obtain $(\tau')^{-1} \approx 0.01$ sec^{-1} at 0.425°K. In view of the doubtful applicability of Griffiths' calculations to He^3, this agreement is surprisingly good.

Our results show that the presence of a very small number of isolated He^4 atoms contributes to the total exchange-lattice relaxation rate by a process whose temperature dependence lies between T^8 and T^9. No theoretical calculations of relaxation times in solid He^3 containing He^4 have yet been published, but it seems a reasonable extension of Griffiths' theory to suppose that an increase in J at each He^4 site[1] would result in a locally enhanced relaxation rate. Even in the purest samples a spin diffusion coefficient derived from $\tau_{SS} \approx (J)^{-1}$ should be large enough to maintain a uniform exchange temperature.

This work will be extended to identify the temperature dependence of the intrinsic relaxation rate, and its variation with density.

We are indebted to R. B. Harrison and W. S. Truscott for the purification and analysis of the samples.

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PRODUCTION OF d-d REACTIONS BY BEAM-PLASMA INTERACTION IN THE STEADY STATE*

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This Letter reports an unusual deuterium plasma generated by a reflex electron beam on the axis of a simple magnetic mirror trap or modified PIG[1] configuration. The plasma is extremely turbulent, appears to be highly ionized, and emits d-d reaction products. It appears that the plasma's unusual nature is due to an interaction with the electron beam. Some earlier reports of electron beam-plasma interaction indicate a plasma blow-up,[2] enhanced ion and electron energies in a restricting magnetic field,[3] significant electron heating in magnetic traps,[4] a high degree of ionization when the plasma is generated along a pressure gradient,[5] and an apparent increase in the energy of some ions and electrons when the plasma is within a magnetic trap and when reduced pressure in the end regions outside the trap permits otherwise unattainable power density in the beam.[6]

We call the present device at Oak Ridge Laboratory "Burnout V," because it is the fifth in a series of modifications we have made to the conventional PIG. Each modification has enhanced this unusual effect until we can detect d-d reaction products originating in the plasma region. We catalog our observations of d-d neutrons, tritons, and protons on Burnout IV and V in Table I. The reaction rates given are estimated from the largest yields observed and the solid angle of the instrument apertures.

The 3-MeV proton data from the plasma of Burnout V are corroborated by triton and neutron measurements from both Burnout IV and V. It is only in Burnout V, however, that we are certain that the d-d protons originate in the plasma, within the hollow anode of the apparatus. The neutron measurements alone are inconclusive because instrument resolution is not sufficient to exclude a possible contribution from the end electrodes, which are strong d-d sources because of dc acceleration. The triton measurements clearly exclude the end electrodes, but do not completely exclude wall reactions within the anode. The proton

Table I. Reaction product yields from "Burnout" experiments. The neutron yield is too large because the end electrodes which are 10^7 sec^{-1} neutron sources could not be completely shielded against. The triton yield [W. D. Jones and R. V. Neidigh, Appl. Phys. Letters 10, 18 (1967)] is also too large because the measurements were made during gas-pulse experiments; however, the end-electrode reactions are positively excluded. Because of uncertainty in plasma volume seen by the detectors the absolute proton yield may be in error by a factor of 5.

Experiment	Particle observed	Detection method	Estimated total reaction rate (sec^{-1} cm^{-3})
Burnout IV	Neutrons	BF^3 counter	$\sim 10^4$
Burnout V	Neutrons	BF^3 counter	$\sim 10^5$
Burnout V	Tritons	Cellulose nitrate	$\sim 10^5$
Burnout V	Protons	Nuclear emulsion	600
Burnout V	Protons	Scintillation counter	10^3

yield is believed to be of the plasma only. Protons were observed both with nuclear emulsions arranged so that the wall reactions could be subtracted, and by scintillation spectroscopy using a CsI crystal. Energy calibration of the scintillator output, shown in Fig. 1, was by an ^{241}Am alpha emitter and more precisely by the 3-MeV protons from the deuterium beam-target reaction at the cathodes. We assumed that the reaction product $^3He^{++}$ could not be observed. Its energy and double charge state result in an orbit diameter too small to reach the cavity wall with an origin near the axis. We noted with interest, however, that as the magnetic field strength exceeds a certain minimum, beam power can be increased. It seems coincidental that this minimum is about the field strength required to contain $^3He^{++}$ ions born on the magnetic axis.

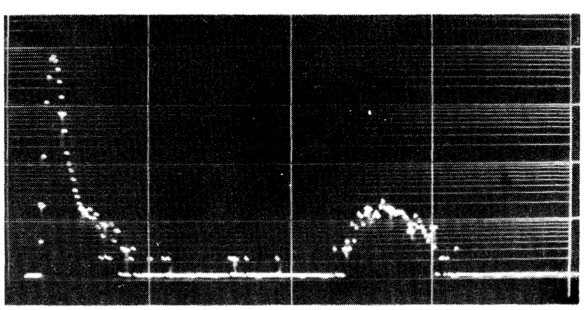

FIG. 1. Energy analysis of the scintillator output. The high-energy peak is the response to 3-MeV protons coming from the midplane region of the machine. Count rate was about one proton per sec. Calibration of the energy scale, not shown, was by 3-MeV protons from reactions occurring at the cathode surfaces. The low-energy background is the crystal response to x rays coming from the machine.

Burnout V has some rather unique features (Fig. 2). Instead of the usual anode ring of the PIG, the anode defines a cavity region. The magnetic field is generated by a coil at each end of the cavity forming a magnetic trap within. Electrons are reflected back and forth through the cavity on the magnetic axis. Deuterium gas is fed into the cavity and is ionized by the electrons. The emitting portions of the cathodes are outside the mirror coils, in high vacuum. The cathodes face each other at either end of the magnetic axis and are positioned so that electrons can reach the anode only by crossing the magnetic field. The magnetic field strength is 50-25-50 kG on the magnetic axis

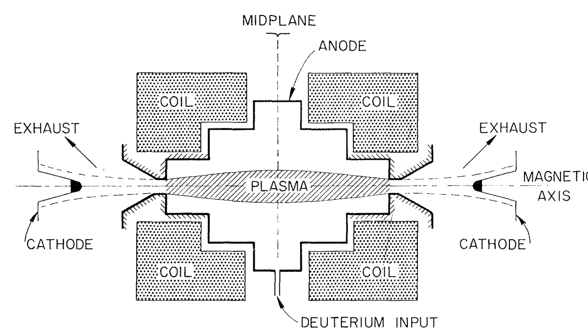

FIG. 2. Burnout V, axial section. The anode structure includes the magnetic trap which is normally 50-25-50 kG. Cathodes are outside the mirrors. All structures are water cooled. Only the cathode tips are incandescent. Ambient pressures are about 5×10^{-3} Torr within the anode and 10^{-5} Torr in the cathode region. The spacing between cathodes is about 100 cm, 50 cm between mirrors. The mirror orifice is 1.27 cm in diameter. The cross-hatched region marked "plasma" locates it within the anode but is not intended to indicate its size. We used 10^3 cm^3 in the calculations requiring a volume.

at the mirror-midplane-mirror positions. Approximate dimensions of the apparatus are given in the caption of Fig. 2.

The operating parameters of Burnout V have changed frequently as improvements in electrode design have permitted greater input power and gas feed rate. At present writing the gas feed rate is 0.25 $cm^3\ sec^{-1}$ (atmospheric) of molecular deuterium, giving a density, without plasma, of 2×10^{14} cm^3 in the anode cavity. The power delivered to the beam is 60 kW at 10 kV accelerating potential. About half of the input power is dissipated by the cathodes and half by the anode. Nearly 10% is dissipated by the midplane section of the anode.

A section through Burnout V at the midplane is shown in Fig. 3. It illustrates the technique of identification of protons with plasma origin. Note that one emulsion sees the plasma and a portion of the liner wall while another emulsion sees the same portion of wall but not the central plasma region. This permits subtraction of a 10% background due to wall reactions. Scintillator response to the background of wall reactions is reduced because the wall section "seen" by the scintillator along reversed 3-MeV proton trajectories is recessed sufficiently to be unavailable to fast deuterons in the plasma.

We wish to enumerate some very interesting observations made on Burnout IV and V. Most have been described in greater detail elsewhere.[5,6]

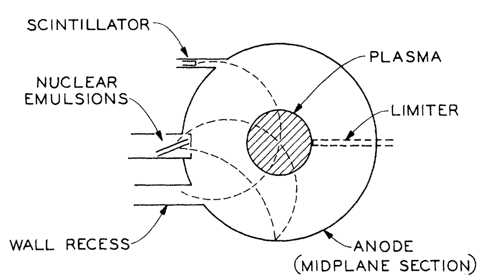

FIG. 3. Burnout V, midplane section. Locations of the scintillator and nuclear emulsions are shown. The dotted lines are 3-MeV proton trajectories. The radius of the electron beam at the midplane is approximately 0.9 cm, the liner 16 cm. The figure shows how the scintillator "sees" the 3-MeV protons from d-d reactions that take place in the plasma and only a recess at the wall, and how the upper nuclear emulsion plate can register 3-MeV protons that can come from the plasma together with some that can come from d-d reactions on a section of the wall, while the lower plate can register only those that can come from the same section of the wall.

(1) We estimated the ion current coming out of the mirrors of Burnout IV by replacing the ion beam with a measured gas flow to an end electrode. We had 75-100% gas-to-ion accountability. Although this did not prove we had a highly ionized plasma, it was a stimulating result. We have about the same accountability on Burnout V by a different technique. The atom input rate, 2×0.25 $cm^3\ sec^{-1}$ (atmospheric), is equated to the ion output rate found by dividing the power dissipated on the cathodes, 30 kW, by the cathode potential, 10 kV:

$$2\times0.25\times3\times10^{19}\ \text{atoms sec}^{-1} \approx (30/10)\,6\times10^{18}\ \text{ions sec}^{-1}.$$

(2) Neutral spectra were virtually absent from the plasma interior of Burnout IV. For example, we observed a 10^2 to 10^3 decrease in the Balmer spectrum when the plasma became turbulent. There is significant Doppler broadening and slanting of the Balmer spectrum at the plasma perimeter, exceeding that seen in the high-intensity arcs of electromagnetic isotope separators.[7] We were not able to determine a temperature from the data because the line profile was not Gaussian, but its width exceeded 500 eV. Plasma probes indicated an average ion energy exceeding 500 eV on the plasma perimeter.

(3) A density of 10^{11} cm^{-3} was found by a neutral beam technique on Burnout IV. We believe the density to be higher than this in Burnout V, perhaps 10^{12} cm^{-3}, from probe data taken at the plasma perimeter and rf radiation in frequency bands which we have assumed represent the ion and electron plasma frequencies.

(4) A plasma limiter inserted radially inward from the wall at the midplane (see Fig. 3) to a point eight times the electron-beam radius reduced the reaction rate to 0. With the limiter at this position the plasma radius was scarely reduced, but the heat removal required to keep the copper from melting exceeded 10^3 J/sec with the rate directly proportional to the square of the magnetic field strength over the range 20-28 kG.

(5) A deuteron originating at the magnetic axis and grazing the plasma limiter must have an energy of at least 100 keV. We have analyzed the plasma ions at this point and found a 100-keV ion flux of 3×10^{14} $cm^{-2}\ sec^{-1}$ directed into the wall. Deuteron energies as great as 170 keV have been detected with the limiter

removed. This, no doubt, is the source of the background wall reactions we see. Such a background, though annoying when attempting to observe only the plasma, is further evidence that some ions have sufficient energy to produce a measurable reaction rate on the most positive surface in the device. Deeply sputtered probes and liner surfaces qualitatively support these observations.

We do not yet have a direct measurement of confinement time. It is a difficult measurement and cannot be done by the usual turn-off procedure because of the immediate influx of neutral gas. We observed in Burnout IV, however, that there were no reactions in the midplane region without magnetic mirrors, even though power input with and without mirrors was comparable. An appreciation of confinement might be obtained from an electron beam-to-ion energy-transfer efficiency consideration. Taking $nkTV = 10^{12} \times 1.6 \times 10^{-12} \times 500 \times 10^3 = 0.8 \times 10^6$ erg as the energy stored in the plasma and dividing by the power input, 60 kW, the time is found to be about 1.3 μsec, or a time roughly equal to the exit time for an ion in the escape cone. Any efficiency less than the 100% used in this calculation must increase the confinement time by the same factor. If a more appropriate guess of the efficiency is made by estimating the confinement time from the plasma density-volume product and the neutral input rate, $10^{15}/2 \times 0.25 \times 3 \times 10^{19} \approx 70$ μsec, corresponding to 2%, then the ions must be confined for many transits between mirrors and hundreds of cyclotron periods.

Another interesting observation is the effect of impurities. We observe that a clean-up time is necessary after start-up, before d-d protons are observed, even though during the clean-up the operating parameters do not seem to change. An introduction of 10% helium into the gas feed reduced the d-d proton production rate to 0, without affecting operating parameters, and a clean-up period was agian necessary after the helium feed was stopped. Likewise, if a probe is overheated, introducing impurities, the reaction rate goes to 0.

We recognize that we have presented diagnostic results which, though not sufficient to exclude beam-target reactions in the plasma, are quite necessary if heating exists. Clearly, more diagnostic experiments establishing density, temperature, and confinement time are in order. The plasma generation technique is technologically simple, and the energy transfer from electron beam to ions is little understood. The possibility of such an understanding, coupled with the simple technology, makes it appear to us that this approach to plasma heating may be a fruitful one. In addition to the ion energy discussed, present diagnostics suggest that the electrons also are heating significantly. This work has been done in the steady state at much less than the technological limit in magnetic field strength and beam-power density. We foresee a new generation of experiments involving greater magnetic fields and the use of gas pulse and beam-power pulse techniques.

We have appreciated the continuous and stimulating exchange of ideas within the thermonuclear project and, in particular, within the Oak Ridge National Laboratory Division of which we are a part. The technical support of the Y-12 Research Services Group has greatly facilitated the experiment.

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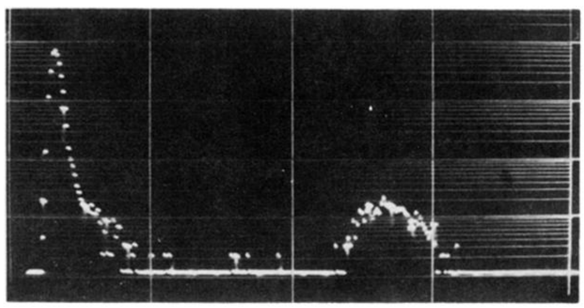

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