LBL-21223

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

Presented at the Second U.S.-Mexico Atomic
Physics Symposium on Two Electron Phenomena,
Cocoyoc, Mexico, January 8-11, 1986

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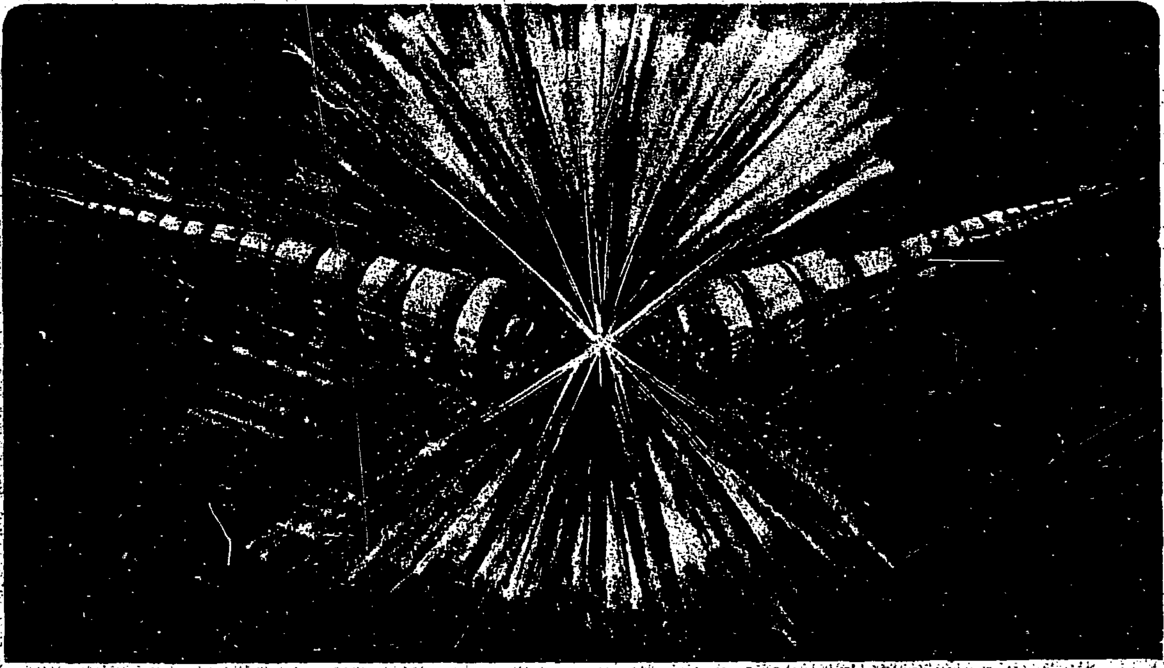
January 1986



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

Neutralization of a Fast Negative-Ion Beam*

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LBL--21223

DE86 011315

Abstract

Neutralization of a fast negative-ion beam, primarily H^-, is discussed in terms of competing one- and two-electron detachment processes in a variety of media: gas (vapor), plasma, liquid sheet, solid foil.

* This work was supported by U.S. DOE Contract No. DE-AC03-76SF00098 and DOD BMDATC MIPR W31RPD63-H087.

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I. Introduction

Beams of energetic neutral atoms are useful in a variety of applications, e.g., heating and fueling fusion plasmas, plasma diagnostics, and possible space applications. In addition, the interaction of an energetic negative ion with a neutralizer medium is an interesting example of a system in which both one- and two-electron processes compete, and in which electron correlation can be a significant factor. This paper treats neutralization of energetic negative ions in a variety of neutralizer media: gas (vapor), solid foil, plasma, liquid sheet. New experiments on neutralization of energetic H^- ions in an Ar plasma and in a liquid sheet are discussed.

An example of the use of an energetic atom beam for plasma diagnostics is as a probe of alpha-particle distribution in a magnetically confined d-t (deuterium-tritium) fusion plasma. The nuclear reaction,

$$d + t \rightarrow \alpha + n + 14.6\ \mathrm{MeV} \tag{1}$$

produces 3.5-MeV alpha particles (He^{++}), which are confined by the magnetic field, and give up their energy to heat the d-t fuel. An essential diagnostic problem for the next generation of tokamaks is to measure the spatial, temporal, and velocity distribution of the alpha particles. Two methods which have been proposed to accomplish this[1-3] require energetic neutral beams:

1-electron transfer $H^0 + He^{++} \rightarrow H^+ + He^+(n\ell)$

$$\hookrightarrow \quad He^+ + h\nu \tag{2}$$

where n and ℓ are quantum numbers of the excited state of He^+, and the spectrum from decay of excited He^+ characterizes the distribution; and

2-electron transfer $Li^0 + He^{++} \rightarrow Li^{++} + He^0$ (3)

where the He^0 atoms can escape the confining magnetic field and are detected for the measurement. Neither method has been tested. The cross section for the reaction in Eq. 3 has been measured,[4,5] while the cross section for the reaction in Eq. 2 is known only for a limited range of energy and for low values of the principal quantum number n.

The most intense neutral beams to date have been produced by electron-capture collisions of positive ions in a gas target. Neutral beams at energies greater than a few hundred keV/amu, however, cannot be efficiently produced by neutralization of positive ions, because, for example, a proton traveling considerably faster than the Bohr velocity (~25 keV) is moving too fast to efficiently capture an electron from a target atom. Energetic negative ions, on the other hand, can be efficiently neutralized by detachment of the extra electron from the negative ion, even at very high energies.[6] An example of this for hydrogen ions is shown in Fig. 1.[7]

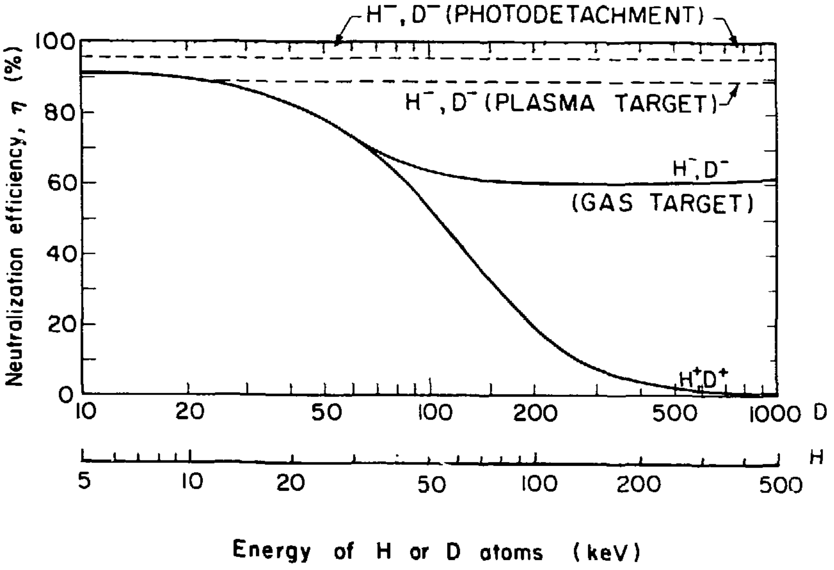

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Fig. 1. Neutralization efficiencies[7] for H^+ (D^+) and H^- (D^-) in gas and plasma targets, and photoneutralization efficiency for H^- (D^-).

The changes of charge-state as an energetic H^- beam passes through a neutralizing medium, at energies where electron capture is an unlikely process, are determined by the reactions in Eqs. 4-6:

1-electron detachment σ_{-0} $$H^- + X \rightarrow H^0 + \ldots \tag{4}$$

2-electron detachment σ_{-+} $$H^- + X \rightarrow H^+ + \ldots \tag{5}$$

electron loss σ_{0+} $$H^0 + X \rightarrow H^+ + \ldots \tag{6}$$

where X is a target atom, molecule, ion, or electron. Charge-state fractions F_i as a function of target thickness π for energetic H^- incident on a target of variable thickness are shown in Fig. 2 for a generic neutralizer; for the

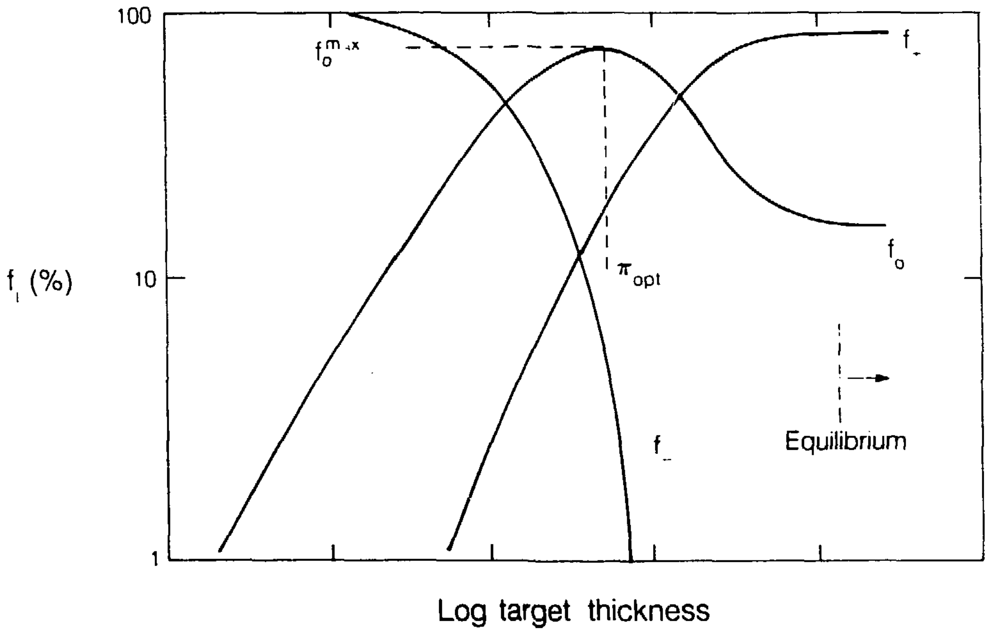

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Fig. 2. Charge-state fractions as a function of target thickness for moderate-energy (e.g., 100 keV/u) H^- incident on a neutralizer.

example shown, electron capture is small but not negligible. The neutral fraction F_0 has a maximum, F_0^{max}, for a target thickness π^{opt}. F_0^{max} at very high energies, at which electron capture can be neglected, can be expressed in terms of the relevant cross sections:

$$F_0^{max} = \left(\frac{\sigma_{-0}}{\sigma_{-0} + \sigma_{-+}}\right) \left(\frac{\sigma_{0+}}{\sigma_{-0} + \sigma_{-+}}\right) \exp \left(\frac{\sigma_{0+}}{\sigma_{-0} + \sigma_{-+} - \sigma_{0+}}\right) \tag{7}$$

and the optimum target thickness π^{opt} is given by:

$$\pi^{opt} = (\sigma_{-0} + \sigma_{-+} - \sigma_{0+})^{-1} \ln \left(\frac{\sigma_{-0} + \sigma_{-+}}{\sigma_{0+}}\right) \quad . \tag{8}$$

The maximum neutral fraction is determined primarily by competition between σ_{-0} and σ_{0+}, while σ_{-+} acts to transform H^- directly to H^+.

II. Gas neutralizer

The maximum neutral fraction F_0^{max} for energetic H^- in favorable gas or vapor neutralizers is 55-60%, over a wide range of energies.[8] F_0^{max} has little energy dependence in fast collisions, because the cross sections σ_{-0} and σ_{0+} have the same energy dependence. F_0^{max} is generally smaller for negative ions other than H^-,[9,10] e.g., about 40% for Li^-, 25% for C^-, and 20% for O^- and Si^-.

A gas neutralizer is fairly simple, and the maximum neutral fraction is moderately high; for large beams at high energies, gas consumption and pumping requirements could be problematic.

III. Foil neutralizer

A foil neutralizer for negative ions is useful only for very high-energy beams, because of the practical limit of producing thin foils: at low energies the electron-detachment cross section is so large that the thinnest practical foil is thicker than π^{opt}. Foils are more typically used for removing several electrons from a fast ion, e.g., increasing the charge state of fast, multiply charged ions in large accelerators, or for changing H^- to H^+ for extraction from a cyclotron. Charge-state fractions have been reported as a function of foil thickness for 200-MeV H^- incident on a carbon foil[11], as shown in Fig. 3. F_0^{max} is about 55% for a thickness of about 20 μgm/cm^2.

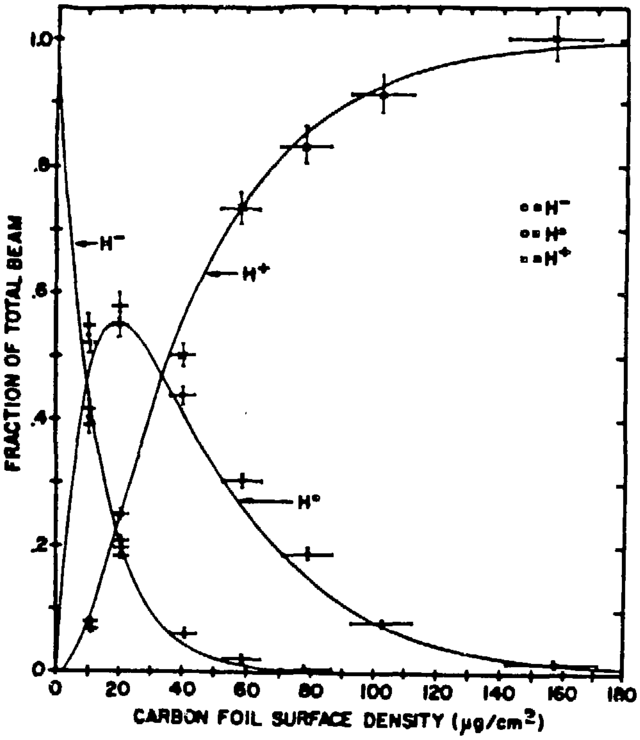

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Fig. 3. Charge-state fractions as a function of foil thickness for 200-MeV H^- incident on a carbon foil.[11]

A foil neutralizer is useful only for multi-MeV H^- beams. Its efficiency is similar to that for a gas neutralizer, but it has the advantage of not requiring differential pumping. Beam intensity is limited because of foil damage or rupture.

IV. Plasma neutralizer

A plasma neutralizer[6] offers several potential advantages over a gas neutralizer for fast incident negative ions: higher efficiency, thinner target, and lower gas consumption. These advantages are a function of the gas chosen for the plasma and the state of ionization of the plasma. Simple estimates give a likely neutralization efficiency of 85-90% for energetic H^-.

Neutralization of a fast H^- beam by a plasma is governed by simple rate equations, including the following processes (remembering that a plasma contains ions and electrons):

$$\sigma_{-0}^{ion}:\ H^- + Y^{q+} \rightarrow H^0 + \ldots$$

$$\sigma_{-0}^{e}:\ H^- + e^- \rightarrow H^0 + 2e^- \tag{9}$$

$$\sigma_{0+}^{ion}:\ H^0 + Y^{q+} \rightarrow H^+ + \ldots$$

$$\sigma_{0+}^{e}:\ H^0 + e^- \rightarrow H^+ + 2e^- \tag{10}$$

$$\sigma_{-+}^{ion}:\ H^- + Y^{q+} \rightarrow H^+ + \ldots$$

$$\sigma_{-+}^{e}:\ H^- + e^- \rightarrow H^+ + 3e^- \tag{11}$$

where Y^{q+} is a target ion in charge state q. The cross sections for collisions with electrons, σ_{ij}^{e}, are known, as well as[12] the electron-loss cross section σ_{0+}^{ion} for collisions with multiply charged ion projectiles; however, the cross sections σ_{-0}^{ion} and σ_{-+}^{ion} are not presently known for $q > 1$. If we make the assumption that, at high energies, σ_{-0}^{ion} and σ_{-+}^{ion} scale the same way as σ_{0+}^{ion}, i.e., as $q^2(\ln E)/E$, where E is the H^- energy, then F_0^{max} will be about 85%, and π^{opt} will decrease as $1/q^2$, i.e., a plasma with a mean charge state of 10 will require a target thickness for maximum neutralization of energetic H^- reduced by a factor of more than 100 compared with a hydrogen plasma, and with a much greater reduction relative to a gas neutralizer.

An example of a calculation of charge-state fractions for 1-MeV H^- incident on an Ar^{3+} plasma neutralizer (with 3 electrons for every Ar^{3+} ion), which used estimated cross sections is shown in Fig. 4. For this example, F_0^{max} is 89%.

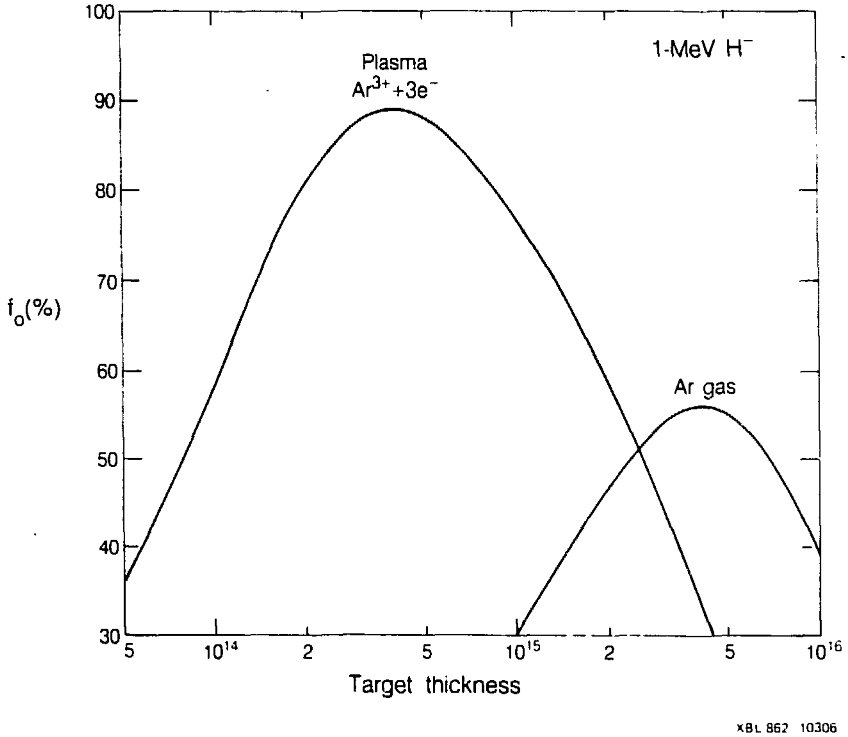

Fig. 4. Calculated H^0 fraction as a function of target thickness for 1-MeV H^- incident on an Ar^{3+} plasma (ion density shown) and on Ar gas (gas density shown). Estimated cross sections were used in the calculation.

A schematic diagram of apparatus which was used to study neutralization of 100-keV H^- in an Ar plasma is shown in Fig. 5. The plasma had a maximum electron density of 5×10^{11} cm^{-3} and a length of 15 cm. The mean Ar-ion charge state was about 2.5, and the gas pressure was in the 5×10^{-5} torr range. The plasma target was designed and built by Ka-ngo Leung at LBL. A neutral fraction of only a few percent has been obtained to date, because the plasma has not been sufficiently thick to achieve F_0^{max}. Work is underway to increase the plasma density and mean charge state, and to determine neutral atom density in the plasma by electron capture of a proton beam.

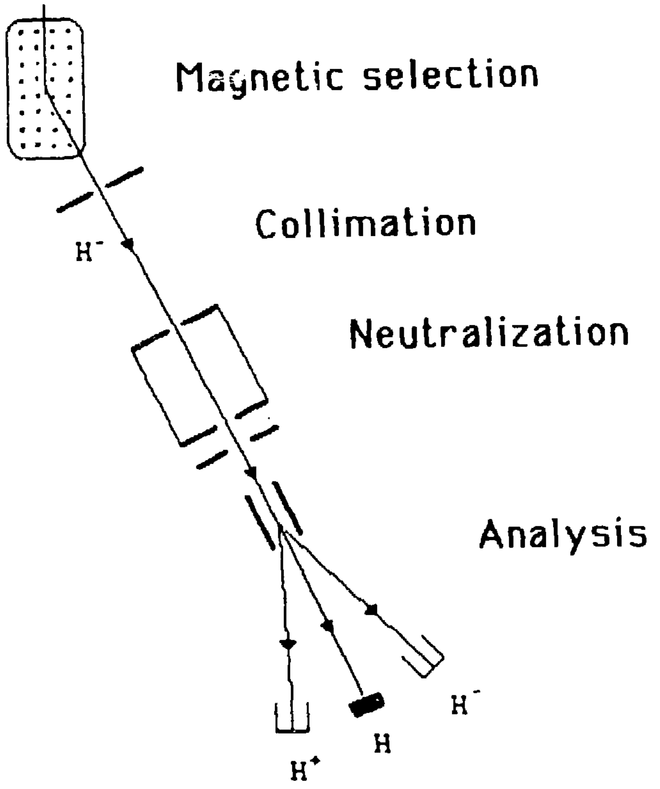

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Fig. 5. Apparatus at LBL for study of neutralization of energetic H^- in a plasma target.

Other experiments have studied neutralization of 3-MeV Li^-, C^-, and Si^- in a hydrogen plasma, and 100-keV H^- in a hydrogen plasma.[13,14]

A plasma neutralizer is expected to be very effective in providing a high neutral fraction if a sufficiently dense plasma can be maintained. Power efficiency and magnetic-field constraints remain to be determined. Measurements and/or calculations of the relevant ion-ion cross sections σ_{-0}^{ion} and σ_{-+}^{ion}, e.g., a negative-ion-positive-ion crossed-beam experiment, would be very useful.

V. Liquid sheet

A liquid sheet has been designed and built at LBL, primarily to increase the charge state of fast multiply charged ions. It consists of a film of Fomblin oil formed by squirting oil onto a high-speed rotating disk. The liquid sheet extends several cm past the edge of the disk. The device is very compact, needs little pumping, and the sheet is self-healing.

We have recently performed a measurement at the LBL SuperHILAC accelerator of neutralization of 17-MeV D^- in a liquid sheet, with the assistance of Jack Gavin, who developed the liquid-sheet technology, and Bruce Rude. The components of the beam in charge states +,o, and - after passage through the liquid sheet (apparatus schematic is shown in Fig. 6) were magnetically separated, and were measured with solid-state detectors. A neutral fraction of 25% was obtained for the thinnest sheet, 2-5 $\mu gm/cm^2$, which could be produced. Optimum neutralization would have required a thinner sheet or a higher beam energy. The maximum H^- intensity that will not destroy the liquid sheet is not yet known. Additional experiments are planned with thinner sheets or with H^- or D^- at higher energies, in order to determine the maximum neutral fraction. Further experiments will study maximum beam intensities. A method will be developed to measure the thickness of thin sheets.

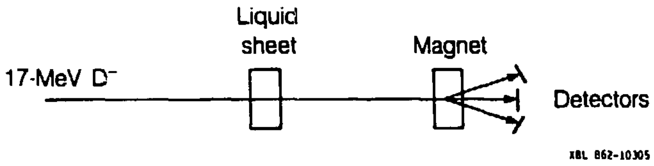

Fig. 6. Apparatus at SuperHILAC for study of neutralization of 17-MeV⁻in a liquid sheet.

A liquid sheet appears to be promising as a neutralizer, with little pumping required and with essentially no consumables. Further experiments are needed.

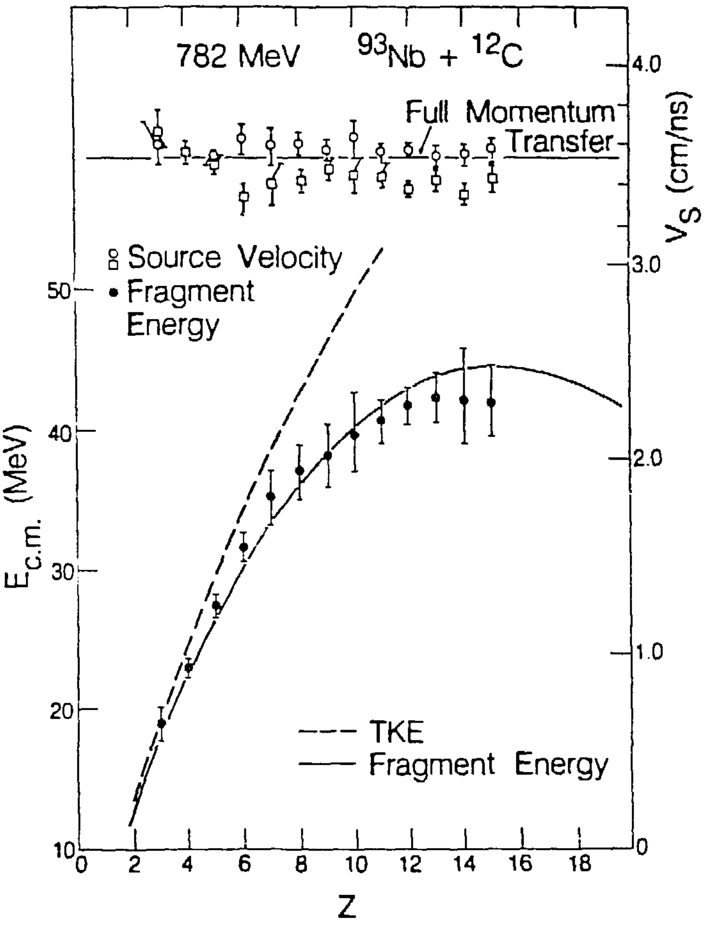

Fig. 6

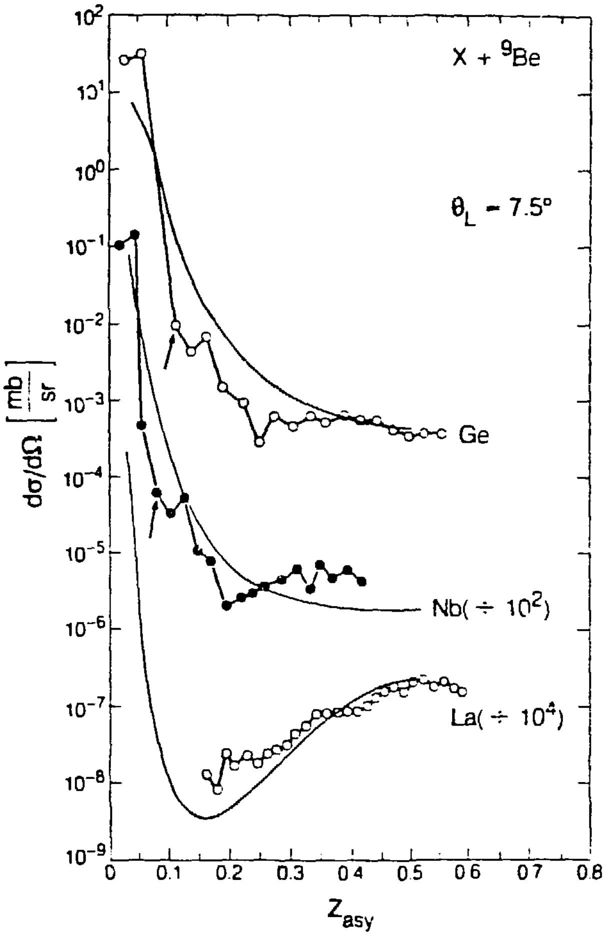

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Fig. 7