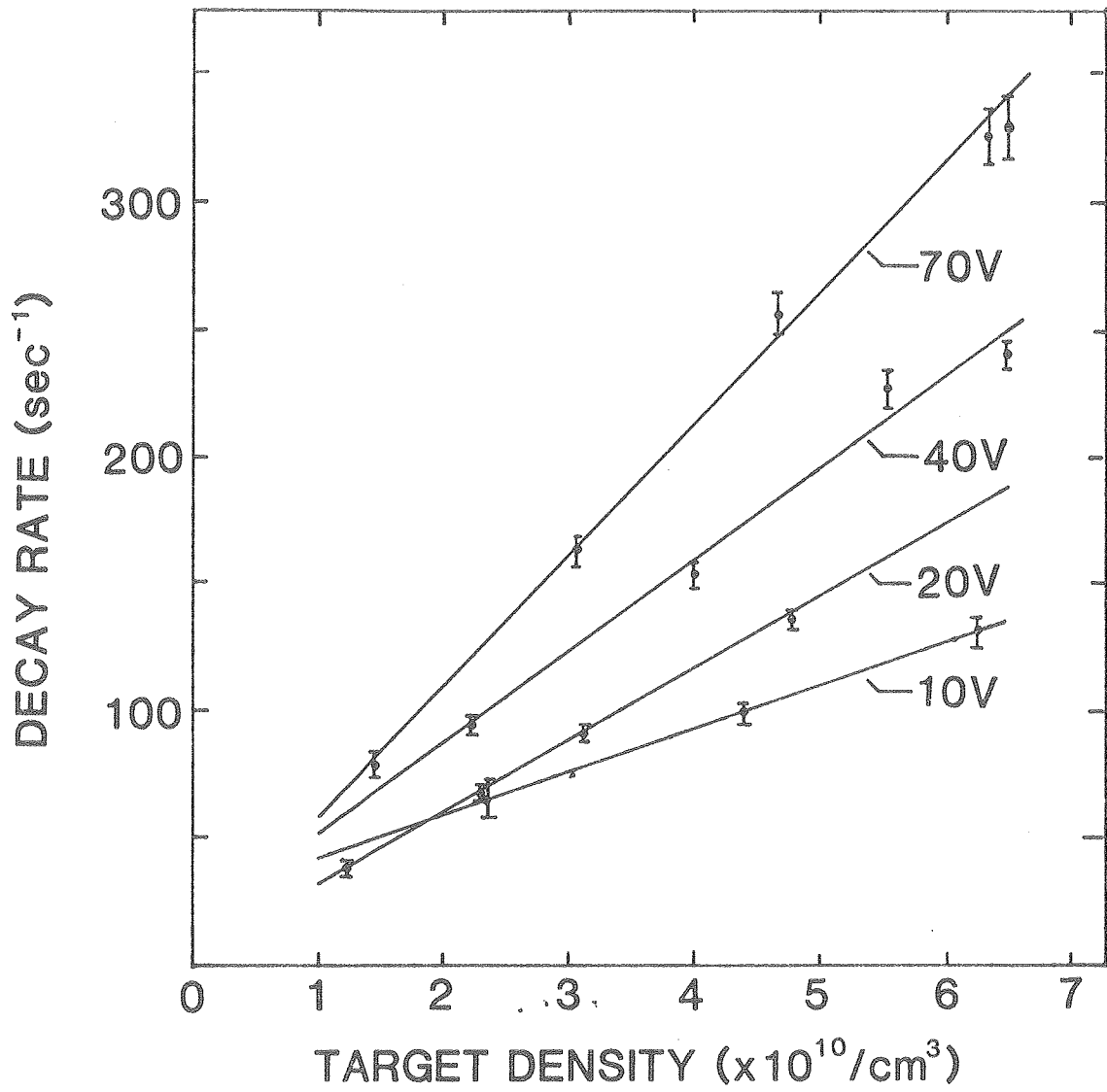


Fig. 3

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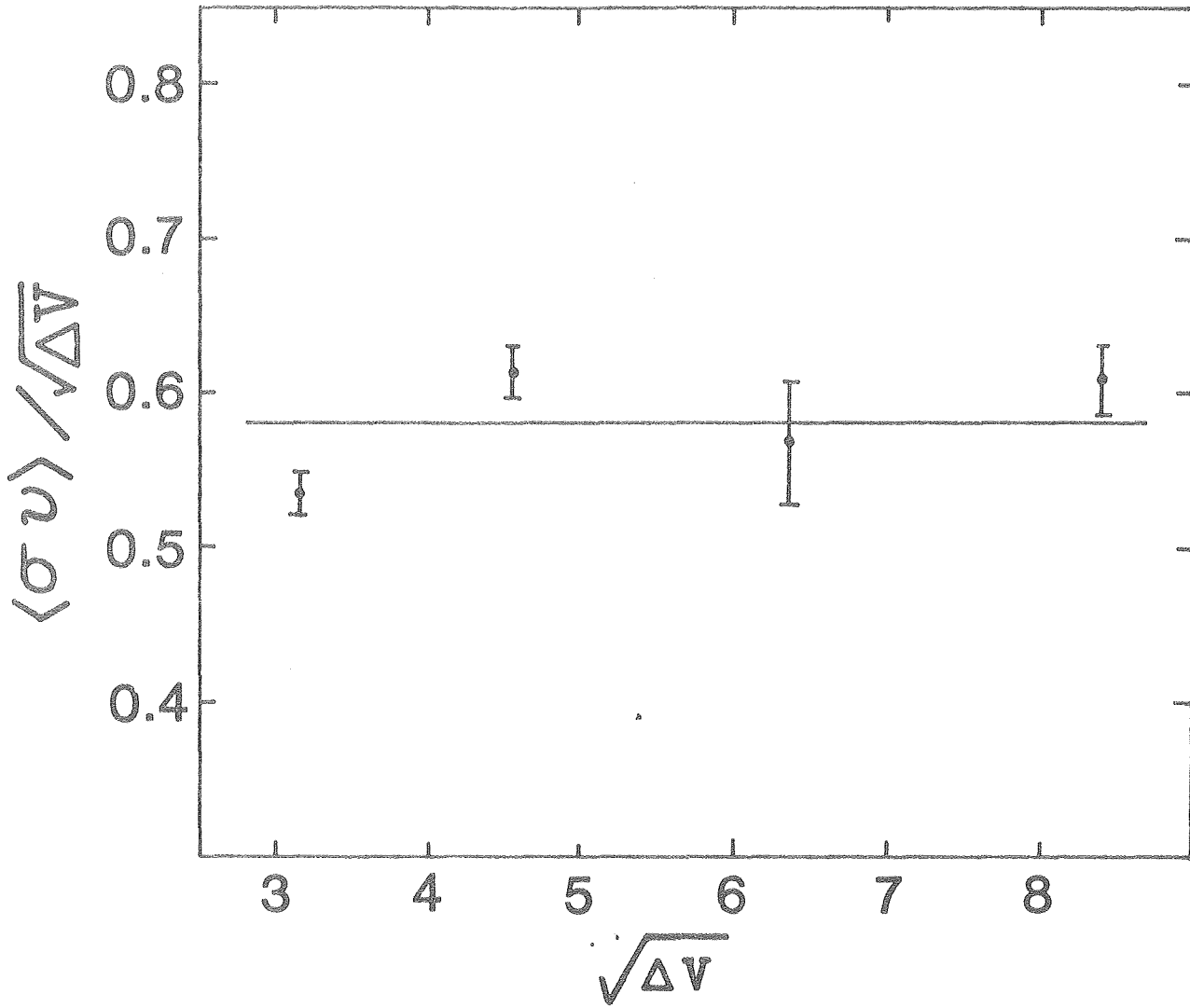


Fig. 4

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