LA-7999-MS

Informal Report

Charge Exchange in Low Energy D and T Beams

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

Charge Exchange in Low Energy D and T Beams

Steven E. King
Nelson Jarmie

MASTER

CONTENTS

ABSTRACT	1
I. Introduction	1
II. Calculation of Non-Equilibrium Charge State Fractions	2
III. Results.	5
IV. Error Analysis	6
V. Conclusions.	6
REFERENCES	7

CHARGE EXCHANGE IN LOW ENERGY D AND T BEAMS

BY

STEVEN E. KING AND NELSON JARMIE

ABSTRACT

The process of charge exchange of deuterons and tritons in a hydrogenic gas target is examined and the charge fraction versus target thickness is calculated and plotted. The approach to equilibrium of the charge exchange interaction is examined at various energies. Finally, the possible effects on a low energy fusion cross section experiment are briefly looked at.

1. INTRODUCTION

An experiment underway at Los Alamos Scientific Laboratory is attempting to measure fusion cross sections for the d+t and t+t reactions at energies from 10 to 120 keV. The target for the experiment is a hydrogenic windowless target with a planned central density of 3×10^{16} nuclei/cm². Planned are both negative and positive beams of deuterons and tritons on hydrogenic targets. At these low energies, it is critical to understand charge exchange processes that occur, in order to design beam current and energy measurement devices, and to determine energy losses in the target.

Charge exchange occurs when a beam of particles, in this case d or t, interacts with a target (D or T) to capture or lose electrons. This interaction eventually comes to an equilibrium which depends on the target composition, the beam composition, and the energy of the ion beam. The purpose of this report is to determine the charge fractions throughout the target and under what conditions equilibrium will be established with a hydrogen target. Also, more specifically, is 3×10^{16} atoms/cm² sufficient target thickness to reach equilibrium?

II. CALCULATION OF NON-EQUILIBRIUM CHARGE STATE FRACTIONS

Table I gives the necessary preliminary data for the calculations for 10-100 keV ions¹.

TABLE I

		<u>d</u>	<u>t</u>
Energy (keV/nucleon)		5-50	3-33
Velocity (10^8 cm/sec)		0.98-3.1	0.8-2.5
Equilibrium	H ⁺	0.16-0.59	0.13-0.485
Charge	H ⁰	0.79-0.41	0.82-0.505
Fractions	H ⁻	0.05-0.004	0.05-0.01

Now we calculate the non-equilibrium ion fractions, F_i 's for d and t on windowless deuterium or tritium targets. The following derivation is from Allison². We will define the total cross section as the probability of a charge changing collision. Angular dependence is neglected since there is little momentum change and only the forward angles matter for the loss or gain of just one electron. The differential change of the beam fraction of a state i is

$$\frac{dF_i(t)}{dt} = \sum_{i \neq i'} \left[\sigma_{i'i} F_{i'}(t) - \sigma_{ii'} F_i(t) \right], \quad (1)$$

where t is the thickness in atoms/cm² into the target, F_i is the fraction of ions in charge state i, and $\sigma_{ii'}$ is the charge changing cross section going from state i to i'. This equation is only for ground state exchanges, and for thin targets, since for thick targets the energy loss changes the cross sections.

Thus, we have a coupled set of differential equations to solve. For initially positive d⁺ and t⁺ beams we may neglect the d⁻ or t⁻ fraction (the equilibrium fraction is at most 5% from Marion¹ or 2%

from Allison²). A calculation of the complete 3 component system using cross sections from Allison² for 10 keV deuterons was done, and the d^- fraction was approximately 2.0% for a 5.0×10^{16} atoms/cm² thick target and negligible ($< 0.1\%$) for a 0.3×10^{16} atoms/cm² thick target. At other energies the contribution should be smaller because of lower d^- equilibrium charge fractions and lower cross sections for interactions involving d^- .

For the two component system, we have two equations

$$\frac{dF_0}{dt} = \frac{-dF_1}{dt} = F_1 \sigma_{10} - F_0 \sigma_{01} \quad , \quad (2)$$

The solutions to these equations are:

$$F_1 = F_1' + P(Z,i) \exp \left[-t(\sigma_{01} + \sigma_{10}) \right] \quad , \quad (3)$$

in which F_1' is the equilibrium fraction of state i, Z is the initial charge state of the beam, and $P(Z,i)$ is a coefficient, which is a function of the cross sections.

For the two component system

$$\begin{aligned} P(1,1) &= F_0' \\ P(1,0) &= -F_0' \end{aligned} \quad (4)$$

In order to calculate the charge fractions for an initially negative d^- or t^- ion beam we are forced to use the three component system. The three differential equations are

$$\frac{dF_{-1}}{dt} = -F_{-1}(\sigma_{-10} + \sigma_{-11}) + F_0 \sigma_{0-1} + F_1 \sigma_{1-1} \quad ,$$

$$\frac{dF_0}{dt} = -F_0(\sigma_{01} + \sigma_{0-1}) + F_1\sigma_{10} + F_{-1}\sigma_{-10} \quad , \quad (5)$$

$$\frac{dF_1}{dt} = -F_1(\sigma_{10} + \sigma_{1-1}) + F_0\sigma_{01} + F_{-1}\sigma_{-11} \quad ,$$

The solution for F_i is

$$F_i = F_i^{\infty} + \left[P(Z, i) \exp(tq) + N(Z, i) \exp(-tq) \right] \exp\left(-\frac{t}{2} \Sigma \sigma_{if}\right) \quad , \quad (6)$$

$$\text{in which } q = 1/2 \left[(g-a)^2 + 4bf \right]^{1/2} \quad ,$$

$$\Sigma \sigma_{if} = -(a+g)$$

$$a = -(\sigma_{0-1} + \sigma_{01} + \sigma_{10}) \quad ,$$

$$b = \sigma_{-10} - \sigma_{10} \quad , \quad (7)$$

$$f = \sigma_{0-1} - \sigma_{1-1} \quad ,$$

$$g = -(\sigma_{-10} + \sigma_{-11} + \sigma_{1-1}) \quad ,$$

$$s = 1/2(g-a) \quad ,$$

and

$$P(-1, 0) = \frac{1}{2q} \left[bF_1^{\infty} + (b + s - q) F_0^{\infty} \right] \quad ,$$

$$N(-1, 0) = -\frac{1}{2q} \left[bF_1^{\infty} + (b + s + q) F_0^{\infty} \right] \quad ,$$

$$P(-1,-1) = P(-1,0)(s+q)/b \quad ,$$

$$N(-1,-1) = N(-1,0)(s-q)/b \quad ,$$

as calculated by Allison.² In the charge fraction calculations performed, the charge changing cross sections of Steir and Barnett³ are used.

III. RESULTS

Fig. 1 is a plot of charge fraction versus target thickness for 100 keV positively charged deuterons (or 150 keV tritons). At lower energies the approach to equilibrium is faster because the charge exchange cross section σ_{10} increases by up to a factor of four and the reverse process σ_{01} cross section decreases by a factor of two. Fig. 2 gives the final charge fraction versus energy for both deuteron and triton positive beams. The calculation was done for 3.0×10^{16} atoms/cm² and 0.3×10^{16} atoms/cm². For the calculation of the error bar, the cross sections were varied by 5% to demonstrate the change in charge fraction for a 100 keV deuteron beam in Fig. 2. For the top two curves the error bar is the width of the line. Figs. 3 and 4 are for a d⁻ beam input (from which a curve for a triton beam may be calculated by multiplying the energy by 1.5). Fig. 3 is similar to Fig. 1 with the variation in charge fractions F_i versus thickness being demonstrated. Again, Fig. 4 is basically the same as Fig. 2 except now F_0/F_0^∞ and F_1/F_1^∞ are plotted. The F_{-1}/F_{-1}^∞ curve is excluded as it varies from 100 to 1.

IV. ERROR ANALYSIS

The major contribution to the uncertainty of the charge fraction is the experimental error in cross sectional measurements. Stier³ set a 5% limit on absolute errors in his measurements. Curran⁴ reports that his group agrees with Stier and several other less extensive measurements to within 5%. Also, Allison and Garcia-Munoz⁵ tabulate six different measurements whose average generally agrees with Stier within 5-8%. Allison and Garcia-Munoz disagree with Marion¹ on the equilibrium fractions by an absolute difference up to 0.03. A standard deviation of several cross sections measured by various groups is usually 7%. Finally, neglecting H⁻ ions for a positively charged beam introduces no more than 2.0% error in the charge fractions.

V. CONCLUSIONS

For the nominal target density (3×10^{16} atoms/cm²) the charge exchange process is sufficiently near equilibrium in the 10-120 keV energy range that the equilibrium values of charge fractions may be used without loss of accuracy. However, a decrease of gas density by 50% or more would result in substantially different fractions whose values are less certain than the equilibrium charge fractions. In any case, energy loss in the target, depending on the average charged fraction, will differ markedly for an initial positive or negative beam.

One reservation in regard to this calculation is that the charge fraction results are an aggregate average and do not reflect the history of an individual particle. In fact, as a result of small cross sections for several of the charge exchanges the mean free path for an exchange may be much larger than the target thickness. Thus the charge history differs for various exiting ions. Since energy loss is dependent on the beam particle charge, different exiting ions will have different losses. Therefore, careful consideration of ion dependent energy measurements must be made. Finally, since a large change of charge fraction versus energy and thickness was found in the region of interest, beam integration devices must be charge independent.

REFERENCES

1. J. B. Marion and F. C. Young, Nuclear Reaction Analysis Graph and Tables, (North-Holland Publishing Co., Amsterdam) 1968.
2. S. K. Allison, "Experimental Results on Charge Collisions of Hydrogen and Helium Atoms and Ions at Kinetic Energies above 0.2 keV," Rev. Mod. Phys., 30, 1137 (1958).
3. P. M. Stier and C. F. Barnett, "Charge Exchange Cross Sections of Hydrogen Ions in Gas," Phys. Rev., 103, 896 (1956).
4. R. K. Curran and T. M. Donahue, "Charge Transfer for Protons in H_2 ," (1959) Office of Naval Research Tech. Report ONR-8.
5. S. K. Allison and M. Garcia-Munoz, "Electron Capture and Loss at High Energies," in Atomic and Molecular Processes, edited by D. R. Bates (Academic Press, New York) 1962.

Figure 1. Charge fractions versus thickness for 100 keV d^+ beam.
 $F_0 = 0.520$ and $F_1 = 0.475$.

Figure 2. Final charge fraction versus energy of d^0 or t^0 from a d^+ or t^+ beam for thicknesses 3.0×10^{16} atoms/cm 2 and 0.3×10^{16} atoms/cm 2 .

Figure 3. Charge fractions versus thickness for 100 keV d^- beam.

Equilibrium values are the same as for the d^+ beam.

$$E_{-1}^{\infty} \leq 0.005.$$

Figure 4. Final charge exchange fractions versus energy for d^- beam.