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Rutherford scattering of neutral atoms: a technique for measuring plasma ion temperatures

**-an analysis of the applicability to the
central cell plasma of TMX**

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June 3, 1980

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ABSTRACT

Rutherford scattering of neutral particles by plasma ions is examined as a method for determining plasma ion temperatures in the central cell of the Tandem Mirror Experiment (TMX).

When a scattering configuration, consisting of a 20-keV-, 10-A-deuterium neutral beam and an energy analyzer with a 1% resolution, is arranged such that only neutral particles scattered by plasma ions over an angle of 10^0 are accepted, central-cell ion temperatures in the 30- to 1000-eV range can be measured. The count rate registered by the detector(s) is estimated to be 2000 counts/ms. Consequently, good statistical accuracy and time resolution are attainable simultaneously.

The results of the calculation are presented such that the scaling of the count rates and the energy broadening with scattering angle, neutral-beam energy, ion temperature, and plasma density can easily be deduced. Neutral helium beams are also considered; they have some advantages over deuterium beams.

The background signal, caused by neutral particles entering the detector after two successive charge-exchange collisions, is examined and ways to completely eliminate this background are indicated.

1.0 INTRODUCTION

During the last decade the use of neutral beams for plasma diagnostics has become increasingly important. A measurement of the attenuation of a neutral beam due to charge exchange with plasma ions gives direct information on the plasma density integrated over the neutral beam path (Osher, 1979; Turner et al., 1976). Neutral beams, injected into a plasma, lead to an enhancement of the neutral particle density and in this way serve as a local

charge-exchange target for plasma ions. Energy analysis of the charge-exchange neutrals leaving the plasma gives spatially resolved information on the ion temperature (Eubank, 1979; Nexsen et al., 1979).

A second, less well known way to determine the ion temperature is to analyze the energy of neutral-beam particles scattered by plasma ions. The broadening of the energy distribution of originally monoenergetic atomic beam particles, elastically scattered at a fixed angle with respect to the beam, is directly related to the ion temperature. In principle, this so-called Rutherford scattering method gives the same information about ions as Thomson scattering does about electrons (Abramov et al., 1971; Alexandrov et al., 1979).

Both methods for determining ion temperatures have their own advantages and disadvantages. In those cases where the plasma ion temperatures are high, say $\gtrsim 500$ eV, the energy analysis of charge-exchange neutrals is certainly favorable. The charge-exchange process in the plasma has a high cross section, and the reionization of the particles prior to energy analysis can efficiently be done by means of gas-stripping cells.

However, at lower ion temperatures the advantages of the charge-exchange method are less evident. Low-energy neutrals created in the plasma have a large probability to be reionized by the plasma. Besides that, the detection efficiency decreases rapidly with particle energy. This is mainly due to the fact that reionization by means of gas-stripping cells is very inefficient at low energies. A way around this problem is to chop the charge-exchange neutral-particle flux leaving the plasma and to determine the energy distribution via time-of-flight of the particles involved (Voss and Cohen, 1979; Hunt, 1979). A drawback of this method, and all other methods involving atomic particles with energies lower than 100 eV, is the poor efficiency of the detectors involved.

The method of determining plasma ion temperatures by means of energy analysis of scattered neutral-beam particles is particularly useful at low ion temperatures. In principle, it yields spatially resolved temperatures. There are two basic limitations: the small scattering cross sections that decrease strongly with increasing scattering angles and the beam attenuation due to charge exchange with plasma ions that increases exponentially with plasma density and plasma dimensions.

On several occasions in the past, theoretical attention has been paid to the Rutherford scattering method. In 1960, Russek pointed out that the energy distribution of neutral particles scattered on plasma contains information on

the plasma ion temperature. However, Russek only considered the case of scattering of light projectile particles on much heavier target particles; a combination that gives very poor results in terms of the energy broadening of the scattered particles. Afrosimov and coworkers (Abramov et al., 1971) treated this method theoretically for the case where projectile and target masses were approximately equal. They tested the method experimentally by injecting 2.6-keV D^+ ions into an unmagnetized hot gas at $T \approx 2300$ K. From the energy broadening of the scattered deuterium ions, the correct gas temperature could be deduced. The application of this technique for measuring ion temperatures of fusion plasmas was further discussed for the cases of the Joint European Torus (JET) and BP11 (a relativistic electron-beam-heated plasma) by Massman (1979).

The possibilities for determining impurity concentrations by this method were considered for the FT tokamak (Brusati, 1978) and for ISX (Burrell et al., 1978).

The first experimental evidence for the applicability of this technique to fusion type plasmas was again given by Afrosimov's group (Aleksandrov et al., 1979). They were able to determine ion temperatures in the T-4 tokamak in this way. A short review of the results is given in Appendix A of this report.

Since the central cell of the Tandem Mirror Experiment (TMX) operates with ion temperatures in the range 50 to 150 eV and has a sufficiently dense plasma, it is worthwhile to investigate the applicability of this neutral-beam scattering method for TMX. A detailed analysis of this application to TMX is presented here.

Section 2 describes the basic principles of the method; it also gives a survey of the functional dependence of the signal level on the various experimental parameters. In Section 3, a scattering arrangement suitable for TMX is described and the attainable count rates are estimated; also the scattering of the neutral beam particles on impurity ions is considered. Finally, Section 4 gives an estimate of the background caused by neutral particles entering the analyzer after two successive charge-exchange processes.

2.0 BASIC PRINCIPLES

Figure 1 shows the basic experimental configuration. A monoenergetic atomic beam with small divergence is injected into a plasma, where both attenuation and scattering take place. Energy analysis of the atoms scattered elastically over an angle θ with respect to the direction of propagation of the neutral beam gives spatially resolved information on the plasma ion temperature. The spatial resolution is determined by the dimensions of the beam in the plasma and the dimensions of the collimators through which the analyzer/detector views the plasma. In the following subsections, we will explore the scattering process in greater detail.

2.1 MOMENTUM AND ENERGY TRANSFER

We assume a beam particle with mass m_1 and initial velocity $\bar{v}_{1i}$ incident on a plasma target particle with mass m_2 and initial velocity $\bar{v}_{2i}$. After the scattering event has taken place, the beam and target particles have velocities $\bar{v}_{1f}$ and $\bar{v}_{2f}$, respectively. All these velocities are defined in the laboratory frame.

Cold Plasma ($T_i = 0$)

A theoretically simple case is one in which $v_{2i} = 0$, i.e., the cold plasma limit: $T_i = 0$. Classical binary collision theory then leads to (Goldstein, 1959; Russek, 1960):

$$\frac{v_{1f}}{v_{1i}} = \frac{\eta \cos \theta + (1 - \eta^2 \sin^2 \theta)^{1/2}}{1 + \eta} \quad , \quad (1)$$

in which $\eta = m_1/m_2$ and θ is the scattering angle in the laboratory frame (Fig. 1). Equation (1) obviously only holds for $0 \leq \sin \theta \leq \eta^{-1}$. The minus sign is of no importance to the present discussion; it represents back-scattering in the center-of-mass frame. For equal target and projectile masses ($\eta = 1$), Eq. (1) reduces to

$$\frac{v_{1f}}{v_{1i}} = \cos \theta \quad . \quad (2)$$

FIG. 1. Schematic diagram of the scattering configuration. A small fraction of the neutral beam particles is scattered by an angle θ , ionized in a gas-stripping cell, and energy analyzed. The spatial resolution depends on the size of the scattering volume determined by beam and detector opening and acceptance solid angles, respectively. The major part of the beam, although attenuated by charge-exchange collisions with plasma ions, is not affected by the scattering processes and is collected in a dump facing the source.

The ratio of final and initial projectile energies E_{1f} and E_{1i} is given by $E_{1f}/E_{1i} = (v_{1f}/v_{1i})^2$. Note that (v_{1f}/v_{1i}) does not depend on the nuclear charge of the plasma ions. Table 1 gives the ratio E_{1f}/E_{1i} for various target and projectile masses.

From Table 1 it is evident that scattering of a monoenergetic atomic beam on a plasma consisting of more than one type of ion results in an energy spectrum which consists of a series of discrete lines, reflecting the various ionic species. The spacing between the various components of this energy spectrum increases with scattering angle. It is larger for helium neutral beams than for deuterium beams.

Warm Plasma ($T_i \neq 0$)

We now consider a plasma temperature not equal to zero ($T_i \neq 0$); i.e., the plasma ions have a certain velocity distribution $f_2(\vec{v}_2)$.

TABLE 1. The ratio of final and initial particle energies E_{1f}/E_{1i} for scattering of deuterium and helium neutral particles on deuterium, carbon and oxygen plasma ions. The charged state of the plasma ion is of no importance for E_{1f}/E_{1i} . $\eta = m_1/m_2$.

E_{1f}/E_{1i}						
	D^0 on D^+	D^0 on C^+	D^0 on O^+	He^0 on D^+	He^0 on C^+	He^0 on O^+
θ	$\eta = 1$	$\eta = 1/6$	$\eta = 1/8$	$\eta = 2$	$\eta = 1/3$	$\eta = 1/4$
5°	0.992	0.999	0.999	0.985	0.998	0.998
10°	0.970	0.995	0.996	0.939	0.990	0.992
15°	0.933	0.989	0.992	0.863	0.978	0.983
20°	0.883	0.980	0.985	0.756	0.961	0.970
25°	0.821	0.969	0.977	0.612	0.939	0.954

In that case the scattered atomic particles will have an energy distribution still peaked around the values given by Eq. (1) and Table 1. However, now the peaks will no longer be delta functions, but will have a shape that is directly related to the plasma-ion velocity distribution.

In general the calculation of the exact shape of this distribution is mathematically complicated. However, Abramov et al. (1971) showed that under certain conditions it can be described by a simple function of the parameters involved. If the velocity of the plasma ions is small compared to that of the neutral-beam atoms ($v_2 \ll v_1$), then the scattering cross section does not depend on the plasma ion velocity. The distribution function of the scattered particles $f(\bar{v}_{1f})$ can then be expressed in terms of the vector components $\bar{v}_{2i\parallel}$ and $\bar{v}_{2i\perp}$, the plasma ion velocity components parallel and perpendicular to the vector $(\bar{v}_{1f} - \bar{v}_{1i})$, respectively. In that case

$$f_1(\bar{v}_{1f}) \sim \iint f_2(\bar{v}_{2i\parallel}, \bar{v}_{2i\perp}) d^2v_{2i} = g(\bar{v}_{2i\parallel}). \quad (3)$$

For a Maxwellian distribution $f_2(\bar{v}_{2i\parallel})$, and scattering angles that are not too large ($\theta \lesssim 10^\circ$), the energy distribution of the scattered beam particles is

$$f_1(E_{1f}) \sim \exp \left[- \frac{1}{4\pi\theta^2} \cdot \frac{(E_{1f} - E_{1f}^0)^2}{E_{1f}^0 kT_i} \right] \quad (4)$$

In this expression E_{1f} and E_{1f}^0 stand for the projectile energies at $T_i \neq 0$ and $T_i = 0$, respectively; E_{1f}^0 is the central energy of the distribution (see Table 1). If we further make the approximation $E_{1f} \approx E_{1i} = E_1$ (see Table 1), the halfwidth of the distribution is

$$\Delta E_1 \approx 4\sigma (\eta kT_i E_1 \ln 2)^{1/2} \quad (5)$$

For scattering angles $\theta \lesssim 10^\circ$ and $(v_2/v_1) \approx (kT_i/E_1)^{1/2} \ll 1$, Eq. (5) is usually sufficiently accurate. For larger scattering angles and larger ion temperatures, with respect to the beam energy, a more careful analysis must be made which usually involves a numerical calculation of the energy distribution. The same holds for non-Maxwellian plasma ion velocity distributions. In that case, only the distribution in the scattering plane is sampled, along the vector $(\vec{v}_{1f} - \vec{v}_{1i})$.

By way of illustration, in the case $m_1 = m_2$, $\theta = 10^\circ$, and $E_1 = 20$ keV, a target particle temperature of 100 eV will result in an energy distribution with a width $\Delta E_1 = 820$ eV (see also Fig. 4 and paragraph 2.2).

2.2 THE SCATTERING CROSS SECTION

In the energy and angle ranges of interest, the scattering cross sections are low, and consequently, little experimental data are available. However, for the angles considered here, the scattering process is well described by the Rutherford scattering theory; i.e., the scattering mechanism is assumed to be pure Coulomb scattering between the two nuclei involved. Evidence supporting this statement is given in Appendix B. Since the Rutherford scattering theory does not predict the electronic configuration of the scattered particle, we also have to determine the probability that the incident neutral particle loses its electron(s) during the collision. In Appendix B it is shown that for the experimental parameters discussed in this report, this probability is very likely to be less than 50%. Therefore, the possibility of electron loss will be disregarded and the Rutherford formula will be used to calculate the number of neutral particles entering the detector.

The Rutherford cross section in the center-of-mass (CM) frame is given by

$$\sigma_R(\Theta) = \left(\frac{q_1 q_2}{8\pi\epsilon_0 \frac{m_1 m_2}{m_1 + m_2} v_r^2} \right)^2 \frac{1}{\sin^4(\Theta/2)}$$

or

$$\sigma_R(\Theta) = \left(\frac{q_1 q_2}{8\pi\epsilon_0 m_1 v_r^2} \right)^2 \frac{(1 + \eta)^2}{\sin^4(\Theta/2)}, \quad (6)$$

where v_r is the relative velocity of the particles, q_1 and q_2 the nuclear charges of projectile and target particles, and Θ the scattering angle in the CM frame. The relation between the angles Θ and θ in the CM and laboratory frames, respectively, is (Goldstein, 1959)

$$\tan \theta = \frac{\sin \Theta}{\cos \Theta + \eta}. \quad (7)$$

For equal masses of projectile and target this reduces to

$$\theta = \Theta/2. \quad (8)$$

Using the relations given by Russek (1960) for conversion of a cross section in the CM frame into one in the laboratory frame, one can prove that

$$\sigma_R(\theta) = \left(\frac{q_1 q_2}{4\pi\epsilon_0 E_1} \right)^2 \frac{(1 + \eta)^2}{4P} \frac{R^2}{[(1 + \eta) - R \cos \theta]^2}, \quad (9)$$

where $P = (1 - \eta^2 \sin^2 \theta)^{1/2}$ and $R = P + \eta \cos \theta$. In the derivation it has been assumed that $v_2 \ll v_1$ so that $v_r \approx v_1$ and $1/2 m_1 v_r^2 \approx E_1$. We now introduce a function $F(\eta, \theta)$ such that

$$\sigma_R(\theta) = \left(\frac{q_1 q_2}{4\pi\epsilon_0 E_1} \right)^2 \frac{\cos \theta}{\sin^4 \theta} F(\eta, \theta) . \quad (10)$$

It can easily be shown that, in the parameter region of interest $0 \leq \eta \leq 2$ and $5^\circ \leq \theta \leq 25^\circ$, the function $F(\eta, \theta)$ deviates from unity less than 10%.

Hence, in deriving the scaling laws for the scattering cross sections, we will assume $F(\eta, \theta) = 1$, which is exact for $\eta = 1$. From Eq. (10), one can draw the following conclusions:

1. The scattering cross section is proportional to the square of the nuclear charges of the projectile as well as the target particles. Consequently, scattering with, for instance, neutral helium beams, is more effective than with deuterium beams.
2. σ_R is independent of the mass of both the beam and plasma particle.
3. The cross section is strongly dependent on the scattering angle. For small angles θ , $\sigma_R(\theta)$ varies roughly with θ^{-4} . Figure 2 shows the function $\cos \theta / \sin^4 \theta$ for the angular range of interest. It is normalized to

FIG. 2. The dependence of the count rate on the scattering angle as given by Eq. (10). The curve gives the function $\cos \theta / \sin^4 \theta$ normalized to unity at $\theta = 10^\circ$. Note there is an additional factor $\sin^{-1} \theta$ in the geometrical factor G , Eq. (12).

unity at $\theta = 10^\circ$. For high count rates, a small scattering angle is obviously favorable. However, the energy broadening due to $T_1 \neq 0$ goes down with decreasing θ [see Eq. (5)]. Also, the scattering angle should be appreciably larger than the opening angle (divergence) of the neutral beam and the collection angle of the detection system since the latter two angles also lead to broadening of the energy distribution.

4. The scattered particle flux is inversely proportional to the neutral beam energy squared. Consequently, one should choose as low a beam energy as possible. However, the width of the energy distribution of the scattered particles is proportional to $E_1^{1/2}$ [Eq. (5)], and also the attenuation of the beam by the plasma usually becomes stronger with lower energies. In Fig. 3 the flux of scattered particles relative to the injected neutral-beam flux is calculated as a function of plasma density for D^0 and He^0 neutral beams of various energies, injected into a deuterium plasma column. Attenuation of the beam before and after the scattering is caused by charge exchange with plasma ions and ionization by plasma electrons and ions. In the calculation of the attenuation, typical TMX central cell parameters have been used: a diameter of the plasma column of 60 cm and plasma electron temperature 50 eV.

The cross sections used in the calculations are taken from Freeman and Jones (1974) and Barnett et al. (1977). The scattered particle flux (relative to the injected flux) is normalized to unity at a plasma density $n_p = 10^{13} \text{ cm}^{-3}$ and a deuterium beam energy $E_1 = 20 \text{ keV}$. Note that $q_1(He^0) = 2q_1(D^0)$. At low plasma densities the attenuation is negligible and the scattered particle flux is proportional to the plasma density. At higher densities, however, the scattered flux decreases due to an exponentially increasing attenuation. Since the attenuation of a helium neutral beam in a deuterium plasma is much smaller than that of a deuterium neutral beam, it is clear that helium beams can be used up to much higher plasma densities. In case of impurity ions, the scattering cross section is proportional to the square of the nuclear charge of these ions, i.e., a few percent of light impurity ions such as carbon and oxygen might lead to a scattering signal comparable to that due to the bulk of the plasma (D^+). Since the energy distribution of the beam particles scattered on impurity ions is shifted with respect to that of beam particles scattered on deuterium ions (Table 1), this effect can in principle be used to measure the impurity content of the plasma. However, although the Rutherford theory probably still gives the correct cross sections for the scattering of the incident particles

FIG. 3. The dependence of the count rate on plasma density and beam energy for deuterium and helium neutral beams. The curves give the function $n_p \eta_{ATT} \sigma_R(\theta)$ [see Eq. (11)] for fixed angle θ , normalized to unity at $n_F = 10^{13} \text{ cm}^{-3}$ and $E_1(D^0) = 20 \text{ keV}$. The deuterium plasma density was assumed to be homogeneous over the diameter ϕ_p of the plasma column which was taken as 60 cm. In case $\phi_p \neq 60 \text{ cm}$, the curves can still be used, provided all numbers given along the horizontal and vertical axes are multiplied by a factor of $60/\phi_p$.

(see Appendix B), nothing is known on the electronic configuration of the scattered particles. Since the neutral particle is more likely to lose its electron(s) the more the impurity ion is stripped, application of the Rutherford formula will overestimate the neutral flux emerging from the plasma more with higher ionic charge of the impurities.

In Fig. 4, some examples are given of energy distributions obtained from scattering of 20-keV deuterium and helium neutral beams on a deuterium plasma with $T_i = 80$ eV (solid lines). For the sake of completeness, the case in which 1% carbon ions are present in the plasma is also shown (dashed lines). In the calculation of the carbon peaks, the Rutherford cross sections were used to calculate the scattered neutral flux. For the reasons mentioned above, these peaks are probably too high.

3.0 APPLICATION OF THE METHOD TO TMX

We will now calculate the energy broadening of the scattered neutral beam particles and estimate the count rates which are attainable when the method is applied to the central cell of TMX.

For the neutral beam we take a "standard" LBL 20-keV, 10-A source (area at the source $7 \times 7 \text{ cm}^2$, see Berkner et al. 1974), which is collimated such that the beam size in the center of the plasma is $5 \times 10 \text{ cm}^2$.

Figure 5 schematically shows the intersection between the neutral beam and the solid angle (γ_x, γ_y) through which the analyzer/detector arrangement views the plasma. A set of two collimators placed in front of the analyzer limits this latter solid angle. In principle, these collimators can be made to coincide with the entrance and exit of the gas stripping cell used to ionize the scattered neutral particles. The two diaphragms are assumed to be rectangular in shape and equal in size. The dimensions in the scattering plane and in the plane perpendicular to that, w_{cx} and w_{cy} respectively, are allowed to be different in order to be able to optimize the shape of the ion optical object seen by the analyzer. The distance between the two collimators is ℓ_c ; the distance ℓ from the first collimator to the center of the scattering volume (A) has to be chosen such that the stripping cell and the analyzer are operated in a sufficiently small magnetic stray field.

For the purpose of calculation, the following parameters were used (see Table 2).

FIG. 4. Examples of theoretical energy distributions for 20-keV-deuterium and helium neutral beams and scattering angles $\theta = 10^\circ, 20^\circ$. The solid lines give the results for scattering on pure deuterium plasma; the dotted lines on plasmas which contain 1% carbon impurities. The intensities of the carbon peaks are probably overestimated for reasons mentioned in the text. Note that the separation between the deuterium and impurity peaks becomes larger with scattering angle and projectile mass.

TABLE 2. Characteristic parameters for scaling calculations.

Plasma parameters

Column diameter	$\phi_p = 60 \text{ cm}$
Column length	$L = 6 \text{ m}$
Density (homogenous)	$n_p = 10^{13} \text{ cm}^{-3}$
Electron temperature	$T_e = 50 \text{ eV}$
Ion temperature	$T_i = 80 \text{ eV}$

Neutral beam parameters

Dimensions in plasma	$w_{bx} = 5 \text{ cm}$ $w_{by} = 10 \text{ cm}$
Energy full-energy component	$E_1 = 20 \text{ keV}$
"Current" density (total)	$J_T(D^0) = 100 \text{ mA/cm}^2$
"Current" density (full-energy component)	$J_F(D^0) = 50 \text{ mA/cm}^2$
Beam divergence	$\beta_x = \pm 1^\circ$

Scattering arrangement

Scattering angle	$\theta = 10^\circ$
Collimator	$\ell = 150 \text{ cm}$ $\ell_c = 25 \text{ cm}$ $w_{cx} = 0.2 \text{ cm}$ $w_{cy} = 0.6 \text{ cm}$

For parameters different from those listed in the table, the scaling can be determined by the use of Figs. 2 and 3 and Eqs. (1, 5, 10, 11 and 12).

3.1 COUNT RATES

The current I_d registered by the analyzer/particle detector combination can be written as

$$I_d = J_F(D^0) \cdot A \cdot \ell_s \cdot n_p \cdot \eta_{AT} \cdot \sigma_R(\theta) \cdot d\omega \cdot \eta_{STR} \cdot \eta_{DET} \quad , \quad (11)$$

where

- $J_F(D^0)$ is the "current" density of the neutral beam full-energy component (50 mA/cm²).
- A is the beam area (as seen by the detector).
- ℓ_s is the interaction length (as seen by the detector); $A \cdot \ell_s$ is the scattering volume.
- n_p is the plasma density (10^{13} cm⁻³).
- η_{AT} takes into account the attenuation of the neutral beam before the scattering takes place and of the scattered neutral particle flux after the scattering has taken place. This attenuation is due to charge exchange with plasma ions and ionization by plasma electrons and ions. The combined cross section for these three processes is equal to 1.33×10^{-15} cm² (Freeman and Jones, 1974). Hence

$$\eta_{AT} = \exp \left(- 1.33 \times 10^{-15} \int n_p d\ell \right) = 0.45 .$$

- See Fig. 3 for the scaling of the product $n_p \cdot \eta_{AT}$.
- $\sigma_R(\theta)$ is the Rutherford scattering cross section; in this case $\sigma_R(10^\circ) = 5.6 \times 10^{-20}$ cm² ster⁻¹.
- $d\omega$ is the solid angle as accepted by the analyzer into which beam particles present in the scattering volume are scattered.
- η_{STR} is the efficiency of the gas stripping cell as for conversion of the neutral particles into ions. If we take N₂ as stripping gas, $\eta_{STR} = 0.15$ is a reasonable number. Note that stripping of neutral helium atoms is more difficult to achieve. For 20-keV helium atoms, the stripping cross section in N₂ is approximately a factor five lower than that for a 20-keV hydrogen beam (Allison and Garcia-Munoz, 1962).
- η_{DET} is the combined efficiency of the particle detector, the energy analyzer and possible ion optics between stripping cell and analyzer. For this we take $\eta_{DET} = 0.25$.

The product $A \cdot \ell_s \cdot d\omega$ is the so-called geometrical factor. If the angles γ_x , γ_y and β_x are small, the scattering volume $A \cdot \ell_s$ can be approximated by the volume of the rectangular box with sides w_{bx} , DE and KL. In that case it can be shown that (see Appendix.C):

$$G = A \cdot f_s \cdot d\omega = \frac{\left(\frac{w_{cx} w_{cy}}{\ell_c^2} \right)^2 w_{bx}}{\sin \theta} \quad (12)$$

for the dimensions mentioned in the beginning of this section:

$G = 6.6 \times 10^{-4} \text{ cm}^3 \cdot \text{ster}$. This finally leads to an ion current registered by the detector

$$I_d = 3.1 \times 10^{-13} \text{ A}.$$

If we further require a time resolution of 1 ms and a subdivision of the signal in ten energy channels, this leads to an average count rate N_d per channel:

$$N_d \approx 200 \text{ counts/ms};$$

i.e., the statistical accuracy reached within 1 ms is about 7%.

The spatial resolution is determined by the dimensions of the scattering volume. In this particular example: $BC = 29 \text{ cm}$, $DE = 15 \text{ cm}$, and $KL = 7.8 \text{ cm}$. Hence, the spatial resolution is poor; it can be enhanced by decreasing the beam width w_{bx} , by increasing the scattering angle and/or by decreasing the distance ℓ between the plasma and the first collimator.

3.2 THE EXPERIMENTAL ENERGY DISTRIBUTION

The measured energy distribution will usually be wider than the one predicted by Eq. (5), solely based on neutral particle collisions with hot plasma ions. It will generally be broadened by the following effects:

1. Due to the divergence of the neutral beam and the finite opening angle of the analyzer, the actual scattering angle will not be exactly $\theta = 10^\circ$ but will have a variation $\Delta\theta = \pm (\beta_x + \gamma_x)$; see Fig. 5. Since β_x was assumed to be 1° and $\gamma_x = w_{cx}/\ell_c = 0.45$, there will be a variation $\Delta\theta = \pm 1.5^\circ$. This causes a variation in the central energy according to Eq. (1). (Since the cross section is strongly θ dependent, it also makes the distribution slightly asymmetric; we will disregard this latter effect here.)

2. A variation of the source extraction voltage during the pulse also leads to a broadening of the distribution. Since we are not interested in the absolute energy, but only in the energy distribution, the extraction voltage may vary from shot to shot. However, within the time resolution of the detection system (1 ms) the extraction voltage should vary less than 1%. We will assume here that during 1 ms the variation in the extraction voltage is negligible. The uncertainty in the neutral beam energy due to the source ion temperature is of the order of a few eV and can therefore be neglected.
3. The energy analyzer has a finite energy resolution. For the collimator dimensions chosen in this specific case, an analyzer with a full-width half-maximum (FWHM) resolving power of 1% is certainly possible.

Figure 6 shows an "experimental" energy distribution obtained for plasmas with various ion temperatures. The halfwidth angular variation is assumed to be $\Delta\theta_{1/2} = \pm 1.5^\circ$ and the analyzer FWHM resolving power ($\Delta E_{1/2}/E$) is taken to be 1%. If we define a measurable ion temperature as one which leads to a 50% increase in the width of the "zero temperature" distribution, then temperatures as low as $T_i = 30$ eV can be measured.

An important feature of this method is that the "zero temperature" distribution (or apparatus profile) can easily be determined by filling the machine with neutral deuterium gas and scattering of the neutral beam on the neutral gas molecules. Since the Rutherford cross section in principle does not depend on the charged state of the particles involved, a 300-K neutral gas pressure of 1.5×10^{-4} Torr simulates a zero-temperature plasma with a density of 10^{13} cm^{-3} .

4.0 DOUBLE-CHARGE-EXCHANGE BACKGROUND

The most important competitive process producing neutral particles with energies in the same range as the Rutherford scattered neutral particles is the following: beam particles are converted into energetic ions via charge-exchange collisions with plasma ions; after a gyration over an angle θ (or $2\pi - \theta$, depending on the polarity of the magnetic field with respect to that of the scattering angle θ), these ions have a certain chance to be neutralized again via a second charge-exchange collision, this time with a neutral beam particle. If this happens in the scattering volume (see paragraph 3.1) and

FIG. 6. Examples of "experimental" energy distributions, i.e., results obtained when the additional broadening due to the beam divergence γ_x and the detector opening angle β_x are taken into account, (see Fig. 5). The overall distributions are given for $\beta_x = +1^\circ$, $\gamma_x = +0.5^\circ$ (i.e., we have assumed $\Delta\theta_{1/2} = \pm 1.5^\circ$) and various plasma ion temperatures.

when these neutral particles are emerging from the plasma within the acceptance solid angle of the analyzer/detector system, they give rise to a background in the energy range of interest. A simple calculation shows that this process has to be taken very seriously: the ratio R of the Rutherford scattering signal and the double-charge-exchange signal is approximately equal to [see also Eq. (11)]

$$R \approx \frac{\left[\frac{n_p \ell_s \sigma_R(\theta) d\omega}{n_p \ell_s \sigma_{cx}} \right]}{\left(\frac{n_b \ell_s \sigma_{cx}}{n_b \ell_s \sigma_{cx}} \right)}, \quad (13)$$

in which σ_{cx} is the charge-exchange cross section, $\sigma_{cs} \approx 10^{-15} \text{ cm}^2$, and n_b is the neutral beam density, $n_b \approx 5 \times 10^9 \text{ cm}^{-3}$. ℓ'_s is the length of that part of the orbit of the gyrating ion from where, if neutralization were to take place somewhere along that part, the emerging neutral particle would enter the analyzer. Consequently $\ell'_s = r_L [w_{cx}/(\ell + \ell_c)]$ (see Fig. 5; r_L is the Larmor radius of the gyrating ion). Since $d\omega \approx (w_{cx} w_{cy})/(\ell + \ell_c)^2$ this leads to

$$R \approx \frac{\sigma_R(\theta) w_{cy}}{\sigma_{cx}^2 n_b r_L (\ell + \ell_c)} \quad (14)$$

For the case considered in Section 3 and a magnetic field $B = 0.1 \text{ T}$, $r_L = 30 \text{ cm}$ and thus: $R \approx 1.3 \times 10^{-3} \ll 1$. Obviously this can not be tolerated. Therefore, the energy of the injected neutral particles has to be chosen such that part of the Larmor orbit of the energetic ions produced in the first charge-exchange process lies outside the plasma column, where the ion can be intercepted, for instance, by a limiter. In case a 20-keV neutral deuterium beam is aimed at the center of the TMX central-cell plasma column ($\rho_p = 60 \text{ cm}$), part of the ion trajectory lies outside the column for magnetic fields smaller than 0.2 T.

Note that only the full-energy ionic component need be blocked in this way; ions with energies equal to one-half or one-third of the source extraction voltage do not affect the Rutherford scattering energy distribution (see Fig. 6).

This problem can partly be avoided by choosing the scattering plane perpendicular to the plane of the gyrating ions. In that case the double-charge-exchange background is much smaller; however, even then it can still be expected to be of the same order of magnitude as the Rutherford scattering signal (see Appendix D). When more deuterium neutral beams are injected into the central cell, there will obviously be an appreciably larger double-charge-exchange background. However, by choosing the extraction voltage of the diagnostic neutral beam source, say 20% higher than that of the other neutral beam sources, this background does not influence the ion temperature measurement (see Fig. 6). Of course all the problems mentioned in this section will be much smaller when a helium beam is used for the diagnostic neutral beam. In case a 20-keV He^0 beam is used, Fig. 3 shows that the product $n_p \eta_{ATT} \sigma_R(\theta)$

is approximately a factor 8 larger than in the 20-keV D^0 reference case. However, the stripping efficiency of a N_2 gas cell goes down by approximately a factor 4 (Allison and Garcia-Munoz, 1962). Consequently, the count-rate to be expected for a 50-mA/cm² He^0 beam is approximately 4000 counts/ms (see Section 3). In conclusion, it can be noted that the double-charge-exchange background can be made completely negligible.

APPENDIX A
EXPERIMENTAL VERIFICATION OF THE RUTHERFORD
SCATTERING METHOD IN FUSION PLASMAS

In January 1979 the first and, to our knowledge, only experimental verification on the applicability of the Rutherford scattering method in fusion plasmas was reported by Afrosimov and coworkers (Aleksandrov et al., 1979).

The experiment was done in the T-4 tokamak with typical plasma parameters in the center of the torus $n_p \approx 2 \times 10^{13} \text{ cm}^{-3}$, $T_i \approx 500 \text{ eV}$ and a plasma diameter of 25 cm. A 8.4-keV He^0 beam with a pulse length of 200 μs and an equivalent current density in the center of the system of $10\text{-}30 \text{ mA/cm}^2$ was injected into a hydrogen plasma. Different types of particles for projectile and target were chosen to avoid problems with a possible double-charge-exchange background (see Section 4). An example of the results is given in Fig. A-1, showing an ion temperature measurement 8 cm from the axis of the plasma.

First, the apparatus profile was determined by aiming the beam directly into the analyzer ($\theta = 0^\circ$; profile 1); then the beam was scattered on neutral hydrogen gas ($\theta = 9^\circ$, profile 2) to obtain the "zero-temperature" profile; and finally the beam was scattered on the plasma ($\theta = 9^\circ$, profile 3). Note that profile 3 is asymmetric; this is due to the fact that the plasma ion velocity v_2 is not much smaller than the neutral beam particle velocity v_{1i} as is required for obtaining a Gaussian profile (e.g., profile 2). In this particular case, $v_{1i}/v_2 \approx 3.2$. The solid line gives the theoretical curve for $T_i = 210 \text{ eV}$. It is claimed that the accuracy of this number is better than $\pm 15 \text{ eV}$.

FIG. A1. Experimental results obtained by Afrosimov and coworkers (Aleksandrov et al, 1979) on the T-4 tokamak.

1. (Δ): Energy distribution of neutral helium beam particles as determined by the energy analyzer directly facing the source (i.e., $\theta = 0^\circ$).

2. ($\square$): Energy distribution of neutral helium beam particles scattered on neutral hydrogen gas over an angle $\theta = 90^\circ$ ($T_i = 0$ case). Open circles ($\circ$): Energy distribution of neutral helium beam particles scattered on a hot hydrogen plasma.

3. (solid line): Theoretical energy distribution for neutral helium particles scattered on a hydrogen plasma with $T_i = 210$ eV over an angle $\theta = 90^\circ$.

APPENDIX B
THE SCATTERING CROSS SECTION

To our knowledge, there are no experimental data on the absolute differential cross sections for scattering of 10- to 30-keV deuterium and helium neutral particles on deuterium ions in the angular range of interest (5 to 25°). However, the scattering in this parameter region is probably well described by Rutherford (Coulomb) scattering of the nuclei involved. The following example is illustrative in that respect: the impact parameter b corresponding to a 10° scattering (in the laboratory frame) of two deuterium particles, one of which has an energy of 20 keV, while the other is at rest is equal to $b = 4.1 \times 10^{-11}$ cm. This is appreciably smaller than the radius of the hydrogen ls electron orbit, and consequently the shielding of the nuclear charge by the electron is negligible in that case. It will be clear that due to the large mass ratio, binary collisions between beam particles and plasma electrons (either bound or free) will not result in scattering over angles as large as those considered here.

Experimental evidence that the Rutherford cross sections can be used is given by Fuls et al. (1957), who measured absolute differential cross sections for the scattering of 25-, 50-, and 100-keV He^+ , Ne^+ and Ar^+ ions on neutral He, Ne and Ar. In Table B-1, the absolute differential cross sections for 25-keV He^+ ions incident on He, Ne and Ar atoms is given for a scattering angle of 10° . The agreement between the experimental and the theoretical (Rutherford) cross sections is good up to target

TABLE B-1. The experimental differential cross section for scattering of 25-keV He^+ ions on various targets. The scattering angle is 10° in all cases. The theoretical Rutherford cross section and the charged-state distribution of the scattered particles is also given.

	He^+ on He^0	He^+ on Ne^0	He^+ on Ar^0
Experimental cross section (cm^2)	5.0×10^{-19}	1.0×10^{-17}	2.0×10^{-17}
Rutherford cross section (cm^2)	5.6×10^{-19}	1.4×10^{-17}	4.6×10^{-17}
He^0 (%)	28	38	56
He^+ (%)	69	59	42
He^{2+} (%)	3	3	2

particles as heavy as neon. Additionally, it can be mentioned that in the He^+ on He^0 and Ne^0 cases the scaling of the experimental cross sections with incident particle energy and scattering angle is accurately described by Eq. (10). This means that the scattering of He^0 and D^0 on deuterium ions and on light impurity ions such as carbon and oxygen can be calculated on the basis of the Rutherford formula. In case of scattering on heavier target ions (atoms), the Coulomb screening of the electron cloud becomes increasingly more important and consequently the cross sections become smaller than those predicted by the Rutherford formula (Table B-1, He^+ on Ar; see also Lane and Everhart, 1960.)

As was already mentioned in paragraph 2.2, the Rutherford theory does not concern itself with the electronic configuration of the scattered particles. Therefore, one additionally has to determine the probability that the neutral particle loses its electron(s) during the collision. Since for the energies considered here, the probability for direct ionization of the beam particles by the plasma ions is an order of magnitude lower than the probability for charge exchange, we will only consider the latter process here (Freeman and Jones, 1974).

For a given scattering angle, due to quantum mechanical interference effects, the charge-exchange probability measured as a function of incident energy exhibits strong oscillatory variations. At fixed incident energy it behaves similarly as a function of scattering angle. These oscillatory variations are strongest for resonant-charge-exchange processes; the charge-exchange probability then can vary between 0.20 and 0.80 (H^+ on H, see Helbig and Everhart, 1965; He^+ on He, see Lockwood et al., 1963). This means that only certain combinations of scattering angle and neutral beam energy give low charge-exchange losses. Unfortunately, measurements on these effects are limited to scattering angles smaller than 5° and do generally not include deuterium particles. However, using the H^+ on H^0 scattering data and the scaling laws given by Helbig and Everhart (1965), one can estimate the charge-exchange probability for 10° scattering of 20-keV D^0 on D^+ to be 0.2-0.3. Similarly, the H^+ on He^0 data given by Helbig and Everhart (1967) indicate that 10° scattering of 20-keV He^0 on D^+ leads to a charge-exchange loss smaller than 0.15.

To our knowledge, no information is available on the charge-exchange probability of deuterium and helium neutrals scattered by impurity ions. It is likely that the probability for neutral particles to lose their electron(s)

during a Rutherford collision with impurity ions becomes larger with increasingly overall charge of the impurity ion, since then more and more unfilled electronic states are available for the neutral particle electron. Therefore, in the case of highly stripped impurity ions, a calculation of the scattered neutral particle flux entering the detector based on Rutherford cross sections will certainly be much too high. Such a calculation for the scattering of deuterium and helium atoms on deuterium plasma ions, however, will yield a theoretical neutral particle flux entering the detector which is at most 50% too high.

APPENDIX C

THE GEOMETRICAL FACTOR G

The geometrical factor G is equal to the product of the scattering volume ($A \cdot \ell_g$) and the solid angle $d\omega$, as defined in paragraph 3.1; see Fig. 5. The scattering volume is made up of area FGIH and length KL. For small beam divergence β_x and small detector opening angles γ_x and γ_y , this volume can be approximated by that of a rectangular box with sides w_{bx} , DE and KL and consequently:

$$G = w_{bx} \cdot DE \cdot KL \cdot d\omega, \quad (C1)$$

where $d\omega$ is the solid angle as accepted by the analyzer into which beam particles (present in the scattering volume) are scattered. The term $d\omega$ is a function of the position in the scattering volume. At point A, $d\omega$ is equal to $(w_{cx} w_{cy}) / (\ell + \ell_c)^2$ while at the points D, E, K and L it is zero. Since the dimensions of the scattering volume are small compared with ℓ , the average solid opening angle of the plane made up by KL and DE is taken to be a good approximation for the average solid opening angle for the total scattering volume. We further take

$$d\omega = d\omega_x d\omega_y,$$

in which $d\omega_x$ is the linear opening angle in the scattering plane (averaged along DE) and $d\omega_y$ the linear opening angle in the plane perpendicular to the scattering plane (averaged along KL); i.e.,

$$d\omega_x = \frac{w_{cx}}{2 \left(\ell + \frac{1}{2} \ell_c \right)}$$

and

$$d\omega_y = \frac{w_{cy}}{2 \left(\ell + \frac{1}{2} \ell_c \right)}.$$

Since

$$DE = \frac{2 \left(\ell + \frac{1}{2} \ell_c \right)}{\ell_c \sin \theta} w_{cx}$$

and

$$KL = \frac{2 \left(\ell + \frac{1}{2} \ell_c \right)}{\ell_c} w_{cy} ,$$

G becomes:

$$G = \frac{\left(w_{cx} w_{cy} \right)^2}{\ell_c^2 \sin \theta} w_{bx} . \quad (C2)$$

APPENDIX D

DOUBLE-CHARGE-EXCHANGE BACKGROUND

Here we will estimate the double-charge-exchange background in case the scattering plane is perpendicular to the plane of the gyrating ion (see Section 4). In that case the Larmor trajectory of the energetic ion created in the first charge-exchange process is not "aiming" at the analyzer entrance and consequently this background will now be appreciably lower than that calculated in Section 4. We will start by considering the diagnostic neutral beam only. At the end we consider the background to be expected from additional neutral beam sources injecting the same species at the same energy as the diagnostic neutral beam source. We make the following simplifying assumptions:

Only a small fraction of the double-charge-exchange neutrals entering the analyzer is harmful to the ion temperature measurement. Those neutral particles which have lost more than a certain amount of energy during their "ionic life", say 10%, are considered not to influence the measurement (see Fig. 6).

A fraction f of the neutral beam particles is trapped. In the extreme case where all neutrals which are converted into ions via collisions with plasma particles are trapped in the magnetic field, this fraction is $f = 0.55$ ($= 1 - \eta_{AT}$; see paragraph 3.1).

We assume that the energetic ions trapped in the magnetic field fill the central cell homogeneously. This is a reasonable assumption since the mean free path for charge exchange of a 20-keV (deuterium) ion in the atomic deuterium background of the neutral beam is of the order of 2000 m, i.e., much larger than the dimensions of the scattering volume (see paragraph 3.1) and the plasma vessel ($n_b \approx 5 \times 10^9 \text{ cm}^{-3}$ and $\sigma_{cx} \approx 10^{-15} \text{ cm}^2$). Only those ions which happen to be present in the scattering volume have a certain chance to enter the analyzer after a neutralizing charge-exchange collision.

Since we are only interested in the number of particles present in the TMX central cell with energies E in the range ΔE , given by $0.9 E_1 \leq E \leq E_1$, it is useful to define an overall characteristic time τ_0 according to which ions with energies in this band are lost. This loss can either be due to particle losses, i.e., losses caused by ions leaking out of the end plugs and by ion-charge exchange with neutral particles, or due to energy losses, caused by collisions with cold plasma electrons (electron drag).

We will assume here that the rate at which ions in the energy band ΔE are lost is proportional to the total number $N_i(\Delta E)$ of these ions present in the central cell.

We can now calculate $N_i(\Delta E)$ as a function of time. If the neutral beam pours in "fresh" neutral particles at a rate Φ ,

$$\frac{dN_i(\Delta E)}{dt} = f - \frac{N_i(\Delta E)}{\tau_0} \quad (D1)$$

and Φ can be written as $\Phi = A_b J_F(D^0)/e$ where $J_F(D^0)$ and A_b are the neutral particle "current" density of the beam full-energy component and the beam area in the center of the plasma, respectively. Since, as we will show later, the time constant τ_0 is much smaller than the neutral beam pulse duration, a steady state is rapidly reached. Consequently:

$$N_i(\Delta E) = f\Phi\tau_0 = fA_b J_F(D^0)\tau_0/e \quad (D2)$$

The rate at which charge-exchange processes take place in the scattering volume $A \cdot \ell_s$ (see paragraph 3.1), leading to neutral particles with energies in the band E , now is given by

$$\frac{dN_n(\Delta E)}{dt} = \frac{N_i(\Delta E)}{V_{cc}} v_i (A \cdot \ell_s) n_b \sigma_{cx} \quad (D3)$$

in which $dN_n(\Delta E)/dt$ is the number of charge-exchange collisions per unit time, V_{cc} the central cell plasma volume, v_i the velocity of the energetic ion and n_b the neutral beam particle density (the neutral particle density can be chosen higher than n_b if there are more neutral particles present.) Since the direction in which these newly created neutral particles are moving is more or less random, only a fraction $d\omega/4\pi$ will enter the detector ($d\omega$ is the detector acceptance solid angle). Consequently, in this simple model the ratio R of the signals due to Rutherford scattering and double-charge-exchange is given by [see Eqs. (11), (D2) and (D3)].

$$R = \frac{4\pi V_{cc}}{A_b v_i f \tau_0} \cdot \frac{n_p}{n_b} \cdot \frac{\sigma_R(\theta)}{\sigma_{cx}} \quad (D4)$$

The only unknown in Eq. (D4) is the lifetime, τ_0 , of energy-excited ions in the energy band ΔE . Of all the possible loss mechanisms mentioned in the beginning of this appendix, the "loss" of particles due to energy losses by collisions with cold plasma electrons probably is the largest. So we will consider only that one: Rose and Clark, (1961) give relations describing the rate at which hot ions with a Maxwellian temperature T_i lose energy to cold electrons with kinetic temperature T_e . In case of a stationary temperature T_e , i.e., the electrons are not heated appreciably, the energy loss of the ions can be written as

$$(T_i - T_e) = (T_i - T_e)_{t=0} \exp(-t/\tau_1) \quad (D5)$$

where

$$\frac{1}{\tau_1} = \frac{10^{-19} Z_i^2 n_p \ln \Lambda}{A_i T_e^{3/2}} \quad (D6)$$

In (D6) Z_i and A_i are the charge and mass number of the ions, respectively. T_e is expressed in keV. Although in the present case we are not considering a Maxwellian ion temperature, we will assume that Eqs. (D5) and (D6) will give a reasonable approximation for an energy loss time; for the parameter values mentioned in paragraph 3.1, i.e., $E_1 = 20$ keV, $n_p = 10^{13} \text{ cm}^{-3}$, $Z_i = 1$, $A_i = 2$, $T_e = 200$ eV and $\ln \Lambda = 16$, Eq. (D6) leads to $\tau_1 = 11$ ms. Equation (D5) then gives a characteristic 10% energy loss time equal to $\tau_0 = 1.2$ ms.

This finally leads to $R \approx 0.6$. (Additional parameters:

$$V_{cc} = 1.7 \times 10^6 \text{ cm}^3, A_b = 50 \text{ cm}^2, v_i = 1.4 \times 10^8 \text{ cm/s}, f = 0.55, \\ n_b = 5 \times 10^9 \text{ cm}^{-3}, \sigma_R(\theta) = 5.6 \times 10^{-20} \text{ cm}^2, \sigma_{cx} = 10^{-15} \text{ cm}^2).$$

This means that under the conditions assumed here, the background signal due to double-charge-exchange processes will be comparable to the Rutherford scattering signal. In reality, the trapping factor f probably is smaller than the value used here. It is also very likely that the decay time τ_0 is smaller due to additional loss mechanisms which were not taken into account.

In case more neutral beams are used, Eq. (D4) can be used to calculate the additional double-charge-exchange background provided these sources have the same current density and particle energies as the diagnostical source. Since in that case the source area A_b will be considerably larger than the 50 cm^2 used in this calculation, the double-charge-exchange background will be much larger. Therefore it is necessary to choose the energy of the diagnostic neutral beam particles sufficiently larger than that of the particles of the heating beams (see Section 4). One could also use a helium neutral beam for the diagnostics beam and apply momentum filtering prior to energy analysis.

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