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SEVERAL ATOMIC-PHYSICS ISSUES CONNECTED WITH THE
USE OF NEUTRAL BEAMS IN FUSION EXPERIMENTS

By

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Energetic neutral beams are used for heating and diagnostics in present magnetic fusion experiments. They are also being considered for use in future large experiments. Atomic physics issues are important for both the production of the neutral beams and the interaction of the beams and the plasma. Interest in neutral beams based on negative hydrogen ions is growing, largely based on advances in producing high current ion sources. An extension of the negative ion approach has been the suggestion to use negative ions of $Z > 1$ elements, such as carbon and oxygen, to form high power neutral beams for plasma heating.

The presence of neutral atoms in hot plasmas can enhance the recombination rate of multiply-charged impurity ions, thus leading in some cases to large energy losses through impurity radiation. The radiation from the decay cascade of excited impurity ions produced by the charge exchange of neutral hydrogen beams and multiply-charged ions has been developed into a powerful diagnostic technique for measuring the impurity levels in tokamaks. Neutral beams have also been proposed to measure the alpha particle distribution in the next generation of fusion experiments.

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I. Introduction

Energetic neutral beams have been one of the most successful heating methods for magnetic fusion experiments [1-8]. Both the production of neutral beams and their interaction with the plasma involve atomic collision physics. Neutral beams are also used for plasma diagnostics.

Neutral beams used on current fusion experiments are produced by forming large currents of positive hydrogen ions (20-100 amps), accelerating the ions electrostatically to high energies (40-120 keV), and neutralizing the ions by charge exchange with hydrogen gas. The energetic neutral atoms then freely cross the confining magnetic field and are ionized in the plasma, at which point they are confined and slow down, colliding with and, thereby, heating the background plasma.

One key issue with positive ion neutral beams has been the presence of H_2^+ and H_3^+ in the ion sources [9-11]. These ions are accelerated along with the H^+ ions and are easily dissociated and neutralized. They result in a substantial portion (often over 50%) of beam power being in H^0 with energies that are one-half and one-third of the accelerator potential. The reduction of H_3^+ and H_2^+ in ion sources has been a goal of positive ion neutral beam research.

Another effort has been to extend the maximum energy of positive ion beams by finding a neutralizing gas which has a higher neutralization fraction than H_2 at ~ 100 keV/amu [12]. A third issue has been the determination of the impurity content of the neutral beam. Sputtering, arcing, and desorption in the ion source can produce ions of C, O, Fe, Cu, Mo, or W, which are then accelerated and neutralized along with the hydrogen ions. One promising technique has been the study of K and L shell vacancy lines produced by the impact of 40-120 keV Cu^+ , for example, on H_2 [13]. One of the problems of

this technique is that the cross sections for the K and L shell vacancy production are poorly known.

The maximum energy of positive ion based neutral beams is limited by the low neutralization rate for H^+ in H_2 at energies greater than about 100 keV/amu [10]. This energy limit translates into a limit on the size of plasma that can be heated by neutral injection since the ionization mean free path is proportional to the energy [14]. The neutralization fraction of H^+ at energies above 100 keV/amu is $\sim 60\%$, and could be higher with photodetachment. The issues relevant to H^+ beams are the development of high current ion sources, acceleration techniques for high voltages, and neutralization of negative ions by gas collisions, plasma collisions, or photodetachment. Many of these issues involve some atomic collision physics.

The advent of electric quadrupole focused RF linear accelerators [15,16] has opened the possibility of using high energy (~ 1 MeV/amu) beams of neutral atoms with $Z > 1$ for plasma heating [17,18]. In this approach, negative ions of oxygen, for example, would be formed and accelerated to ~ 1 MeV/amu, and then neutralized by photodetachment. The neutral oxygen would then be injected into the tokamak, or mirror machine, where it would be ionized, confined, and would heat the plasma.

Neutral hydrogen beams can increase the impurity radiation losses in fusion experiments by enhancing the recombination rate of multiply-charged ions [19-21]. The charge transfer between neutral hydrogen atoms in the beam and impurity ions may be a significant contribution to the total recombination of the impurity ions. Impurity radiation enhanced by charge-exchange recombination was recently found to be the largest contribution to the electron cooling on DITE [22], thus severely limiting the effectiveness of neutral beam heating on DITE.

The charge transfer between neutral hydrogen beams and multiply-ionized ions, particularly fully ionized ions, produces excited states of the ions which can be detected spectroscopically. This technique can be used to measure the time-dependent density profile of the fully-stripped impurities [23-25].

Neutral lithium beams have been proposed as a diagnostic for alpha particle heating. The reaction $\text{Li}^0 + \text{He}^{++} \rightarrow \text{He}^0$ would be used to neutralize the alpha so that it would become unconfined and could be detected outside of the plasma.

All of these techniques involve the use of neutral beams either to heat plasmas, or to diagnose the plasma constituents and heating effectiveness.

II. Neutral Beam Systems From Positive Hydrogen Ions

Neutral beams have been the most successful heating method for fusion experiments. They are used not only for general heating, but for fueling and producing electrostatic confinement in mirror experiments. Table I lists some of the neutral beam systems being used, developed, or planned for tokamaks in the United States. They are all based on positive ion technology.

Four atomic physics issues of interest in the positive ion beam program are: the reduction of H_2^+ and H_3^+ in the ion source, increasing the neutralization efficiency of H^+ at higher energies, measuring the H_2^+ and H_3^+ content of the ion beam extracted from the ion source, and measuring the impurity content in the neutral beam. The first item, increasing the H^+ fraction compared to the H_2^+ and H_3^+ fraction, is important since the H_2^+ and H_3^+ lead to substantial components of the beam power in neutral atoms of one-half and one-third of the accelerating voltage. H_2^+ and H_3^+ are formed from H_2 by the following collisions [26]:

and

The reaction $\text{H}_2 + \text{e}^- \rightarrow 2\text{H}^0$ requires about 8.5 eV. Thus one can maximize the H^0 production and minimize the H_2^+ and H_3^+ production by depressing the population of electrons with energies above 15.8 eV. This has been accomplished by Ehlers and Leung [11] with magnetic filters in the ion source (Fig. 1). The magnetic filters reduce the passage of high energy electrons into the extraction region, thereby reducing the H_2^+ production (Fig. 2). This leads to an enhancement of H^+ compared to H_2^+ and H_3^+ .

The cusp fields depicted in Fig. 1 increase the plasma confinement in the ion source, thereby reducing the recombination of H^+ on the walls to form H_2 . Increasing the H^+/H_2 ratio increases the H^+/H_2^+ , H^+/H_3^+ ratios. Thus, the most successful strategy has been to minimize the production of H_2 , and then to minimize the ionization of H_2 that is formed.

A second possible application of atomic collisions to positive ion neutral beam physics is to use non-hydrogen neutralizer gases [12]. The neutralization fraction of H^+ on H_2 is below that of a number of other gases or H^+ energies above 80 keV/amu (Fig. 3). In particular, helium and neon offer substantial enhancements over H_2 (Fig. 4) at energies above 100 keV/amu.

The basic physics is that neutralization is a competition between charge exchange of H^+ with the gas and ionization of the subsequent H^0 atoms by collisions with the same gas. Helium and neon are good at high energies because they have fairly tightly bound electrons with higher orbital speeds than for H_2 , and thus have charge-exchange cross sections which are larger at

high energies than those of H_2 . The helium and neon atoms are also small and compact, and thus have smaller ionization cross sections for H^0 than does H_2 . The combination of these two effects thus gives a higher neutralization fraction for He and Ne compared to H_2 .

The practical implications of this study are that one can either increase the efficiency of a high energy beam system for a fixed energy (~ 100 keV/amu), or operate at a higher energy for a fixed efficiency (Table II). The major disadvantages of this approach are that, if helium is used, the pumping problems for the beam lines are increased, and, with either helium or neon, the efficiency of 100 keV/amu beams is still too low to be very attractive. However, if some other gas were found that could do even better than He or Ne at $E_H \sim 100$ keV/amu, then higher energy hydrogen beams, based on positive ions, could become more attractive.

A third issue is the measurement of the H_2^+ and H_3^+ content of megawatt level ion beams extracted from the ion sources [27,28]. Since the H^+ , H_2^+ and H_3^+ ions all have the same energy, they will have different velocities, and thus the decay radiation from excited states of fast H^0 produced from H_m^+ (fast) + $H_2 \rightarrow H^0$ (fast) will have different doppler shifts. Thus measurements of the doppler shifted line intensities for the three species and a knowledge of the cross sections for producing the excited states of H^0 would enable one to measure the relative fractions of H^+ , H_2^+ , and H_3^+ in the beam. These cross sections have recently been measured [29], and the technique will be applied to present neutral beams. This technique is a compliment to conventional mass analysis [30].

A fourth issue in positive ion beam systems is the impurity content in the beams. Sputtering, arcing, desorption, and vaporization of the ion source components can lead to the production of ions of C, O, Ti, Fe, Ni, Cu, Mo, or

W (essentially any structural material or contaminant in the ion source). These ions can then be accelerated along with the protons and neutralized in the gas cell where the protons are neutralized. Large currents of metals can lead to plasma contamination problems with enhanced radiation losses. It is thus important to measure the impurity level in the beam and design the ion source to produce no more than an acceptable level of impurities [10].

Given the high power levels in the beam ($10\text{-}30 \text{ kW/cm}^2$), it is often difficult to place probes in the beam, or to perform mass analysis of the beam. One non-perturbing technique that is being pursued is to let the beam collide with a background gas (H_2 , Xe, etc.) [13]. Inner shell vacancies are formed in both the beam impurity atoms and the target (Xe) atoms. The resultant Xrays from the radiative decay of these atoms and ions could then be measured and analyzed to determine the impurity concentration of the beam. Accurate interpretation of the Xray data requires a knowledge of the inner shell vacancy production cross sections for both the impurity and target atoms. No thin target data exists, but some attempts are being made to measure the cross sections (e.g., $\text{Cu} + \text{Xe} \rightarrow \text{Cu}^*, \text{Xe}^*$, etc.) at energies of 40-120 keV for Cu [13]. Accurate and plentiful cross sections would allow the wide application of this technique to present beam systems.

III. Neutral Hydrogen Beams From Negative Ions

The need to penetrate and heat large toroidal plasmas and to sustain the electrostatic potential of mirror plasmas, has led to an interest in increasing the energy of neutral hydrogen beams to energies above the 80-100 keV/amu, which is the practical limit for positive ion neutral beam systems [7,8,10]. The neutralization efficiency of these high energy positive ion beams is too low (Fig. 3) to make practical beams attractive for high

energies.

Since, at high velocities it is much easier to knock one electron off H^- than to add an electron to H^+ , there is interest in beam systems based on H^- ion sources [31]. We shall make no attempt to review the extensive literature or research (see [31], for example) in this area, but we will mention a few relevant, exciting developments in the field.

A neutral beam system consists of at least three components: an ion source, an accelerator, and a neutralizer. Most of the research in the negative ion program has been concentrated on producing high current negative ion sources. This research has centered on at least four approaches [31]. One of the most promising of these approaches has been the conversion on an alkali coated surface of H^+ to H^- [32-34]. Extracted currents up to one ampere have been achieved with reasonable gas efficiencies. The detailed mechanisms of the negative ion production mechanism are not thoroughly understood. The protons are accelerated to energies of 100 eV to 1 keV, and then strike an alkali coated metal surface. The alkali lowers the work function of the surface so that the H^+ ion can convert to H^- (Fig. 5). Some mixture of reflection of H^+ [35] and double charge exchange of H^+ with the alkali vapor and desorption of adsorbed H^0 on the surface is thought to account for the H^- production. This type of source is quite promising.

Another approach is the volume production of negative ions. Bacal and co-workers [31,36] have found unexpectedly large densities of H^- in low temperature H^+ discharges. The suspected reactions are

The major mechanism is expected to be (3), and the major unresolved question is how vibrationally excited H_2 is produced. Hiskes and co-workers are investigating the production and relaxation of vibrationally excited molecules by wall collisions. T. Green and co-workers at Culham [37] have constructed a small-scale volume ion source based on these ideas. Volume sources are appealing since they might be simpler than surface sources and would not involve the use of an alkali.

A second element in a neutral beam system is the acceleration of the ions. Electrostatic acceleration is used on all current positive ion based neutral beam systems (up to 160 keV). Negative ion systems in the 150-500 keV energy range also plan to use electrostatic acceleration, primarily because it is electrically efficient and, probably, can handle large currents and powers. However, practical limits of voltage standoff, insulation, parasitic effects, and power handling tend to limit their maximum energy to about 500 keV.

Above 500 keV, RF accelerators seem to be more feasible. At least two approaches, the RFQ [38] and the Meqalac [39], have been proposed. The RFQ accelerator is actively being developed at Los Alamos Scientific Laboratory for a variety of uses. Both the RFQ and Meqalac use electric quadrupole focusing to avoid the space charge blow-up of the beam, and thus can accelerate beams with velocities in the $10^8 - 10^9$ cm/sec range. One major disadvantage of RF accelerator systems is that their electrical efficiency is likely to be fifty percent or less.

The third major element in a neutral beam system is the neutralizer. The

conversion efficiency of H^- into H^0 in hydrogen can be as high as $\sim 60\%$ for the optimum cell thickness [10]. Conversion efficiencies of up to eighty-five percent might be possible with plasma cell neutralizers (Berkner et al. [31]), although the technical issues involved in the construction of such a cell are formidable. Photodetachment of the negative ions (0.75 eV binding energy) is a promising technique using lasers. A neutralization efficiency approaching one-hundred percent neutralization is theoretically possible. The key issues are the construction of electrically efficient simple laser systems of the appropriate wavelength.

Recent studies [40] of systems using oxygen iodine chemical lasers look hopeful. The lasers could be $\sim 10\%$ efficient, are reasonably simple, and operate steady state.

IV. Light Atom Beams From Negative Ions

The chief problem of hydrogen neutral beams formed from positive hydrogen ions is the low maximum energy at which the positive ions can be neutralized efficiently. This practical upper limit, at an energy of 160-200 keV, means that penetration is poor for the large dense plasmas of interest for reactors, and that high currents are required to produce high power levels. The large beam currents, in turn, lead to large pumping systems, difficult reliability problems, and large port requirements. The use of negative hydrogen ions would allow the beam energy to be raised, but still leaves pumping, reliability, and port size questions, if large current (~ 50 amp) sources can be built at all.

We have recently proposed [17] the use of neutral beams of atoms with $Z > 1$ (C, O, Si) with very high energies (~ 1 MeV/amu). Dawson [41] has proposed the use of high energy charged beams of singly ionized atoms (B^+ , Na^+ ,

etc.). In our scheme, the basic idea is that negative ions of Li, C, O, or Si would be formed, accelerated to ~ 1 MeV/amu by a linear RF accelerator, such as a RFQ [32], and neutralized by either photodetachment or a plasma neutralizer (Fig. 6). The key questions are the ion source, the accelerator, the neutralizer, and the advantages of this technique compared to other heating and current drive techniques. The general philosophy has been to use as high an energy as possible to reduce the required beam current. Reducing the current has the potential for reducing the beam cross section, the gas load and pumping requirements, and the system complexity, thereby increasing the system reliability.

We have investigated the heating and current drive potentially possible with such beams using Monte Carlo techniques. The history of a typical neutral beam atom in the plasma begins with its ionization by proton and electron impact collisions. At that point, the singly charged ion begins to gyrate and drift in the magnetic field (Fig. 7). As the ion moves, it undergoes further ionizations, and the Larmor radius becomes smaller ($\rho_L \propto 1/q$, where ρ is the Larmor radius, and q is the charge), and the drift orbit shrinks so that the ion penetrates to the plasma center. The combination of penetration as a neutral and as a drifting ion undergoing successive ionizations in the plasma provides a very centrally peaked heating profile (Figs. 8, 9). The drifting depletes the heating at the edge where it is least effective, since the energy is best contained at the plasma center. In our code, we follow the history of the particle until it has completely slowed down. In the Dawson scheme [41], the penetration and trapping is accomplished completely with changes in orbit due to successive ionizations.

One of the key issues is the proton impact ionization cross sections. We have used a prescription due to Gryzinski [42] (Fig. 10). We need the cross

sections for $A^{+q} + p \rightarrow A^{+q+1} + e^- + p$ for $0 < q < Z - 1$ for Li, C, O, and Si. The penetration is not extremely dependent on the cross sections, since most of the penetration usually occurs before $q = Z/2$, but a factor of four or five in the cross sections would significantly change our results.

The upper limit on the beam energy is set by the opacity of the plasma for the neutral beams, and the requirement that low charge states ($q = 1, 2$, etc.) have Larmor orbits that are confined. In practical terms, this limits us to a few MeV/amu for INTOR-sized plasmas.

The limit due to the requirement that most of the beam be stopped in the plasma gives a maximum energy that scales as Z^2 . Since the binding energies of the valence electrons are roughly the same for all elements (~ 10 eV), the cross section for the removal of a particular valence electron is roughly the same at the same relative velocity (same energy/amu). Since $\sigma \propto 1/E$ in the high energy limit, the cross sections for each bound electron are equal for $E_Z = ZE_D$, where E_Z is the energy of the atom with atomic number Z , and E_D is the energy of a deuteron. There are also $\sim Z$ bound electrons, increasing the total ionization cross section by a factor of Z , so that $E_Z \sim Z^2 E_D$ for a cross-section scaling (Fig. 1). Thus since $P = IE$, where P is the desired beam power, I is the neutral beam current, and E is the beam energy, $I_Z = I_D/Z^2$ for constant power. Increasing the Z of the beam can increase the allowed beam energy and lower the required current (Table III) for a fixed required cross section for a given plasma penetration. Clearly, the upper limit of this scaling cannot be extended indefinitely since the Larmor orbit of the singly ionized ion must be smaller than the plasma, a consideration which limits us to $Z \lesssim 20$ and energies of no more than several MeV/amu.

Impurities can have a deleterious effect on the plasma confinement by increasing the radiation losses. However, the impurity atoms are injected at

a very high energy, and there are not very many of them. In fact, the measured impurity levels in conventional neutral beams of one to three percent [43] implies that conventional beams would inject more impurities per megawatt than the high energy beams. For instance, a one percent oxygen impurity in a 150 keV beam would result in the injection of 0.067 amps/MW. A 16 MeV oxygen beam would inject 0.062 amps/MW of oxygen, thus implying that by this criterion the pure oxygen beam is actually "cleaner" than conventional beams. In addition, at temperatures of 5-10 keV, the low-Z impurities discussed should be fully ionized, and, therefore, should not radiate strongly (Fig. 12).

A study has also been carried out which concludes that these beams would be useful in maintaining the electrostatic potential in tandem mirror end plugs [18].

Having investigated the plasma physics issues involved with the beams, we then need to investigate the practical issues involved in building them. The first issue is an ion source. Lithium, carbon, oxygen, and silicon all have electron affinities (0.62 eV, 1.27 eV, 1.46 eV, and 1.39 eV, respectively) comparable to or larger than hydrogens, so an ion source with currents comparable to the 1A or so of H^- already produced should be feasible.

We have investigated four approaches, all of which closely parallel the work in H^- ion sources. The first approach is to use a double charge-exchange source. A positive ion beam would pass through an alkali vapor cell, where conversion yields of ten to fifty percent have been obtained depending upon the ion, the vapor used, and the velocity. A second approach would be the use of surface plasma sources similar to those used in the hydrogen negative ion program (Fig. 13). The use of CO and O_2 as feed gases should provide reasonable currents of C^- or O^- . A third method would be to use surface

sputter sources in which beams of ions, such as Cs^+ , sputter negative ions from a substrate of C, for instance, producing C^- . A fourth approach is the use of laser photodissociation of NaLi molecules with a dye laser to produce Li^- . All of these approaches are discussed more fully by Grisham et al. [17]. A fifth approach, even more speculative, would be a volume production source based on the electron impact or photodissociation of molecules such as NO_x into O^- and other products. Since only modest currents (1-2 amps) are required per ion source, many candidate ion source technologies may be feasible.

The second issue is the accelerator. Since we are interested in the multi-ampere multi-MeV energy range, electrostatic accelerators are probably not feasible. Conventional linear RF accelerators suffer space charge blow-up problems at the low velocities ($\beta \sim 0.01 - 0.05$) of beam requirements. However, recent developments in RF technology using electric quadrupole focusing have made RF accelerators useable in the $v = 10^8 - 10^9 \text{ cm/sec}$ range. We have investigated primarily the RFQ [15] being developed at Los Alamos. The accelerator has wide acceptance properties and a high capture efficiency. The Los Alamos group is constructing a 2 MeV, 100 mA D^+ RFQ accelerator. They have operated a smaller scale RFQ very successfully. Based on their design studies, it appears that accelerators for 1 MeV/amu Li^- , C^- , and O^- could probably be built. The preliminary estimate of the gross electrical efficiency of such accelerator systems is $\sim 30-40\%$, one of the chief disadvantages of the RFQ based schemes compared to direct RF heating of the plasma. Design studies have been done also by LASL which indicate that a RFQ might be able to carry up to three amperes of beam per channel. Such a high current accelerator would mean that 50 MW of power could be provided with one or two beams, leading to a much simpler beam system than would be possible

with D^+ and D^- based beam systems.

The output aperture of the beams is also small (diameters of 2-10cm), with power densities of 200-1000 kW/cm², allowing the use of small ports and holes in the blanket structure.

The last issue is the neutralizer. Gas neutralizers work quite well for H^- and less well for Li^- and other negative ions (Table IV). In fact, the efficiencies of fifty percent and less essentially preclude the serious consideration of gas neutralizers for neutral $Z > 1$ beams.

More promising is photodetachment of the negative ions using lasers. The very high power density in the beam and the small number of beams required makes the laser photodetachment problem not as severe as one might think from the experience with D^- . The lasers systems being investigated for D^- would all be useable for Li^- since its detachment threshold is below the hydrogen detachment threshold. However, the detachment energies of C^- , O^- , and Si^- are all much above H^- detachment energies, and shorter wavelength lasers need to be used. Argon-ion (at 4880 Å and 5145 Å) and krypton-ion lasers (at 6471 Å) could be used, but are less efficient than the $\sim 1 \mu$ lasers envisaged for D^- detachment. Plasma neutralizers might be capable of neutralizing as much as $\sim 80\%$ of a light atom negative ion beam, but realistic systems need to be investigated.

A beam system would then consist of the ion source, accelerator, neutralizer, coupling to the tokamak, power dump, and all of the usual associated hardware (Fig. 14). The optimum beam would consist of a single beam channel (3 A of D^- at 15-30 MeV) with a couple of shielded ion sources (one operating and one spare), a single channel accelerator, bending magnets, and a photodetachment system. Such a system has the potential of being simple and reliable.

At least three advantages are offered by light atom neutral beams: centrally-peaked heating, high-power density, and low-pumping requirements. Their chief disadvantages are that the electrical efficiency of the RF accelerators is lower than that of electrostatic accelerators (below 400 keV), and that photodetachment, which remains to be developed, is probably required for neutralizing the beam.

V. Charge-Exchange Recombination Energy Losses in Tokamaks

One potential problem with neutral beams of any sort was the interaction of the neutral beam and the multiply-charged impurities. At one point, it was feared that the impurities would significantly increase the ionization rate of the neutral atoms, and lead to poor penetration of the beams. Subsequent work led to the identification of the dominant process as charge transfer with a much smaller cross section than would be expected for ionization.

However, the cross section for the process $H^0 + A^{+q} \rightarrow H^+ + A^{+(q-1)}$ is still in the $10^{-15} - 10^{-14} \text{ cm}^2$ range. This could produce an appreciable "recombination" rate for the impurity, especially when the impurity has two or fewer bound electrons, and dielectronic recombination is unimportant. The product ion is usually left in an excited state with $n \sim q^{3/4}$ [46]; the radiative decay of the excited state has been observed in ORMAK [23], ISX [47], T-4 [24], T-10 [48], and PDX [25].

The charge transfer between the beam neutrals and the multiply-charged impurities can lead to large recombination rates. This can then alter the ionization balance of the impurities, producing lower charge states with more bound electrons which can radiate strongly. The enhanced radiative losses are due almost entirely to electron impact rather than the direct recombination radiation. This effect has been investigated theoretically [19,20,21]. The

enhanced radiation has been observed on PLT [49], but was not a significant part of the power balance.

However, charge-exchange recombination has been shown recently to be one of the dominant effects in preventing the neutral beams on DITE from raising the electron temperature [22]. The beam-neutral-induced charge-exchange recombination enhanced the impurity radiation losses enough to prevent the beam from heating the electrons. When the beams were turned on, a number of carbon, oxygen, and titanium line intensities increased by a factor of ten or more (Fig. 16). The total radiation as measured by a bolometer also rose by about a factor of nine. As soon as the beams were turned off, the radiation fell back to a level comparable to the preinjection value.

The enhanced line emission is also toroidally asymmetric. There are two injectors on DITE (Fig. 17). A spectrometer and a bolometer look at the intersection of the beam and the plasma. The radiation and the OVIII line enhancements are about a factor of two to three 180° away from the beam, but are factors of eight to ten in the beam (Fig. 18).

These experimental results were modeled using a code that included charge-exchange recombination (Hulse [19]) modified to include either radial or toroidal diffusion. The enhancements in the impurity radiation were consistent with the model. Other effects, such as rapid impurity diffusion, could be ruled out. The toroidal asymmetry could be explained by a simple model whereby the impurities diffused along the field lines out of the beam line of sight and were ionized before they reached the far side of the torus. The experimental observations were consistent with the model.

The conditions on DITE of a low energy (25 keV), high power beam with a relatively high impurity content in the plasma are fortunately not typical of larger experiments in which the injection energy is higher and the plasma

often cleaner than DITE. Thus, it would not be expected that charge-exchange recombination would be the dominant part of the power balance in larger experiments, but it can alter spectroscopic estimates of radiated power losses, and it needs to be considered on each experiment.

Charge-exchange recombination with both the background "recycling" neutrals and the beam neutrals alters the radial charge state distribution and must be included in analyzing impurity diffusion rates deduced from plasma spectroscopy measurements.

VI. Charge-Exchange Recombination Diagnostics

As mentioned previously, charge-exchange recombination can be used as a plasma diagnostic. The radiative decay spectra from the charge exchange of

has been observed on a number of tokamaks [23,24,25,47,48]. A powerful diagnostic technique was developed first by Afrosimov et al. [24,48] who injected a narrow, collimated neutral doping beam, and measured the decay cascade photons from charge exchange on T-4 and T-10. By modulating the beam, the charge-exchange recombination signal could be unambiguously measured.

This technique has been further refined on the PDX tokamak at Princeton [25]. A 25 keV diagnostic neutral beam with a power of 4 to 11 kW is used (Fig. 19) in conjunction with a grazing incidence spectrometer. The diagnostic beam injector can be rotated so that the intersection of the beam and the spectrometer field of view can be at any radial location, thus

allowing radial scans. The absolute density of neutrals from the beam can be determined from beam attenuation calculations based on the measured plasma temperature and density profiles, and the measured beam intensity with no plasma present. The local reaction rate is then $n_{H^0} n_1^q \sigma_{CX}^{q \rightarrow q-1} v_{H^0} (v_{H^0} \gg v_1^q)$ for each beam energy species. A knowledge of cross sections for populating the various n, l levels of the impurity is needed to measure n_1^q .

In practical terms, the simplest impurities to study are the fully ionized ones, particularly the low-Z impurities, such as carbon and oxygen. These are fully ionized in the center of PDX due to the high electron temperature which is usually greater than one kilovolt. Since C^{+6} and O^{+8} have no bound electrons, they have no electron impact excitation lines, and cannot be detected by conventional spectroscopy. However, as C and O are typically the dominant impurity species in most tokamak plasmas, it is particularly important to be able to determine their densities in the plasma core. Increases in impurity content during neutral beam heating have been inferred in PDX through indirect measurements [50], but verification awaits the ability to measure C^{6+} and O^{8+} in the plasma core.

The charge transfer technique provides a unique method for measuring the density of fully-ionized impurities. In addition, the charge transfer rate and the subsequent radiation decay rates are relatively independent of the electron density and temperature. The strong dependence of electron excitation rates on both the electron temperature and density, and the difficulty of measuring these parameters accurately, makes analysis of spectroscopic data of electron excitation lines to determine the density of partially ionized impurities a difficult technique. Thus charge-exchange recombination is potentially a very powerful technique, because of both its unique ability to measure the fully-ionized impurity density and its relative

independence of uncertainties in the measured electron temperature. In addition, the use of the crossed neutral beam and spectrometer sight line to give radial localization eliminates the large uncertainties which arise from use of Abel inversion techniques.

In the PDX results, the beam induced signal for the ($n=3 \rightarrow n=2$) 102 Å line of OVIII can be as large as a factor of two greater than the background intensity due to both electron excitation and charge exchange with the intrinsic thermal neutrals along the viewing chord of the spectrometer (Fig. 20). The 500 Hz square wave modulation of the beam can be seen clearly. Low level signals can be detected through cross correlation analysis of the beam pulses and the spectrometer signal. The radial profiles of fully-stripped carbon and oxygen can thus be measured (Fig. 21).

There are several points to note about these profiles. The first is that the profiles are clearly not in coronal equilibrium. The fully-stripped impurities persist out to the edge and even into the limiter shadow where electron temperatures are much too low to produce these ions. This indicates the strong role impurity diffusion plays in determining the charge state balance. An impurity diffusion calculation indicated that diffusion coefficients of the order of $10,000 \text{ cm}^2/\text{sec}$ are necessary to explain the observed impurity distribution.

This technique depends crucially on knowledge of the cross sections for populating the n, l levels of C^{+6} and O^{+8} , since the photons from the radiative cascade are observed. A variety of calculations were used [46,51-54]. Better theoretical knowledge of the cross sections, both for the fully-stripped and partially-ionized targets, and any experiments not conducted in a plasma, would be very welcome.

It is worth noting that the quantitative information this diagnostic

provides would not be available without the recent work [46,51-54] of the theoretical atomic physics community. It is encouraging that the C and O densities obtained with the charge-exchange diagnostic in PDX agree with independent measurements of the plasma impurity content.

VII. Alpha-Particle Diagnostics

Heating by fusion-product alpha particles is expected to be the dominant equilibrium heat source in fusion reactors. During the next ten years there will be a number of fusion experiments which will use deuterium and tritium to produce alpha particles. On these near term experiments, it is likely that alpha-particle heating will only be a small part of the power balance (beam heating will dominate). Thus, it would be useful to measure the behavior of alpha particles in the near term DT experiments to increase our confidence about extrapolations to experiments with substantial alpha-particle heating.

One such proposed technique [55,56] is to use a "merged-beam" approach to neutralize the 3.5 MeV alpha particles by double charge exchange ($\text{Li}^0 + \text{He}^{++} \rightarrow \text{He}^0$) of a 6 MeV neutral lithium beam (Fig. 22). The neutral alphas would then be detected at the plasma edge. The key questions are the production of the 6 MeV Li^0 beam, its penetration into the plasma, and the cross section for double charge exchange of He^{++} and Li^0 .

The technology of such a lithium beam is discussed in [56] and is also covered in Section IV of this paper. The beam looks feasible, but is somewhat expensive compared to other typical diagnostics on tokamaks. The most feasible beam would be based on Li^- . Li^- would be formed, accelerated in a RFQ, and neutralized by a gas neutralizer cell.

The double charge-exchange cross section has been measured [57,58] and calculated [59] (Fig. 23). This cross section can be used to calculate

expected signal strengths and He^0 energy spectra. Both the magnitude of the signals and their energy spectra depend on the confined alpha distribution (Fig. 24). The magnitude of the expected signal is such that a Li^0 beam of ~ 50 mA would be sufficient.

Several remaining questions with this technique concern the penetration of the neutral lithium beam and the excited state distribution of the neutral helium product. If the lithium neutral atoms are ionized by two-step processes (excitation followed by ionization) induced by proton collisions at such a rate that the beam is significantly attenuated, then the technique becomes harder. The beam current would need to be raised and the lithium neutral density in the detector line of sight would become harder to determine. Excited lithium is not likely to have a much smaller double charge-exchange cross section than ground state lithium, since the two electrons that are transferred are the $1s^2$ electrons [59]. Excited helium atoms would be more easily ionized than ground state helium, so a knowledge of the n distribution of the He product would be useful in estimating how much helium would not be ionized in the plasma, but could escape the plasma and be detected.

At the present, there are no definite plans to use this diagnostic on TFTR or JET, but the Nagoya group may use the technique on their R-tokamak. Serious D-T operation is at least six years away for both TFTR and JET, so a decision on this diagnostic has been postponed for a few years.

The use of charge-exchange recombination radiation for the detection of alpha particles had originally been examined in [55] and set aside due to the low signal levels compared to background light, and due to insufficient information on the sources of noise and, hence, the ultimate sensitivity in spectroscopic measurements in the 300 Å wavelength region in tokamak

spectra. However, the availability of modulated doping beams which allow phase sensitive detection techniques and ongoing experiments on PDX [25,50] to examine noise levels in such measurements indicate that the question should be re-examined. The density of thermalized alphas can be measured in a manner similar to the detection of O^{8+} and C^{6+} described above. With the available doping beam on TFTR [60], the alpha particle density expected in a $Q = 1$ discharge in TFTR ($n_\alpha \approx 10^{12} \text{cm}^{-3}$) should be measurable. The possibility of also measuring the alpha particle velocity distribution requires significantly greater sensitivity and is still under evaluation.

VIII. Speculations About the Future

Many of the present uses of neutral beams in plasma physics were discussed in the previous sections. In recent years, neutral beams have successfully introduced more power to tokamak plasmas than has any other heating technique, and they have in the process driven tokamak plasmas to the highest temperatures yet achieved. The process by which they transfer energy to the plasma is relatively well understood, which means that the extrapolation of heating in future tokamaks based upon present results is moderately straightforward. However, the future of neutral beam heating is in doubt. Positive ion based neutral beams are large, complicated, and expensive systems. The energy limit of $\sim 80 \text{ keV/AMU}$ places an upper limit on the size of the plasma they can heat.

Radio-frequency heating, particularly ICRF (25-100 MHz), has been quite promising. Power levels up to 3 MW have been used on PLT. RF is intrinsically a simpler and cheaper technology than positive ion based neutral beams. It also offers the possibility of higher electrical efficiency than neutral beams. The major questions still left to be resolved are whether high

powers of RF can be delivered and launched into the torus without excessive breakdown and other problems, and whether the plasma will be heated efficiently at high powers with RF. If RF works, then neutral beams will not likely be used on future toroidal experiments. On the other hand, mirror machines will probably always require neutral beams to maintain the electrostatic potential.

If neutral beams have a future beyond that of diagnostic doping beams, it is with negative ions. Mirror machines need high energies (200-500 keV, at least) for reactors and tokamaks could use the high energies for better performance. Current drive (a requirement for steady-state operation) for tokamaks with beams requires the use of 300-2000 keV deuterium beams for reactor-sized plasmas. These energies are only possible with negative ions. It is likely that 10 amp sources can be built. The surface conversion sources are the most advanced, but other approaches are promising also. At energies of 300-400 keV, electrostatically accelerated H^- or D^- beams could almost be competitive with RF heating providing that photodetachment is feasible.

At higher energies, RF accelerators are probably necessary. Unfortunately, RF accelerators are less electrically efficient than the electrostatic accelerators suitable for lower energies. Once RF acceleration is used, the logic tends to draw one toward the light atom schemes, chiefly because of the possibility of using only one or two beams to supply all of the heating power.

All of this hinges on RF heating not working, so a final decision on what path to follow will not be made until high power RF experiments have produced definitive results, a process that will take quite a few years.

Charge-exchange recombination has been shown to be important on some experiments, but not on the larger, hotter machines. However, it is only a

factor of three to ten times smaller than the dominant energy loss terms, so improperly chosen operating conditions (a dirty machine with high power injection) could make it important. The process thus needs to be kept in mind, but it should be possible to operate experiments in such a way as to avoid excessive radiation losses caused by charge-exchange recombination.

Charge-exchange recombination is fast becoming a highly useful diagnostic technique, particularly when small, well collimated, intense diagnostic neutral beams can be used. It can supply unique data on the transport of fully-stripped impurities, and will be extended to partially-stripped impurities as well. The technique provides impurity density profiles that are much less subject to uncertainties in the atomic physics rates and measured electron temperature and density profiles than the usual electron impact excitation spectroscopic data. Coupled with careful analysis, the technique should significantly increase our understanding of impurity confinement in plasmas.

The next generation of fusion experiments will have small alpha-particle populations, and there will be interest in measuring them. Such measurements probably will be made in 1988-1990 when D-T operation will be routine on TFTR and JET.

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TABLE I
Neutral Beam Systems for Tokamaks in the United States

ENERGY	ION	POWER	EXPERIMENT	DATE
40 keV	D^0, H^0	3 MW	PLT	1978
50 keV	D^0, H^0	8 MW	PDX	1981
80 keV	D^0, H^0	7 MW	D-III	1983
120 keV	D^0	20 MW	TFTR	1984
150 keV	D^0	60 MW	FED	1990

TABLE II
Energies Which Yield Equivalent Neutralization in Different Gases
Taken from [12]

D^+ Energy	F_{∞} in H_2	D^+ Energy in He which gives the same F_{∞}	D^+ Energy in Ne which gives the same F_{∞}
160	0.29	195	155
200	0.19	245	225
240	0.13	297	300

TABLE III
Current and Voltage Scaling for Different Elements
For a 50 MW Beam System (100% Neutralization)

	D	Li	C	O	Si
Z	1	3	6	8	14
Beam Energy	500 keV	4.5 MeV	18 MeV	32 MeV	98 MeV
Beam Current	100 amps	11 amps	2.8 amps	1.56 amps	0.5 amps

TABLE IV

Maximum Neutralization Fraction in Various Gases at 7 MeV [44,45]

H^-	Li^-	C^-	O^-	Si^-
~ 62%	50%	28%	21%	23%

FIGURE CAPTIONS

- Fig. 1. Schematic diagram of ion source showing; (a) the ring cusp, (b) the longitudinal line-cusp, and (c) the longitudinal line-cusp with magnetic filter. The extraction grid is on the left. (taken from [11]).
- Fig. 2. Hydrogen ion species distribution as a function of discharge current for the case with (solid lines) and without (dotted lines) the magnetic filter. (taken from [11]).
- Fig. 3. Equilibrium neutral fraction, $F_{O^{\infty}}$, of an H beam in various gases. (taken from [12]).
- Fig. 4. The ratios, $F_{O^{\infty}}^x / F_{O^{\infty}}^{H_2}$, of the equilibrium fraction of an H beam in various gases divided by the equilibrium fraction in H_2 . (taken from [12]).
- Fig. 5. Schematic illustration of reflection and desorption for H^- surface production.
- Fig. 6. Schematic illustration of neutral injection of $Z > 1$ neutral atom beams into a tokamak. (taken from [17]).
- Fig. 7. Typical drift orbit of an oxygen ion (born from an oxygen atom injected at 32 MeV counter to the plasma current) is shown as it undergoes successive ionizations as far as O^{+4} . (taken from [17]).
- Fig. 8. Heating deposition profiles in an INTOR-sized plasma for 2 MeV D^0 (made from D^-), 46 MeV Na^+ , 150 keV D^0 (made from D^+ yielding neutral power fractions of 60% at full energy, 24% at one-half energy, and 16% at one-third energy), 2 MeV D^0 made from D^- , the initial birth profile of the 16 MeV O^+ resulting from the ionization of co-injected O^0 , and the final profile of the O^{+8} resulting from injection of the O^0 . (taken from [17]).

- Fig. 9. Integrated power deposited inside a given radius for the four beams of Fig. 8. (taken from [17]).
- Fig. 10. Ionization cross sections for carbon extrapolated from Gryzinski [37].
- Fig. 11. The energy at which the neutral ionization cross section is $0.5 \times 10^{-16} \text{ cm}^2$, $0.7 \times 10^{-16} \text{ cm}^2$, $1.0 \times 10^{-16} \text{ cm}^2$, $1.7 \times 10^{-16} \text{ cm}^2$, and $2.2 \times 10^{-16} \text{ cm}^2$, respectively, as a function of atomic number. Also, plotted as a dotted line is the line $E = Z^2$ normalized to $E = 400 \text{ keV}$ at $Z = 1$, demonstrating that $E = Z^2$ scaling is roughly correct.
- Fig. 12. The most abundant charge state in coronal equilibrium present in a plasma of a given element at a given electron temperature. The curves are for the filled labeled subshells. Calculated using the rates in [19].
- Fig. 13. Conceptual design of the Ehlers-Leung type surface plasma source which might be used for light negative ion production. For C^- production, the working gas would probably be an inert gas, such as argon. For O^- production, one might use a metallic converter plate and oxygen as the working gas. (taken from [17]).
- Fig. 14. Example of a possible light atom beam module. Negative ions are produced, deflected around an analyzing magnet to remove ionic and neutral impurities, preaccelerated, and focused into a Los Alamos RF quadrupole accelerator. The accelerated ions are aimed with a deflection magnet through a neutralizer. For any ions heavier than Li^- , a photodetachment neutralizer would probably be used, preceded by magnetic quadrupoles to focus the beam. (taken from [17]).
- Fig. 15. Conceptual design of a single channel high power system. One-to-several amps of O^- or another prolific light negative ion is

extracted from one of the alternate sources (the other serving as a spare). The beam is accelerated to 16-32 MeV in a single RF quadrupole accelerator channel, and is subsequently aimed, focused by magnetic quadrupoles, and neutralized by photodetachment. (taken from [17]).

Fig. 16. The time variation of the line enhancement ratios of carbon, oxygen, and titanium impurity ions for a low density discharge (taken from [22]). The solid lines are experimental, the broken lines are theoretical.

Fig. 17. Plan of DITE showing the location of the neutral injection lines and the principal diagnostics. (taken from [22]).

Fig. 18. Total radiation and line enhancement ratio for OVIII observed close to the C line injector. The toroidal asymmetry is clearly shown when the "A" and "C" injectors are used in turn. (taken from [22]).

Fig. 19. Schematic of experimental apparatus for low-Z impurity diagnostic on PDX. (taken from [25]).

Fig. 20. Excitation of OVIII 102 Å ($n=3$ and $n=2$) emission by charge exchange with the pulsed diagnostic neutral beam in PDX. (taken from [25]).

Fig. 21. Radial profiles of fully ionized oxygen and carbon during the steady state phase of the discharge. Limiter radius is at 30 cm. Closed circles: $R > R_{pl}$. Open circles: $R < R_{pl}$. $R_{pl} = 147$ cm. The solid lines are Radial profiles of C^{6+} and O^{8+} calculated from impurity transport code. C. E. - distribution expected from coronal equilibrium assuming a constant impurity density. $D =$ constant impurity diffusion coefficient. (taken from [25]).

Fig. 22. Schematic illustration of fast alpha diagnostic. (taken from [55]).

Fig. 23. Double charge-exchange cross section for $\text{He}^{++} + \text{Li}^0 \rightarrow \text{He}^0 + \text{Li}^{++}$ from [57] and [58]. The curve has been extrapolated below 28 keV and above 800 keV. (taken from [56]).

Fig. 24. Velocity distributions (normalized to the same peak amplitude) of the emerging He^0 at 20° as a function of the Li^0 beam velocity for the (a) classical, and (b) nonclassical particle velocity distribution. The arrows indicate the beam injection velocities at $v_{\text{beam}}/v_0 = 0.4, 0.6, 0.8$, and 1.0 , where v_0 is the alpha particle birth velocity. (taken from [56]).

82 P 0164

FIG. 1

#82P0i63

FIG. 2

81X0330

FIG. 3

81X0331

FIG. 4

#82P0179

FIG. 5

FIG. 6

81X0685

FIG. 7

FIG. 8

FIG. 9

#82P0166

FIG. 10

81P0048

FIG. 11

82P0021

FIG. 12

FIG. 13

TWO STAGE Li^- MODULE USING AN ELECTRON BOMBARDMENT Li^- SOURCE

FIG. 14

FIG. 15

#82P0167

FIG. 16

82P0162

FIG. 17

#82P0161

FIG. 18

FIG. 19

#82X0248

FIG. 20

FIG. 21

FIG. 22

81X1327

FIG. 23

81 X 1330

FIG. 24