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BY

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Multi-MeV Li^{o} Beam as a Diagnostic for Fast Confined Alpha Particles

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ABSTRACT

We discuss a method of measuring the velocity distribution of confined energetic alpha particles resulting from deuterium-tritium fusion reactions in a magnetically contained plasma. We calculate the characteristics of the signals to be expected from injecting multi-MeV Li^{o} into the plasma to undergo double charge-exchange reactions with the alpha particles. Neutralized alpha particles then escape from the plasma to be detected by a charge-exchange analyzer. We also examine the feasibility of producing a Li^{o} beam of the required current and energy, and we discuss a conceptual design for an appropriate beam system.

I. Introduction

Many magnetic confinement fusion reactor concepts rely upon substantial heating of the plasma by the D-T fusion-product alpha particles as they slow down classically. However, a number of authors [1] have studied anomalous processes which might alter the slowing down of the alpha particles, thereby changing their energy transfer to the plasma. In general, these anomalous processes could lead to loss of the fast alphas from the central portion of the plasma, or they could change the rate at which the fast alpha particles slow down and heat the ions and electrons. The anomalous loss of alpha particles from the central portion of a plasma being heated to ignition could increase the $n\tau_E$, auxiliary heating power, and β required for ignition. Anomalous ion heating by alpha particles could lead to a reduction in ignition requirements. In addition, the loss of alpha particles from the whole plasma could result in accelerated erosion of the reactor first wall from blistering [2,3] due to bombardment by the escaping energetic alpha particles. Given the large costs and lead times associated with reactor-sized experiments, it is desirable to discover at the earliest possible date whether the fusion-product alpha particles slow down in a classical manner through binary coulomb collisions, or whether instead they are subject to anomalous processes prior to thermalization. The first generation of D-T burning tokamaks is unlikely to provide answers about alpha confinement through the power balance alone. At Q=1 alpha particle heating will account for only about a fifth of the input power to the plasma, even if the alpha particles thermalize completely

before they are lost. Consequently, a diagnostic is needed to measure the slowing down spectrum of the confined alpha particles in much the same way that charge-exchange analyzers have measured the slowing down spectrum of beam-injected ions by looking at the charge-exchange flux [4].

In the normal course of events, however, the fast confined alpha particles should have little chance for double charge exchange in the hot core of a Q=1 plasma. Recently, Post et. al. [5] proposed that one might locally enhance the charge-exchange probability of the alpha particles by injecting a neutral doping beam. This beam would undergo single or double charge-exchange events with fast alpha particles. One might observe either the doppler-shifted de-excitation radiation from the decay of excited He^{+} states populated by single charge exchange, or the fast He^{o} escaping from the plasma after acquiring two electrons through double charge exchange with the beams.

The charge-exchange cross sections for He^{++} decline rapidly at relative velocities above $\sim 4 \times 10^{8}$ cm/sec because the orbital velocities of the bound electrons in Helium are of this order. Since the D-T fusion-product alpha particles are born at $\sim 1.3 \times 10^{9}$ cm/sec, the doping beam must be capable of velocities about as high as the birth velocity (corresponding to 880 keV/amu) in order to have a significant probability of charge exchange. From this velocity requirement it follows that the successful development of this diagnostic method will pose significant technical difficulties.

This paper relates the results of a study we have done of

one approach to the alpha particle diagnostic: double charge exchange from a doping beam, followed by analysis of the velocity distribution of the resulting He^{o} which escapes. We compute the expected signals, and we discuss a possible design for the diagnostic. We have chosen to use double charge exchange because the background problem should be much less severe than would be the case in looking at the doppler-shifted radiation following single charge exchange. The signal from the latter process would be about the same intensity as bremsstrahlung, which is itself expected to constitute only a small fraction of the background near 300 Å.

The present paper extends the work of Ref. 5. in that it studies the use of a specific reaction, and explores the appropriate beam technology required, for an alpha diagnostic based upon the atomic processes discussed in Ref. 5.

II. Choice of a Doping Beam

The requirement that the beam energy should be able to reach as high as ~ 880 keV/amu mandates the use of negative ions as precursors to a neutral beam, regardless of the beam used.

In order to minimize the cost, one would prefer to use the lightest doping atom possible, since this would result in the lowest beam energy requirement. Accordingly, the most obvious candidate for a double charge-exchange doping beam is ^{3}He, for which the negative ions can be made in adequate quantity (10's of mA) [6,7]. Unfortunately the He^{o} resulting from neutralization of He^{-} will be predominately in a long-lived metastable state, $[He^{+}\ (1s2p\,^{3}S)]$[8]. It would be extremely difficult to determine

either the double charge-exchange cross section for the metastable component of the beam or the percentage of the beam in the ground state. Further, the metastable portion of the beam could not be quenched without ionizing most of it [9].

These considerations lead one to choose the next lightest atom, ^6Li, as the probe beam. The beam resulting from neutralization of $^6Li^-$ should be primarily in the ground state or in a state which will rapidly decay to the ground state.

III. Signal Computation

At the time of Ref. 5, the cross section for the reaction $Li^o + He^{++} \longrightarrow Li^{++} + He^o$ was not known. Since then two groups have measured this cross section as a function of energy [10,11], obtaining good agreement with each other. Figure 1 shows the cross-section curve used in these calculations. This is a composite of the measurements by References 10 and 11. The curve has been extrapolated at energies below 28 keV and above 800 keV.

We have used the cross section in Fig. 1 to calculate the characteristics of the He^o flux resulting from double charge exchange. We have done these calculations for two assumed alpha particle velocity distribution functions. The first, which we shall refer to as the "classical distribution," is that which would result from slowing down of the alpha particles entirely by classical binary collisions on a TFTR plasma [5] with $T_e = 10$ keV, $T_i = 20$ keV, and $n_e = 1 \times 10^{14}$ cm^{-3}. The other distribution, which we shall refer to as "nonclassical," is the classical distribution multiplied by a $(v/v_o)^4$ term, where v_o is the birth velocity of the fusion-product alpha particles.

Such a distribution might result from a process which caused rapid loss of the fast alpha particles. Comparing the results arising from these two distributions gives us an indication of the sensitivity of the emerging flux to gross variations in the alpha particle containment.

Figure 2 shows $\langle\sigma v\rangle$ as a function of the Li^{o} doping beam velocity for the classical (a) and the assumed nonclassical distribution (b). Thus, if one put in a doping beam at successively different velocities, one would observe very different count rates and (below $v_{beam} = 10^{9}$ cm sec^{-1}) opposing gradients as a function of beam energy, depending upon which of the two alpha distribution functions existed in the plasma. These characteristics become more apparent in Fig. 3, which shows the differential reaction rate as a function of detector angle at various Li^{o} beam velocities for the classical and nonclassical distributions. It is also apparent in this figure that the He^{o} analyzer must be located in a forward direction if the signal level is to be maximized. This is a natural consequence of the velocity selectivity of the reaction. Alpha particles are most likely to have low velocities relative to the beam if they are going in somewhat the same direction.

One would also like to be able to discern differences in the distribution function from the results of a single beam energy. That this should be the case is shown by Fig. 4, which gives the velocity distributions of the He^{o} emerging at 20° (relative to the beam direction) for the (a) classical and (b) nonclassical alpha velocity distributions. These are shown for four different

Li^o injection velocities. We can see that at Li^o velocities below ~ 1.1×10^9 cm sec^{-1} the shapes and centroids of the He^o distributions are quite sensitive to the alpha velocity distributions. At $v_{beam}/v_o = 0.8$, for instance, the centroid of He^o for the classical distribution is shifted down by ~ 1.7×10^8 cm sec^{-1} relative to the injection velocity, while for the non-classical distribution the centroid of the He^o is shifted up by ~ 1.3×10^8 cm sec^{-1} with respect to the beam energy. In addition, the signal forms resulting from the two assumed distributions differ markedly in shape and width, and, as indicated by Fig. 3, would have somewhat different signal intensities.

Accordingly, we see that this technique yields a number of observables to probe the alpha particle velocity distribution function. At a fixed beam energy, one can measure the shape, intensity, and velocity centroid shift of the emerging He^o. In addition, with a capability to vary the beam energy, one can measure the rate of change of the He^o flux as a function of the Li^o velocity.

In order to get an idea of the beam technology required, we need a crude estimate of the expected signal level. If we use the detection geometry assumptions in Ref. 5, then with Q=1, an alpha particle density of 10^{12} cm^{-3}, an injected Li^o beam of 45 mA-equivalent, and subsequent reduction of the beam by one e-folding through ionization, we arrive at a He^o flux of ~ 8×10^5 cm^{-2} sec^{-1} at an analyzer entrance at 20° relative to the beam direction and located 5 meters from the interaction volume. This is intended as an estimate only; the actual signal flux might be

somewhat lower due, for instance, to processes such as ionization or charge exchange of the emerging He^{o}. This becomes a severe problem for He^{o} at energies below 500 keV (at which energy the loss is about one e-folding). A signal level of the order estimated here should be detectable with relatively conventional techniques similar to those presently employed for charge-exchange analysis of the bulk ion energies in tokamaks.

IV. Required Technology

The requirement of a Li^{o} beam of several 10's of milliamps-equivalent current at several MeV cannot be met by any existing hardware. However, as we shall briefly discuss, the technological base for development of such a beam appears to exist. A fuller discussion of technological and design considerations of light atom beams for another application (heating) can be found in Ref. 12.

IV. 1 He^{o} Analyzer

Figure 5 shows a conceptual design of an analyzer for the escaping He^{o} resulting from neutralization of the alpha particles in the plasma. At the entrance of the analyzer, a thin foil strips most of the He^{o} back to the alpha particles, which are deflected by a magnet so as to strike detectors. The magnet's purpose is twofold: to momentum analyze the He^{++}, and to allow the detectors to be located behind neutron shielding. If they can be adequately shielded, the most desirable detectors will probably be position-sensitive surface detectors. These would allow energy resolution in addition to that provided by the magnet, and would also permit the rejection of much residual neutron

noise, since neutrons would generally only lose small amounts of energy in the thin detectors.

IV. 2 Source

The best documented method for producing Li^- is a two step process wherein Li^+ is extracted from an arc source. The positive ions then pass through a metal vapor where a fraction of them acquires two electrons to become negative ions. The most developed approach to high current production of Li^+ is with the calutron type sources of Oak Ridge National Laboratory. These have a long history, and have yielded Li^+ current densities of as much as 72 mA/cm^2 [13], and total Li^+ currents as large as 1.2 amps [14] while operating continuously. Some measurements have been made of positive-to-negative ion conversion efficiencies with small beams. Approximately 9% of a 5 keV Li^+ beam was converted to Li^- while passing through a cesium vapor cell [15]. Thus a source to produce ~ 100 mA of Li^- might consist of a Li^+ source using calutron technology and extracting the beam in an accel-decel mode, followed by a transverse supersonic cesium jet.

There are at least two other possible alternative approaches to a high current Li^- source. One possibility is to produce the negative ions directly with a surface plasma source similar to one of the types being developed for D^- production [16,17,18]. However, while such sources are very attractive for making negative ions from gaseous feedstocks, they may be less suitable for producing negative ions of a substance, such as lithium, which has a lower vapor pressure than does the cesium which dopes the converter

surface. Another method which might be highly desirable, but which is unexplored at this time, is photodissociation of NaLi molecules in a molecular beam into Na^+ and Li^- using 2350-2400 Å photons from a laser [19].

IV. 3 Accelerator

Accelerating 100 mA to energies as high as 5.3 MeV would be an intractable problem for a conventional electrostatic accelerator. A RF linear accelerator with electric quadrupole focusing [20,21] is a much more suitable choice, since the electrical potentials with respect to ground that are required can be much lower than the final beam energy, and the velocity-independent electric quadrupole focusing allows one to input a low velocity beam with high space charge density. RF quadrupole (RFQ) accelerators [20], which are being developed at Los Alamos Scientific Laboratory, seem to be especially appropriate for this application. They appear to be capable of accelerating the full 100 mA current in a single accelerator channel, they can have a large entrance aperture to accept the Li^- beam, and they can readily be pumped through gridded ducts. A preliminary design of a RFQ to accelerate 100 mA of Li^- to 6 MeV has been done by LASL [20]. In the design of Ref. 20, the input aperture radius would be large (8.47 cm, of which about half could be filled with beam), and the output beam would have a radius of about a centimeter. The normalized emmitance acceptance would be ~ .21 cm mrad [22]. This should be adequate to use with the two stage Li^- source, but the acceptance could probably be further increased if the source optics required it [22]. Using

50 MHz RF at 223 kV, the length would be about 7 meters. The Li^- would be electrostatically preaccelerated to 100 keV prior to injection into the RFQ. The capture and transmission efficiency of a RFQ can be high (~ 93% for this case, in the absence of premature stripping losses), which is desirable since the Li^- is not easy to make.

Although much information about the alpha particle velocity distribution function can be obtained by injecting the Li^0 beam at a single energy, it is clearly desirable to have the capability to inject at any of several discrete energies (continuous variability, while useful, is not required). Changing the energy of a RF accelerator is not as straightforward as would be the case with an electrostatic accelerator. However, Ref. 20 has discussed methods of incorporating energy variability which should be adequate for this application. These possible methods include following the RFQ with independently phased cavities, varying the frequency, or varying the drive voltages to sections of the RFQ.

IV. 4 Neutralizer

Unlike heavier negative ions, Li^- can be neutralized quite efficiently by passage through a thin gas cell. At 6-7 MeV, a nitrogen cell has been observed to neutralize ~ 45% of a Li^- beam [23,24], and a hydrogen gas cell can give a neutral yield of ~ 54% [23]. Since the nitrogen can be kept at a much lower vapor pressure than can hydrogen by cryocondensation pumping, and since we would like to minimize the gas load to the accelerator in order to suppress premature stripping, we would choose nitrogen rather than

hydrogen as the neutralizer gas. The neutralization efficiency obtainable with a gas cell is adequate for this diagnostic application, where power efficiency is not of paramount importance. However, if photodetachment neutralizers were developed for D^- heating beams, then one could be adapted for use with Li^- to yield a higher neutral fraction. The photodetachment cross section for Li^- has been calculated [25] to be grossly similar in shape to that of D^-, but larger. Accordingly, any photodetachment system for D^- should also be effective with Li^-.

IV. 5 Beam System

Figure 6 shows a conceptual design of a Li^0 beam incorporating a two-stage Li^- source and a RFQ accelerator. The analyzing magnet after the source section allows drifting metal vapor to be condensed before the accelerator. The deflection magnet after the RFQ permits the accelerator to be shielded from the direct neutron flux of the tokamak. Focusing magnetic quadrupoles would probably be necessary prior to the neutralizer. A gas neutralizer would necessarily be followed by a deflection magnet (probably air core) and cooled dumps for the residual ions. These ions, both positive and negative, could carry as much as ~ 300 KW. Fortunately, at the gas cell thickness which yields the maximum neutral fraction, the power in the unneutralized remnant is about equally divided between the positive and the negative ions [24], so the power density on the dumps is decreased. A more comprehensive discussion of system aspects of light atom beams is contained in Ref. 12.

V. Conclusion

Our calculations indicate that this technique can yield useful

information about the velocity distribution function of the fast confined alpha particles resulting from D-T fusion reactions. It appears that Li^{o} is the most desirable doping beam to use, with a charge-exchange analyzer to measure the escaping He^{o} which results. The 100 mA Li^{-} beam at several MeV which is required for this diagnostic will need significant development, but from our study it does appear possible based upon our present state of knowledge. There are some atomic physics questions requiring further theoretical examination-namely excitation of Li^{o}, the double charge-exchange cross sections for any significant excited states of Li^{o}, and the distribution and fate of excited states of helium resulting from double charge exchange. Nonetheless, neutralization of the fast alphas by an energetic neutral lithium beam seems to hold promise as a viable and feasible measurement technique.

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FIGURE CAPTIONS

1. Double charge-exchange cross section for $He^{++} + Li^{o} \longrightarrow He^{o} + Li^{++}$ from References 10 and 11. The curve has been extrapolated below 28 keV and above 800 keV.
2. Values of $\langle\sigma v\rangle$ for the (a) classical and (b) nonclassical alpha particle velocity distribution functions.
3. Differential $\langle\sigma v\rangle$ for the (a) classical and (b) nonclassical alpha particle velocity distributions shown as a function of the angle between the neutral particle detector and the doping beam for several beam velocities. v_o is the alpha birth velocity of 1.3×10^9 cm sec^{-1}.
4. Velocity distributions (normalized to the same peak amplitude) of the emerging He^{o} at 20° as a function of the Li^{o} beam velocity for the (a) classical and (b) nonclassical particle velocity distributions. The arrows indicate the beam injection velocities at $v_{beam}/v_o = 0.4, 0.6, 0.8$, and 1.0, where v_o is the alpha particle birth velocity.
5. Conceptual design of a neutral helium analyzer. The stripped helium ions are magnetically deflected to effect momentum analysis and shielding of the detectors.
6. Conceptual design (not to scale) of a beamline to produce multi-MeV Li^{o}.

REFERENCES

[1] Ya. I. Kolesnichenko, "The Role of Alpha Particles in Tokamak Reactors," Nucl. Fusion 20, 727 (1980), and references contained therein.

[2] L. M. Hively, G. H. Miley, "Fusion Product Bombardment of a Tokamak First Wall," Nucl. Fusion 17, 1031 (1977).

[3] L. M. Hively, G. H. Miley, "Prompt and Non-Prompt Contributions to Fusion Product Bombardment of a Tokamak First Wall," Nucl. Fusion 20, 969 (1980).

[4] R. J. Goldston, "Charge-Exchange Spectra Near the Injection Energy in Tokamaks Equipped with Tangential Neutral Beams," Nucl. Fusion 15, 651 (1975).

[5] D. E. Post, D. R. Mikkelsen, R. A. Hulse, L. D. Stewart, J. C. Weisheit, "Techniques for Measuring the Alpha Particle Distribution in Magnetically Confined Plasmas," Journal of Fusion Energy 1, 129 (1981).

[6] E. B. Hooper, Jr., P. A. Pinosy, P. Poulsen, C. F. Burrell, L. R. Grisham, and D. E. Post, "High Current Source of He^- Ions," Rev. Sci. Instrum. 51, 1066 (1980).

[7] K. W. Ehlers and K. N. Leung, "He^- Ion Production for Alpha Particle Distribution Measurements in Tokamaks," Bull. Am. Phys. Soc. 25, 698 (1980).

[8] A. S. Schlacter, "Metastable Contamination of Fast He^0 Beams Produced from He^-," Bull. Am. Phys. Soc. 25, 698 (1980).

[9] L. R. Grisham, D. E. Post, J. C. Weisheit, H. P. Eubank, D. R. Mikkelsen, L. D. Stewart, "Status Report of the Fusion Alpha Confinement Test March 1980," Princeton University

Plasma Physics Laboratory Report PPPL - 1661 (1980).

[10] R. W. McCullough, T. V. Goffe, M. Lennon, M. B. Shah, H. B. Gilbody, "Electron Capture by He^{+} and He^{2+} Ions in Li Vapor," Abstracts of XII International Conference on the Physics of Electronic and Atomic Collisions, Sheldon Datz, Ed., Gatlinburg, Tenn., July 15-21, 1981, Vol. 2, 661 (1981).

[11] G. A. Murray, J. Stone, M. Mayo, and F. J. Morgan, "Single and Double Electron Transfer in He^{2+} + Li Collisions," to be published in Phys. Ref. A.

[12] L. R. Grisham, D. E. Post, D. R. Mikkelsen, H. P. Eubank, "Plasma Heating with Multi-MeV Neutral Atom Beams," Nuclear Technology/Fusion 2, (April 1982).

[13] "Aspects of the Physics, Chemistry and Technology of High Intensity Heavy Ion Sources," G. D. Alton, Nuclear Instruments and Methods 189, 15-42 (1981).

[14] L. O. Love, R. N. Goslin, W. A. Bell, H. B. Greene, and K. W. Prater, "Investigation of the Possibilities of Lithium Isotope Collection Using Alpha-2 Equipment," Oak Ridge National Laboratory Report ORNL-Y-728 (1951).

[15] P. Tykesson, "The Production of Negative Heavy Ion Beams through Charge-Exchange Process," Symposium of Northeastern Accelerator Personnel, Oak Ridge, Tennessee, October 23-25, 1978.

[16] K. W. Ehlers and K. N. Leung, "Multicusp Negative Ion Source," Rev. Sci. Instrum. 51, 721 (1980).

[17] W. K. Dagenhart, W. L. Stirling, H. H. Haselton, G. G. Kelley, J. Kim, C. C. Tsai, and J. H. Whealton, "Modified Calutron Negative Ion Source Operation and Future Plans," Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, New York, October 1980, Th. Sluyters, Ed., BNL 51304, 217 (1981).

[18] K. Prelec, "Progress in the Development of High Current Steady-State H^-/D^- Sources at BNL," Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven, New York, October 1980, Th. Sluyters, Ed., BNL 51304, 145 (1981).

[19] C. W. Stwalley, University of Iowa, private communication (1980).

[20] T. P. Wangler and R. H. Stokes, "The Radio Frequency Quadrupole Linear Accelerator," IEEE Transactions on Nuclear Science NS-28, 1494 (1981).

[21] R. M. Mobley, J. J. Brodonski, G. M. Gammel, J. T. Keane, A. W. Maschke, and R. T. Sanders, "MEQALAC (Multiple Electrostatic Quadrupole Linac): A New Approach to Low Beta RF Acceleration," IEEE Transactions on Nuclear Science NS-28, 1500 (1981).

[22] T. P. Wangler, Los Alamos Scientific Laboratory, private communication (1981).

[23] J. P. Aldridge and J. D. King, "Charge-Exchange Cross-Sections for Li^- Ions at 6 MeV," Los Alamos Scientific Laboratory Report LA-8682-MS (1981).

[24] L. R. Grisham, D. E. Post, B. M. Johnson, K. W. Jones, J. Barrette, T. H. Kruse, I. Tserruya and Wang Da-Hai,

"Efficiencies of Gas Neutralizers for Multi-MeV Beams of Light Negative Ions," Review of Scientific Instruments 53(3) (March 1982).

[25] D. W. Norcross and D. L. Moores, "Photodetachment of Li^- and Na^-," Atomic Physics 3: Proceedings of the Third International Conference on Atomic Physics, August 1972, Boulder, Colorado, S. J. Smith and G. K. Walter, Eds., Plenum Press, New York - London, p. 261-267 (1973).

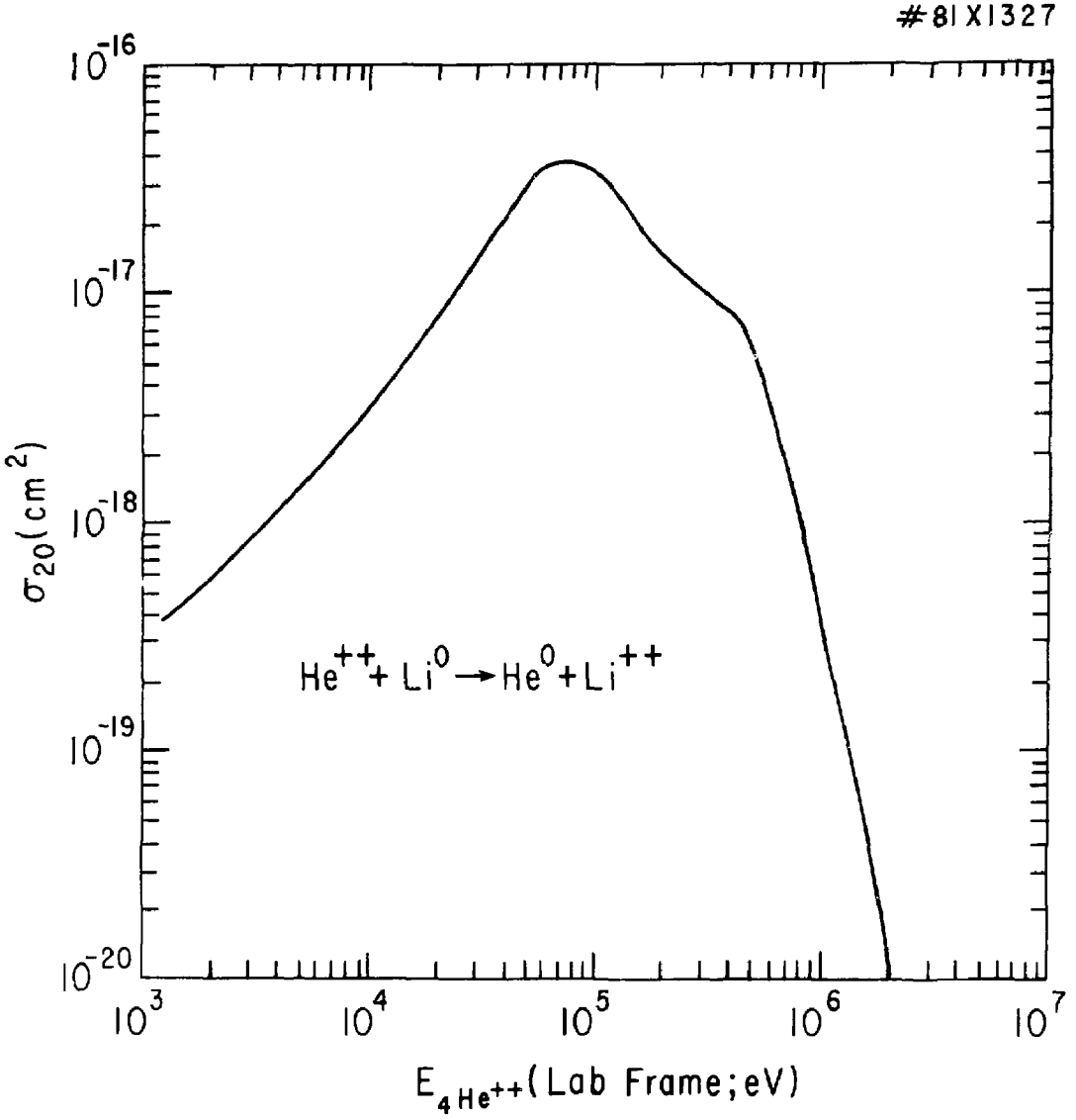
#81X1327
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
$\sigma_{20}(cm^2)$
$He^{++} + Li^0 \rightarrow He^0 + Li^{++}$
10^3
10^4
10^5
10^6
10^7
$E_{^4He^{++}}$(Lab Frame; eV)

FIG. 1

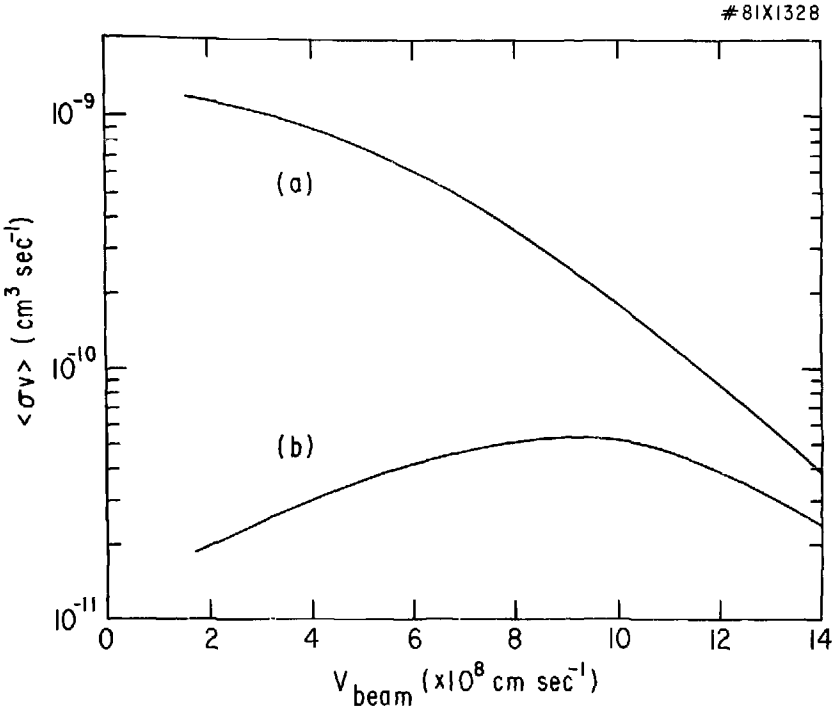
#81X1328
10^{-9}
10^{-10}
10^{-11}
$\langle\sigma v\rangle$ (cm^3 sec^{-1})
(a)
(b)
0
2
4
6
8
10
12
14
V_{beam} ($\times 10^8$ cm sec^{-1})

FIG. 2

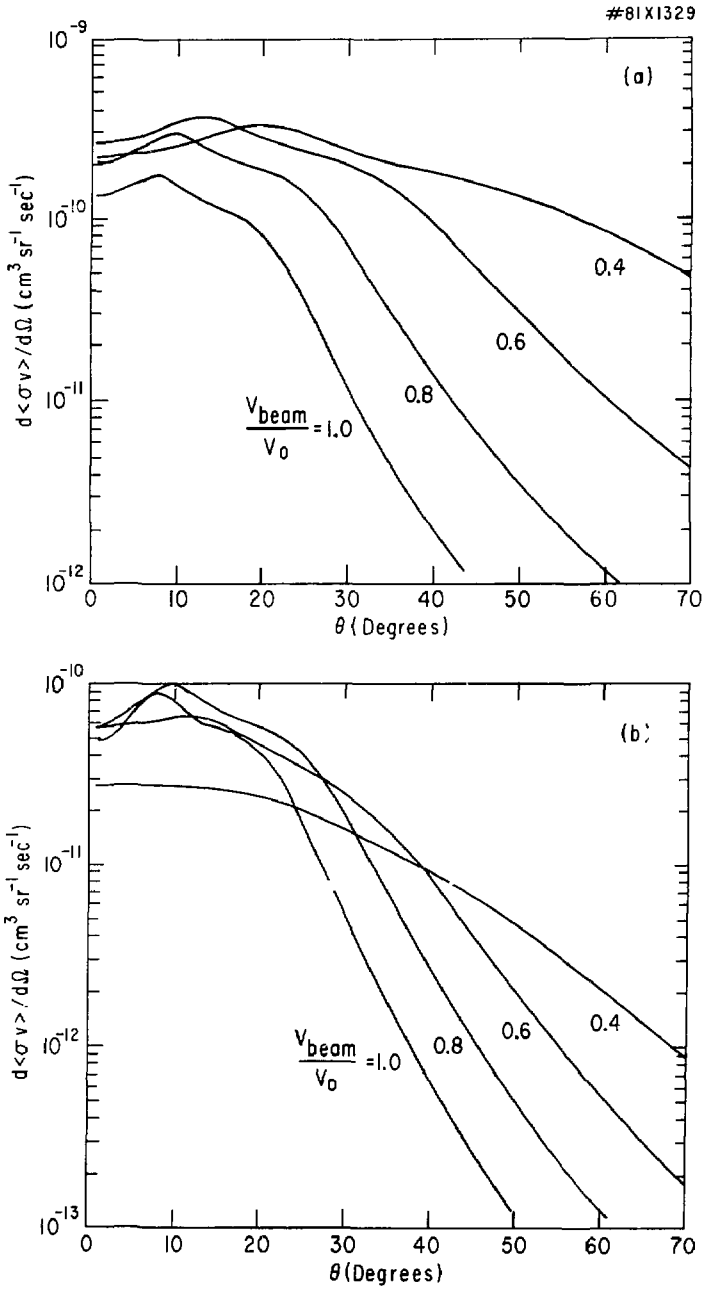
#81X1329
(a)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$d<\sigma v>/d\Omega$ ($cm^3 sr^{-1} sec^{-1}$)
$\frac{V_{beam}}{V_0} = 1.0$
0.8
0.6
0.4
0
10
20
30
40
50
60
70
θ (Degrees)
(b)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$d<\sigma v>/d\Omega$ ($cm^3 sr^{-1} sec^{-1}$)
$\frac{V_{beam}}{V_0} = 1.0$
0.8
0.6
0.4
0
10
20
30
40
50
60
70
θ (Degrees)

FIG. 3

#81 X 1330

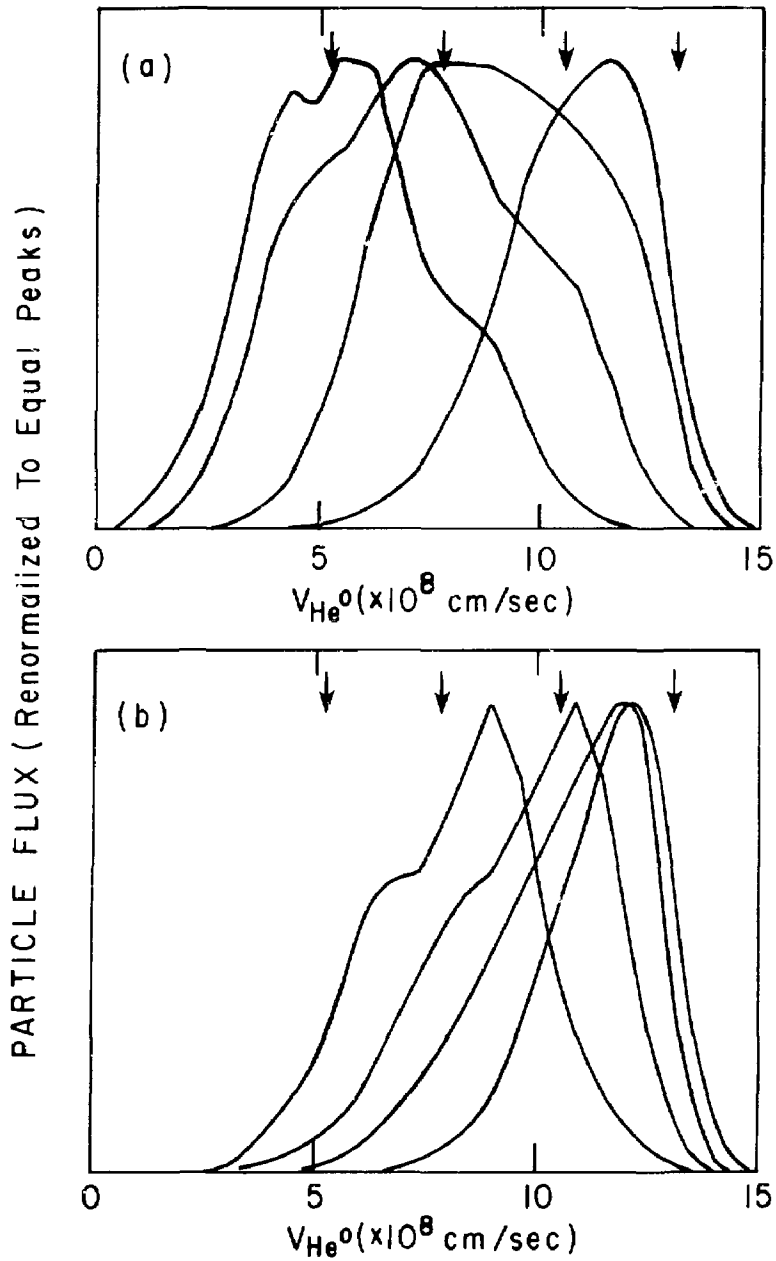

FIG. 4

81X1342

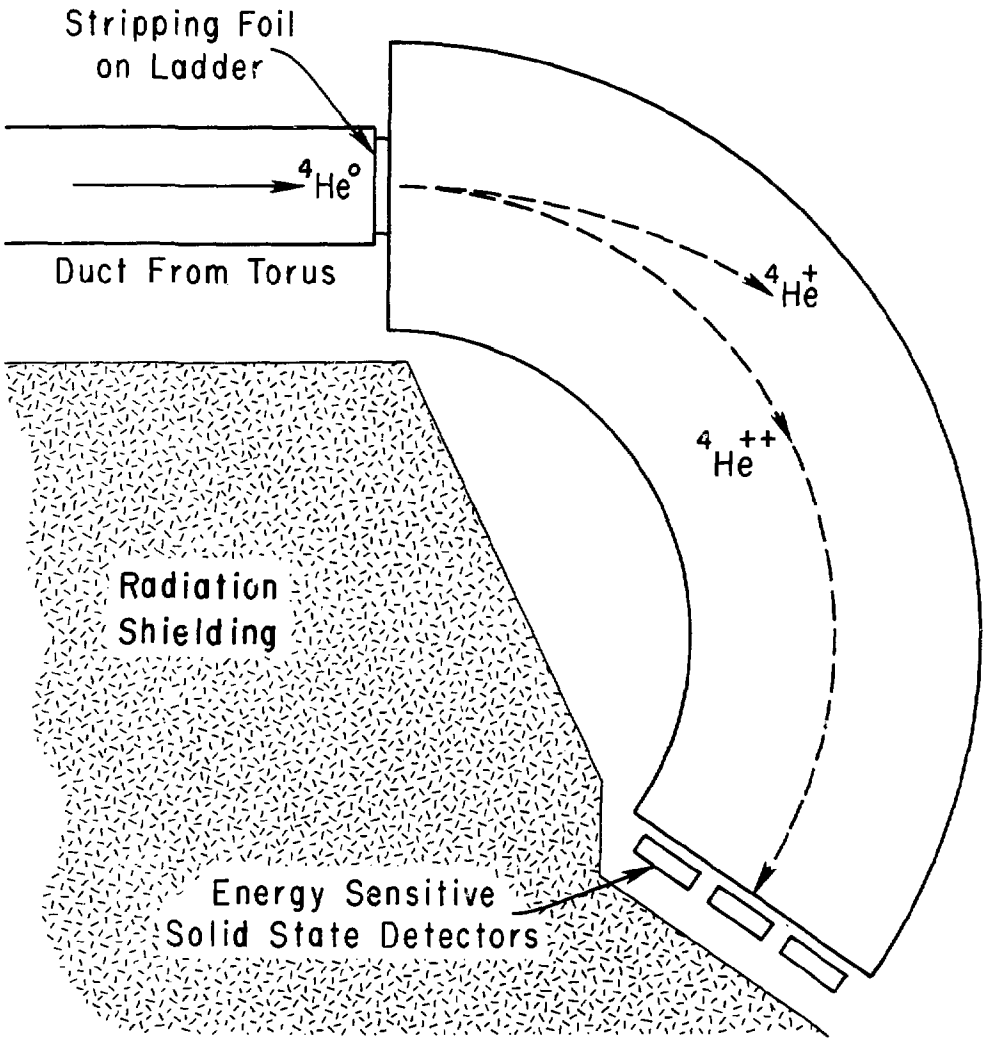

FIG. 5

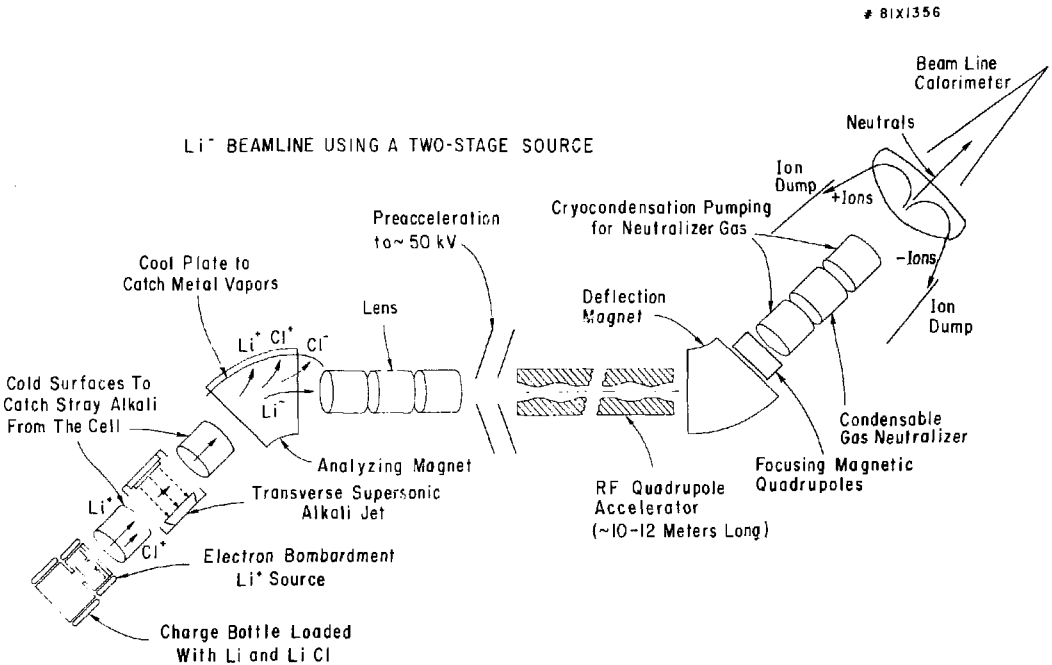
81X1356
Li⁻ BEAMLINE USING A TWO-STAGE SOURCE
Beam Line Calorimeter
Neutrals
Ion Dump
+Ions
-Ions
Ion Dump
Cryocondensation Pumping for Neutralizer Gas
Preacceleration to ~ 50 kV
Cool Plate to Catch Metal Vapors
Lens
Deflection Magnet
Li⁺ Cl⁺ Cl⁻
Li⁻
Cold Surfaces To Catch Stray Alkali From The Cell
Analyzing Magnet
Condensable Gas Neutralizer
Focusing Magnetic Quadrupoles
Transverse Supersonic Alkali Jet
RF Quadrupole Accelerator (~10-12 Meters Long)
Li⁺
Cl⁺
Electron Bombardment Li⁺ Source
Charge Bottle Loaded With Li and Li Cl

FIG. 6