Lawrence Berkeley National Laboratory
Recent Work

Title

ELECTRON CAPTURE FOR FAST HIGHLY CHARGED IONS IN GAS TARGETS: AN EMPIRICAL SCALING RULE

Permalink

https://escholarship.org/uc/item/4938718v

Author

Schlachter, A.S.

Publication Date

1983-03-01

eScholarship.org Powered by the California Digital Library
University of California

LBL-15835
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

RECEIVED
LAWRENCE
BERKELEY LABORATORY
APR 15 1983
LIBRARY AND
DOCUMENTS SECTION

Submitted to Physical Review A

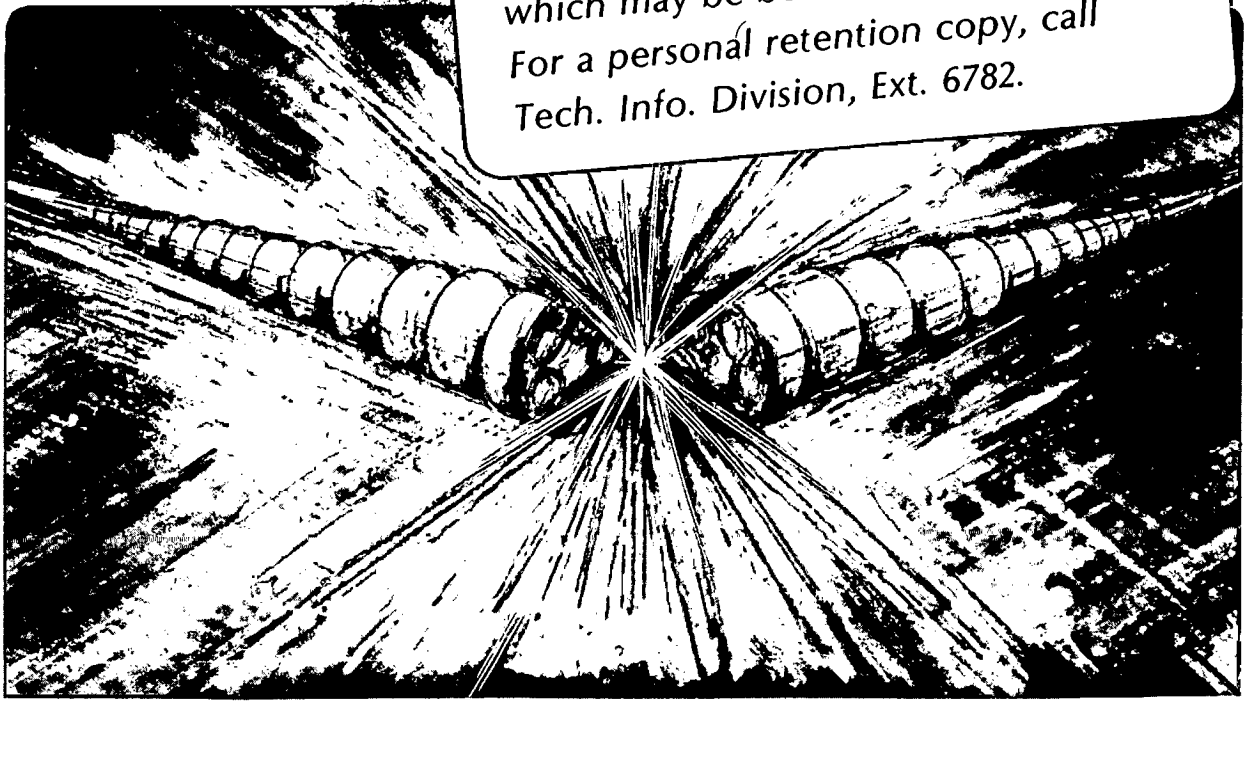
ELECTRON CAPTURE FOR FAST HIGHLY CHARGED IONS IN GAS TARGETS: AN EMPIRICAL SCALING RULE

A.S. Schlachter, J.W. Stearns, W.G. Graham,
K.H. Berkner, R.V. Pyle, and J.A. Tanis

March 1983

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 6782.

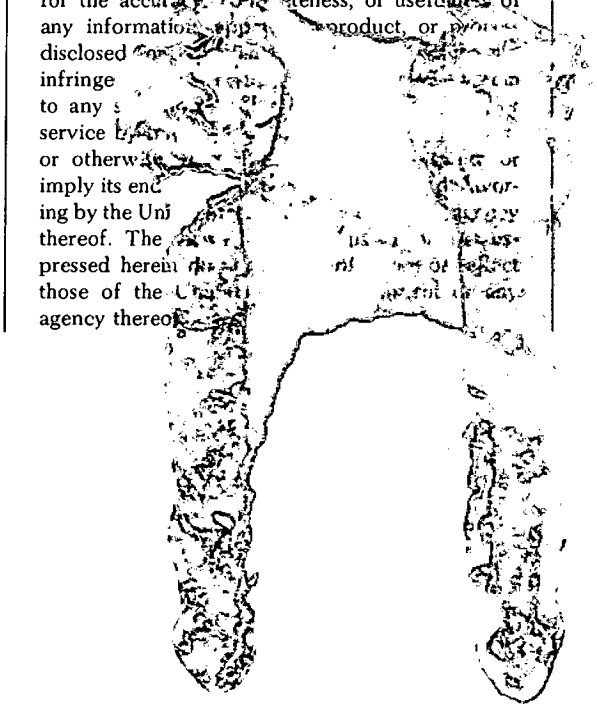


Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-15835

LEGAL NOTICE

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.



Lawrence Berkeley Laboratory is an equal opportunity employer.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Electron Capture for Fast Highly Charged Ions in Gas Targets: An Empirical Scaling Rule*

A. S. Schlachter, J. W. Stearns, W. G. Graham,†
K. H. Berkner, R. V. Pyle, and J. A. Tanis ‡

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

A universal empirical scaling rule for electron-capture cross sections is reported for fast, highly charged ions in atomic and molecular targets. Projectiles range in energy from 0.3-8.5 Mev/amu, with charge states as high as 59^+. This rule permits prediction of electron-capture cross sections for a wide variety of projectile-target combinations.

*This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Applied Plasma Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

†Present Address: The New University of Ulster, Coleraine, BT52 1SA, Northern Ireland

‡Present Address: Western Michigan University, Kalamazoo, MI 49008

PACS No. 34.70. + e
Charge Transfer

March 11, 1983

Charge-transfer cross sections for fast, highly stripped projectiles in gas targets are useful for testing theoretical calculations as well as for a variety of applications including accelerator design, beam transport and fusion plasmas. Given the vast number of combinations of projectile species, energy, and charge state, and the large number of possible gas and vapor targets, scaling rules are useful, if they exist, for predicting the magnitude of unmeasured cross sections. We have empirically found a universal scaling rule, which permits prediction of electron-capture cross sections for a wide range of fast, highly charged projectiles in gas targets. This result is, to our best knowledge, the first empirical scaling rule for electron capture which includes the target dependence.

The present work is a generalization of our previous scaling rule[1] for electron capture by fast highly charged iron ions in an H_2 target, in which we found that the electron-capture cross section σ can be described by

$$\sigma = 1.2 \times 10^{-8} q^{3.15} E^{-4.48} \text{ cm}^2 \qquad (1)$$

for projectile energies greater than 275 keV/amu, where E is the energy of the iron projectile in keV/amu and q is the projectile charge state. Alonso and Gould[2] have found, for fast lead and xenon ions in N_2, a q dependence of approximately 2.9-3.3; in addition, these authors have found a velocity dependence of about $v^{-5.8}$ or $E^{-2.9}$, based on data over a limited range of velocities. Knudsen et al.[3] found that electron-capture cross sections scale as σ/q and $E/q^{4/7}$ in a given target, and, based on the Lenz-Jensen atomic model, cross sections could

be described in reduced coordinates $\sigma Z_2^{2/3}/q$ and $E/(q^{4/7}\ Z_2^{16/21})$, where Z_2 is the target atomic number. Ryufuku[4] has found that cross sections in atomic hydrogen could be scaled in the reduced coordinates $\sigma/q^{1.07}$ and $E/q^{0.35}$, while Janev et al.[5] found $E/q^{0.5}$ to be a suitable scaling parameter for electron capture from inner shells of Ar atom targets.

We have taken a generalized empirical approach to scaling electron-capture cross sections for a large variety of projectiles and targets: we chose generalized reduced coordinates

$$\tilde{\sigma} = \sigma\, Z_2^{c_1}/q^{c_2}$$
$$\tilde{E} = E/(Z_2^{c_3}\ q^{c_4}) \qquad (2)$$

where σ is the electron-capture cross section, q is the projectile charge state, E is the projectile energy per nucleon, Z_2 is the atomic number of the target, and c_1 - c_4 are adjustable scaling parameters. A non-linear least-squares fitting routine was used to adjust parameters c_1 to c_4 to selected electron-capture cross-section data. We began by fitting our experimental cross sections,[1,6] the success of which encouraged us to test the result with other cross-section data available in the literature.[7-15] The best values for the reduced parameters were found to be

$$\tilde{\sigma} = \sigma\, Z_2^{1.8}/q^{0.5}$$
$$\tilde{E} = E/(Z_2^{1.25}\ q^{0.7}) \qquad (3)$$

with σ in cm^2 and E in keV/amu. The parameters c_1-c_4 are not

uniquely determined; many sets of parameters will fit the data nearly as well, with any one parameter varying by as much as 25%. We do not attach physical significance to the exact value of each parameter, but rather to the fact that all cross-section values reduce in this representation.

We also fit an analytic expression of the form

$$\tilde{\sigma} = \frac{P_1}{P_2 P_3 \tilde{E}(P_4 + P_5)} \left[1 - \exp(-P_2 \tilde{E}^{P_4})\right] \left[1 - \exp(-P_3 \tilde{E}^{P_5})\right] \quad (4)$$

to the reduced data, where P_1 - P_5 are fitting parameters. This form was chosen to match the general shape of the scaled data, e.g., to have a high-energy asymptotic form of $\tilde{E}^{-x}$ (x determined by the fit), and to approach a constant value P_1, independent of $\tilde{E}$, for low values of $\tilde{E}$. The other parameters determine the location of the two bends and slopes of the analytic function.. The best fit to the data is

$$\tilde{\sigma} = \frac{1.1 \times 10^{-8}}{\tilde{E}^{4.8}} \left[1 - \exp(-0.037\, \tilde{E}^{2.2})\right] \left[1 - \exp(-2.44 \times 10^{-5}\, \tilde{E}^{2.6})\right]. \quad (5)$$

Cross-section data for a wide variety of targets, from measurements by the present authors, [1,6] are shown in Fig. 1. Figure 2 shows representative data obtained by others.[7-15] All data in both figures are shown in the reduced coordinates of Eqn. 3, and the curve in all figures is the representation of Eqn. 5; approximately 70% of the data lie within a factor of 2 of the curve. Equation 5 was tested with much more data than are shown in the figures; all data tested fit as well as

those shown, subject to several restrictions:

$$10 \leqslant \tilde{E} \tag{6a}$$

where $\tilde{E}$ is defined in Eqn. 3, with energy E in keV/amu; and

$$q \geqslant 3 \tag{6b}$$

i.e., the reduction method does not scale the data well for singly and doubly charged ions, nor for low reduced energies. We have observed that the charge-state restriction (6b) can be removed if q is replaced by q + 0.4.

The scaling rule has only been tested for

$$\tilde{E} < 1000 \tag{6c}$$

and its use should be restricted to smaller values, since it is possible that the curve will continue to bend with increasing steepness for higher values of $\tilde{E}$.

At high reduced energies, Eq. 5 asymptotically approaches

$$\sigma = 1.1 \times 10^{-8}\ q^{3.9}\ Z_2^{4.2}/E^{4.8} \quad . \tag{7}$$

The energy and charge state dependences are similar to, but somewhat greater than, our previous result (Eq. 1) for iron ions in an H_2 target. The new feature of this result is the target atomic-number dependence, allowing prediction of electron-capture cross sections for many targets.

Crothers and Todd[16] have shown that semiclassical theory accounts for q^3 scaling in electron-capture in atomic hydrogen at intermediate energies, and that semiclassical OBK, eikonal, continuum intermediate-state and continuum distorted-wave theories all lead to q^3 scaling. In the limit of high velocities, OBK and more modern theories[17] predict a q^5 dependence. The asymptotic charge-state dependence observed in the present result is $q^{3.9}$.

Eichler and Narumi[18] have compared the Born approximation with the classical-trajectory eikonal approximation: the second Born approximation gives rise to a v^{-11} term ($E^{-5.5}$), which will dominate the first Born term, which varies as v^{-12} (E^{-6}), while the classical-trajectory eikonal approximation only predicts the v^{-12} (E^{-6}) velocity dependence. We observe a v^{-9} dependence on velocity for large velocities, rather than the theoretically expected v^{-11} or v^{-12}.

It seems likely that, were data to exist for much higher reduced energies, the asymptotic behavior we observe (Eqn.7) would have to be modified. The q dependence may approach q^5 and the velocity dependence v^{-12}.

We note that electron-capture cross sections in H_2 were treated here by dividing the measured cross section by 2 and then using $Z_2 = 1$. Knudsen et al.[19] find a ratio of about 3.8 for the electron-capture cross section for fast highly charged projectiles in H_2 and H targets. The factor of 2 we used in our analysis does not imply a constant ratio for electron-capture cross sections in H_2 and H targets. Measured cross sections for N_2 in the present work were also compared with the empirical scaling rule by dividing the cross section by 2 and then using $Z_2 = 7$.

In summary, an empirical scaling rule has been found for single-electron capture by fast highly charged projectiles in gas targets, which can be used to predict cross sections for many projectile-target systems in the reduced energy range $10 < \tilde{E} < 1000$. To our knowledge, this is the first empirically determined target Z_2 dependence which has been included in a scaling rule for electron capture. We also find projectile charge state, projectile energy, and target atomic-number dependences for electron-capture cross sections in the limit of high reduced energy: $q^{3.9}$, $E^{-4.8}$, and $Z_2^{4.2}$.

Acknowlegments

This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Applied Plasma Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. One of us (WGG) would like to acknowledge support from NATO under Research Grant No.1910. We also acknowledge Dr. J. H. McGuire for helpful discussions.

References

1. K. H. Berkner, W. G. Graham, R. V. Pyle, A. S. Schlachter, and J. W. Stearns, Phys. Rev. A 23, 2891 (1981).
2. J. Alonso and H. Gould, Phys. Rev. A 26, 1134 (1982).
3. H. Knudsen, H. K. Haugen, and P. Hvelplund, Phys. Rev. A 23, 597 (1981).
4. H. Ryufuku, Phys. Rev. A 25, 720 (1982).
5. R. K. Janev, L. P. Presnyakov, and V. P. Shevelko, Phys. Lett. 76A, 121 (1980).
6. W. G. Graham, K. H. Berkner, R. V. Pyle, A. S. Schlachter, J. W. Stearns, and J. A. Tanis, to be submitted to Phys. Rev. A.
7. T. Tonuma, I. Kohno, Y. Miyazawa, F. Yoshida, T. Karasawa, T. Takahashi, and S. Konno, J. Phys. Soc. Jpn. 34, 148 (1973).
8. J. Alonso, D. Dietrich, and H. Gould, IEEE Trans. Nucl. Sci. NS-26, 3686 (1979).
9. H. D. Betz, Rev. Mod. Phys. 44, 465 (1972).

10. J. A. Tanis, E. M. Bernstein, M. P. Stockli, W. G. Graham, K. H. Berkner, D. J. Markevich, R. H. McFarland, R. V. Pyle, J. W. Stearns, and J. E. Willis, to be published.

11. S. M. Ferguson, J. R. Macdonald, T. Chiao, L. D. Ellsworth, and S. A. Savoy, Phys. Rev. A 8, 2417 (1973).

12. S. Datz, H. O. Lutz, L. B. Bridwell, C. D. Moak, H. D. Betz, and L. D. Ellsworth, Phys. Rev. A 2, 430 (1970).

13. V. S., Nikolaev, I. S. Dmitriev, L. N. Fateeva, Ya. A. Teplova, Zh. Eksp. Teor. Fiz. 40, 989 (1967). [Sov. Phys. - JETP 13, 695 (1967).

14. J. A. Tanis, E. M. Bernstein, W. G. Graham, M. Clark, S. M. Shafroth, B. M. Johnson, K. W. Jones, and M. Meron, Phys. Rev. Lett. 49, 1325 (1982).

15. T. R. Dillingham, J. R. Macdonald, and P. Richard, Phys. Rev. A 24, 1237 (1981).

16. D. S. F. Crothers and N. R. Todd, J. Phys. B 13, 2277 (1980).

17. J. R. Oppenheimer, Phys. Rev. 31, 349 (1928); H. C. Brinkman and H. A. Kramers, Proc. Acad. Sci. Amsterdam 33, 973 (1930); J. S. Briggs, J. Phys. B 10, 3075 (1977); J. H. Macek and S. Alston, Phys. Rev. A 26, 250 (1982); J. H. McGuire, to be published in IEEE Trans. Nucl. Sci. (April 1983).

18. J. Eichler and H. Narumi, Z. Phys. A 295, 209 (1980); and references therein.

19. H. Knudsen, H. K. Haugen, and P. Hvelplund, Phys. Rev. A 24, 2287 (1981).

Figure Caption

Fig. 1 Reduced plot of single-electron-capture cross sections[1,6] for fast highly charged ions with charge state q incident on gas targets with atomic number Z_2. Cross sections in molecules are divided by 2 and plotted with the atomic Z_2. The line is an empirical fit (Eq.5) to the cross sections. The symbols used to represent the targets are shown in the figure.

Fig. 2 Same as Fig. 1, with electron-capture cross-section data from Refs. 7-15. The same curve, Eq. 5, is shown in all figures.

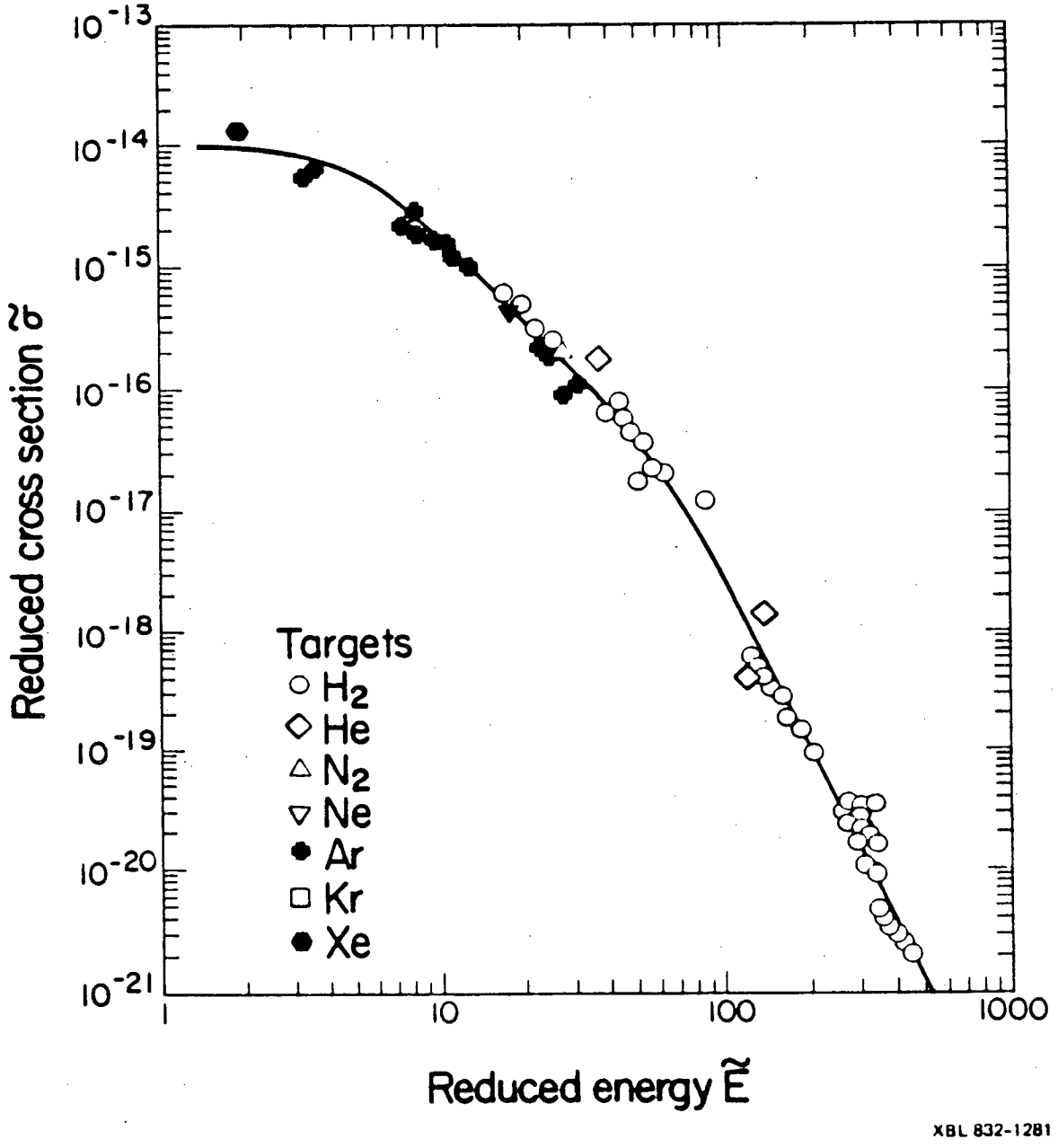

Reduced cross section $\tilde{\sigma}$
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
Targets
H_2
He
N_2
Ne
Ar
Kr
Xe
1
10
100
1000
Reduced energy $\tilde{E}$
XBL 832-1281

Fig. 1

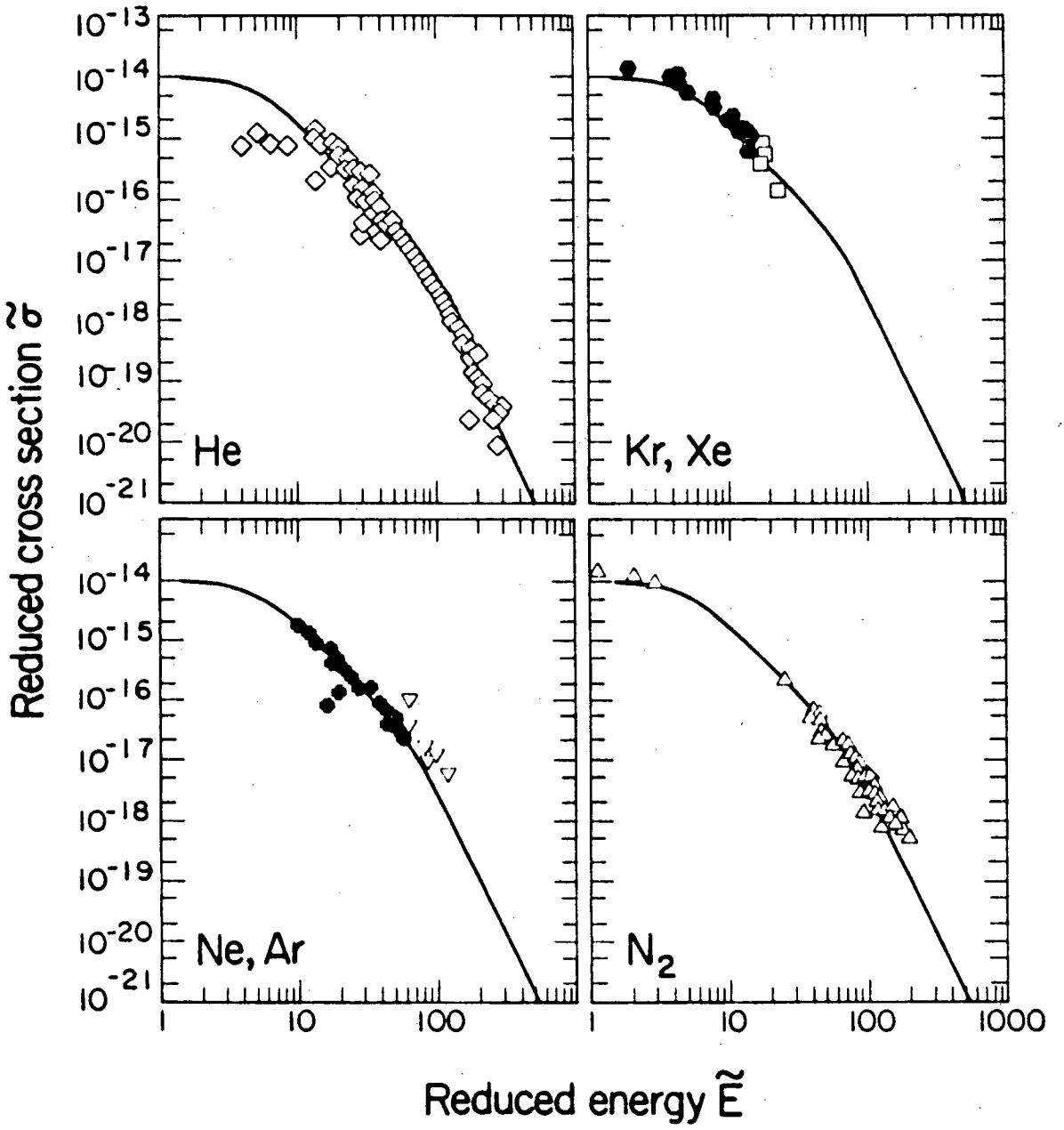

Reduced cross section $\tilde{\sigma}$
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
He
Kr, Xe
Ne, Ar
N_2
1
10
100
1000
Reduced energy $\tilde{E}$
XBL 832-1280

Fig. 2

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720