Some Considerations Concerning Fusion Alpha Particle Diagnostics

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Some Considerations Concerning Fusion Alpha Particle Diagnostics (in English)

Abstract

The conditions necessary for neutral doping beams suitable for diagnosing the alpha particles in high-temperature or burning D-T fusion plasmas are investigated for the example of JET extended performance plasma parameters. It turns out that step processes have to be taken into account for the beam attenuation calculations. The necessary neutral doping beam current densities have to be beyond about 200 mA/cm^2 for sufficient photon density rates and neutral $^4He^o$ rates, respectively, and the neutral particle energy should be above about 200 keV/amu.

1. Introduction

The ignition and burning of the D-T fusion reactor will rely on the thermonuclear heating of the plasma by the α-particles as the charged part of the fusion products. The interaction of the α-particles (born at a kinetic energy of 3.517 MeV) with the plasma as well as the energy transfer from the α-particles to the plasma has not been experimentally treated yet. There are several theoretical investigations /1-8/, that predict collective phenomena to be important and both favourable and deleterious processes might occur, one example being the instability /7/, in which a shear Alfvén wave is resonating with the bounce motion of trapped α-particles /3/. Hence the experimental investigation of fusion α-particle behaviour in the next large tokamak experiments with D-T operation (TFTR and JET) seems to be a very important task.

Burrell /9/ proposed to use doping beams to detect fully stripped impurity ions in tokamak plasmas, and Post and others /10-14/ extensively developed techniques for measuring the α-particle distribution in magnetically confined plasmas: The feasibility of measuring the alpha-particle distribution using neutral doping beams of H, H_2, ^3He, and Li is assessed by investigating single and double charge exchange reactions resulting in promptly emitted decay photons and $^4He^o$ atoms, respectively, and the corresponding atomic physics needs are indicated /15, 16/.

The aim of the present report is to study the parameter range of neutral particle beams that are suitable for the α-particle diagnostics of plasma parameters expected for an ignition experiment /17/ as well as those for JET /18,19/ active operation. The report summarizes the relevant material, which is important for the evaluation of the parameter range of beams and detectors for such type of diagnostics. In addition to the fundamental processes described by the Princeton group /10-13, 15, 16/ the step processes are taken into account here, since the influence of these step processes on the penetration of the diagnostic neutral beams into the hot plasmas is not negligible /20/. Hence the main problems treated in this report are the attenuation of the neutral doping beams of H, H_2, ^3He, and Li injected into plasmas of ZEPHYR and JET parameters, respectively, the charge exchange and the expected photon fluxes for single charge exchange or neutral ^4He densities for double charge exchange, respectively.

2. Neutral Particle Beam Attenuation in the Plasma

The application of neutral doping beam injection for the diagnostic of completely stripped ions was proposed to determine the ion temperature (or ion energy distribution) /9, 21, 22/ or the α-particle energy distribution /10-16/. The energy distribution of the α-particles can be deduced from the spectral line profile observation after a single charge exchange process into an excited level of $^4He^+$ or by the measurements of the $^4He^o$ after a double charge exchange process. According to the proposal of Post and coworkers /10/ the neutral doping beam energy should range from a few hundreds to about 880 keV/amu. For both processes the neutral beam density should be made as high as possible to obtain sufficient intensity for the spectroscopic and enough signal for the neutral $^4He^o$ measurements.

There are, however, several mechanisms like ionization by the plasma ions and electrons, like charge exchange with the plasma protons, deuterons and/or tritons, like ionization and charge exchange with the α-particles, and ionization and charge exchange with impurities, that all tend to reduce the neutral particle density of the injected diagnostic neutral beams. The effect of each of these processes as function of the energy of the incident neutral particle can best be judged by the relevant cross sections. According to the Princeton proposal /10-13/ light element neutral doping beams as those of hydrogen, helium and lithium are taken into consideration, because for heavier elements the maximum necessary energy (of 880 keV/amu) gets up too high. In the following figures 1 to 8 the available cross section data involved are given as functions of the neutral particle energy for some elements as hydrogen, helium,lithium, nitrogen and potassium. They include the ionization and charge exchange with the plasma ions (hydrogen isotopes and impurities). The references are always indicated in the relevant figures.

The given presentation of cross sections as functions of the neutral particle energy is appropriate as long as the plasma particle velocity is negligible compared to the injected neutral particle speed. This does not hold, however, for the electrons (assuming the electron temperature to be in the same order of magnitude as the ion temperature in the plasma) as well as for the alpha particles, that are born at an energy of 3.517 MeV. For comparison therefore the electron ionization rates (divided by the relevant neutral particle velocity) are given for different typical electron temperatures. The evaluation of this "averaged electron ionization term" is given in Appendix A, while the corresponding evaluation of the approximations for the sum of the alpha particle ionization and the charge exchange rates, called "averaged alpha particle ionization plus charge exchange term", is found in Appendix B.

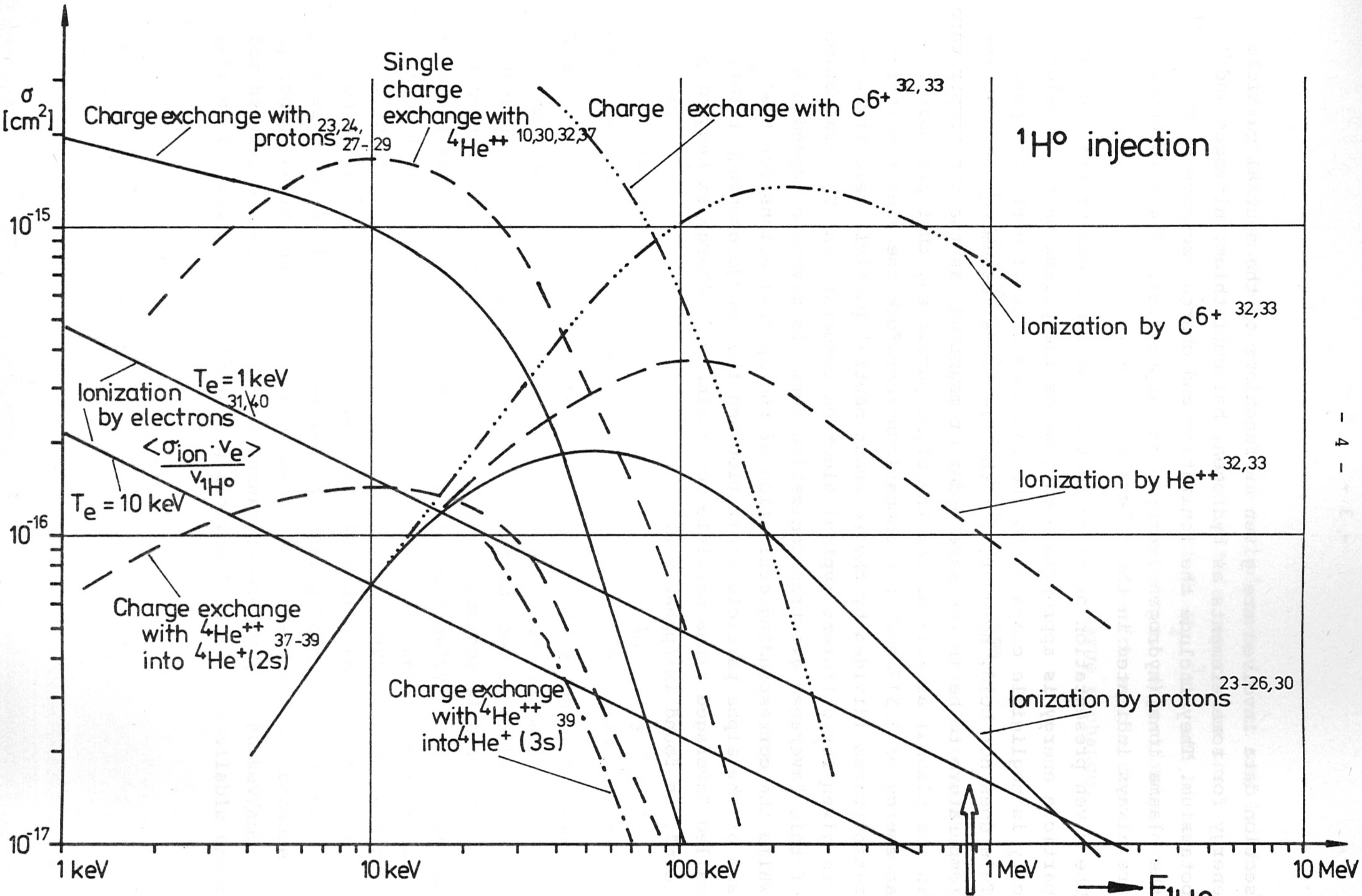


Fig. 1 Cross sections for atomic hydrogen injection

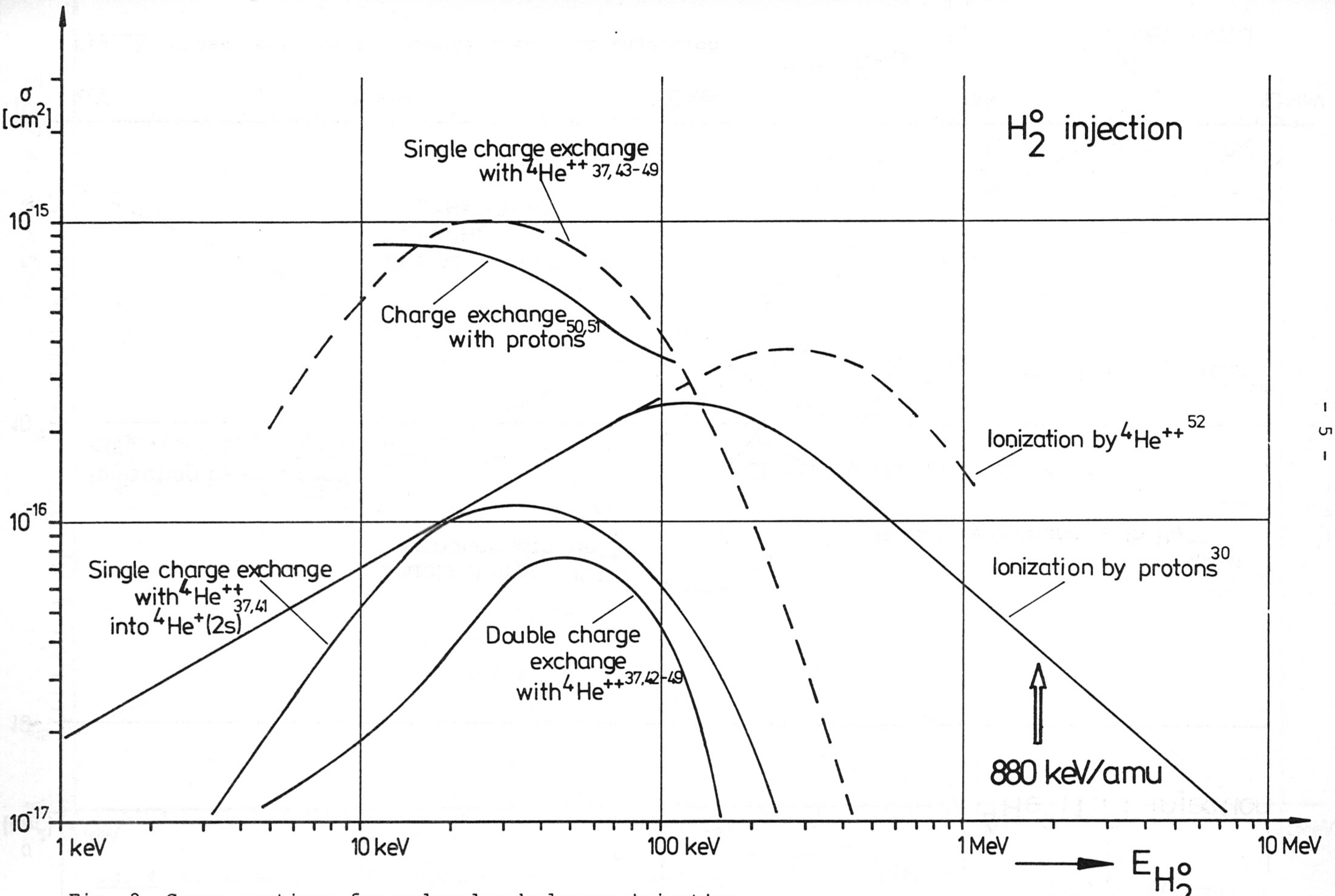
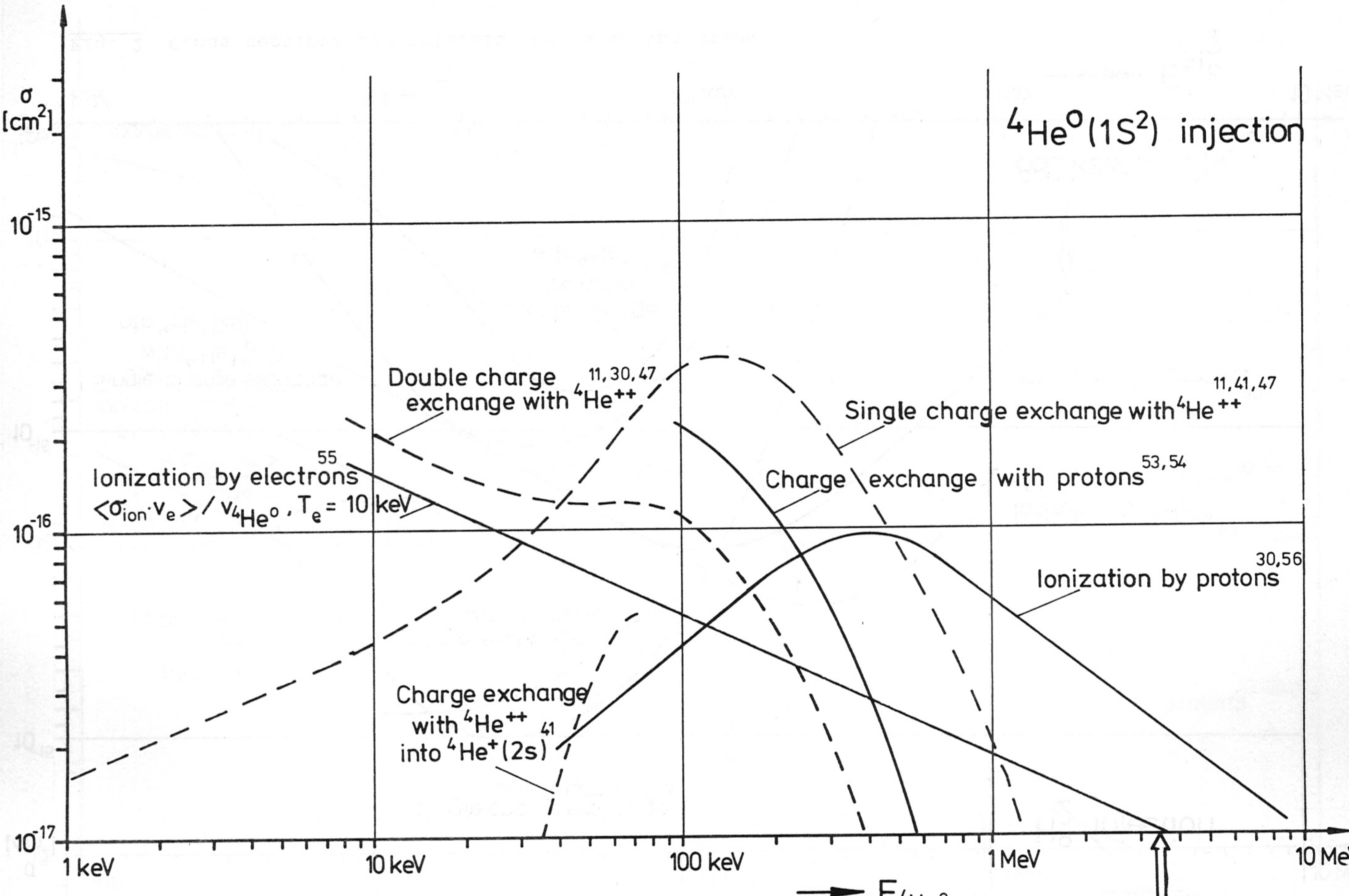
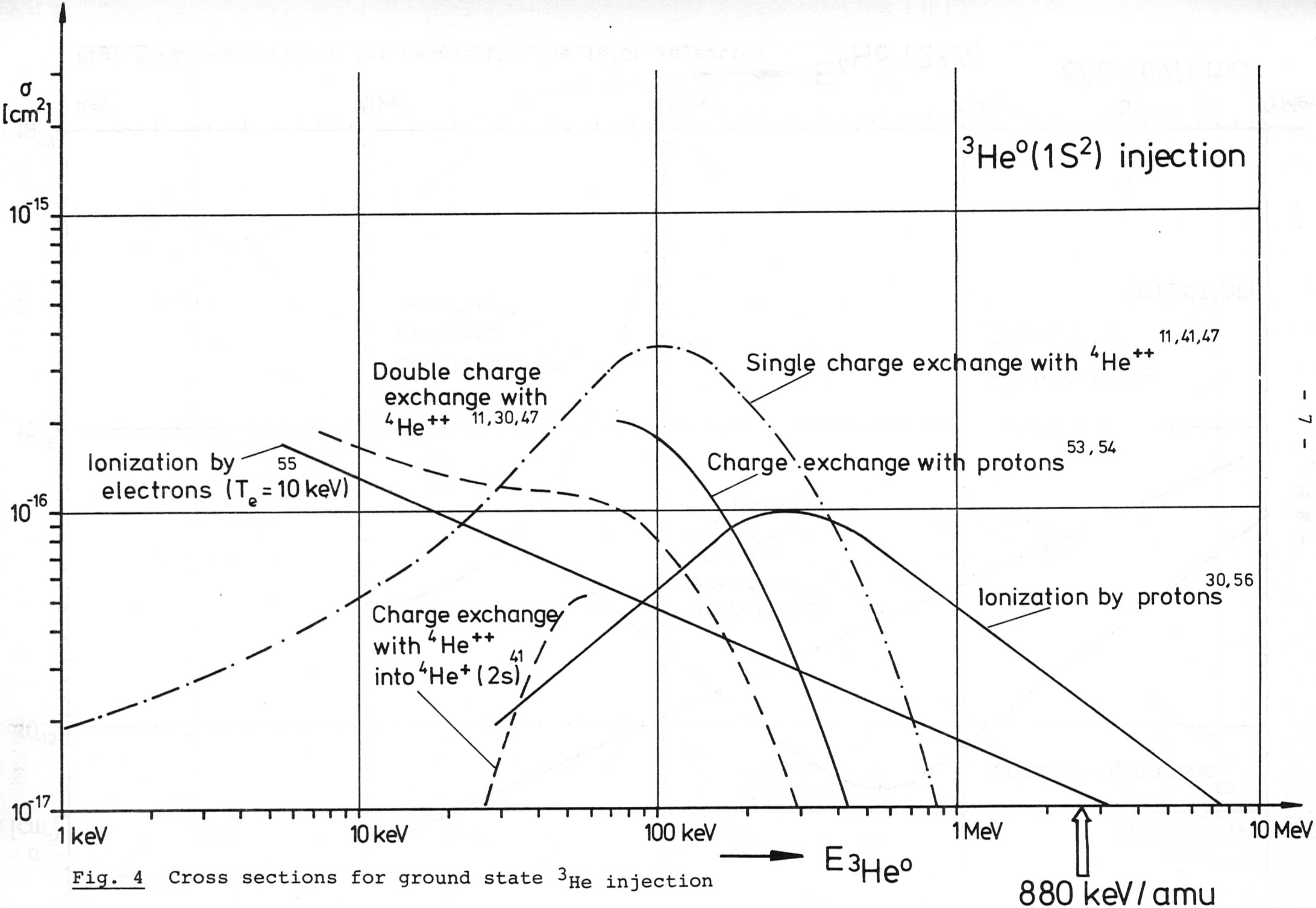


Fig. 2 Cross sections for molecular hydrogen injection



<u>Fig. 3</u> Cross sections for ground state ^{4}He injection



<u>Fig. 4</u> Cross sections for ground state ^{3}He injection

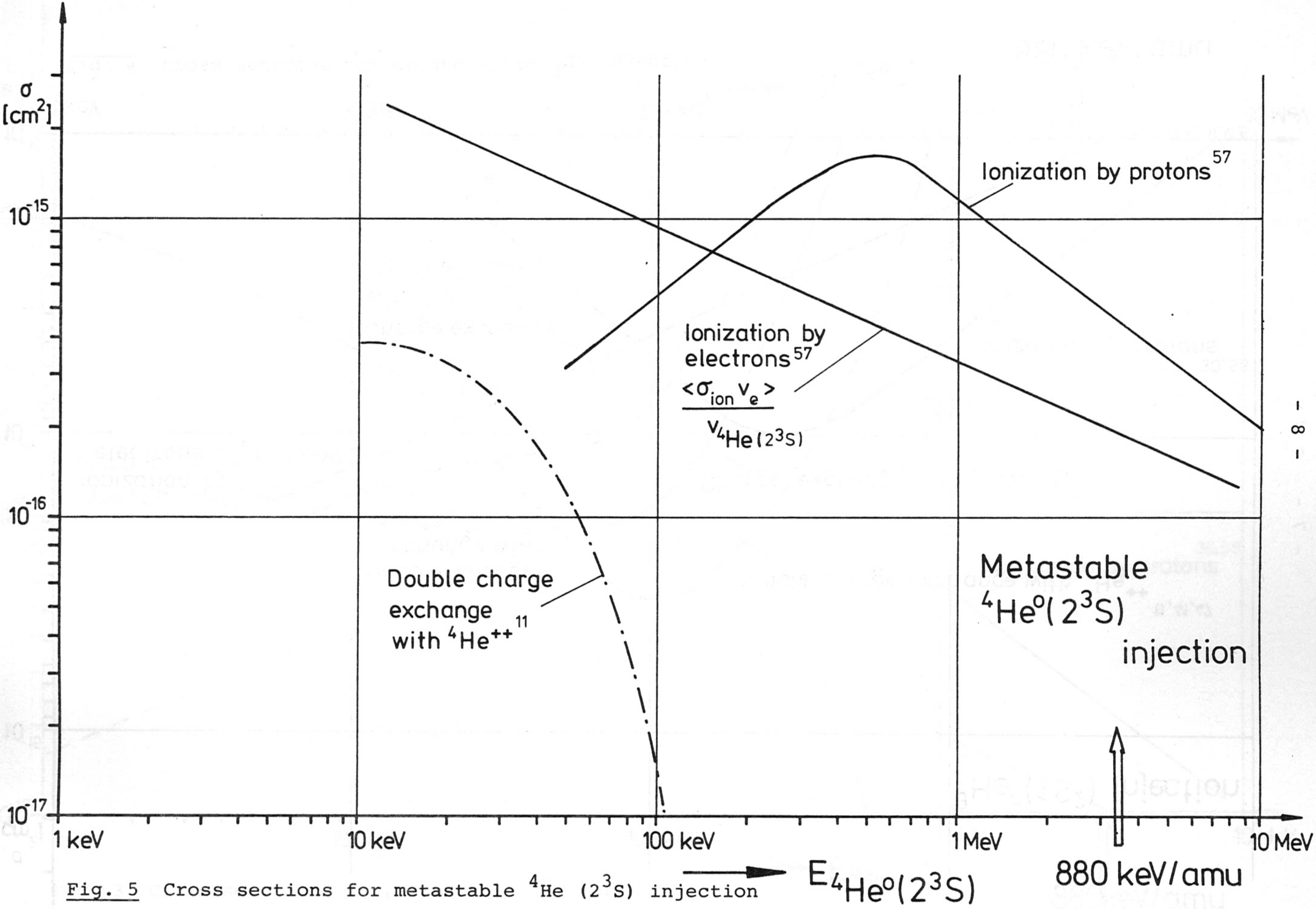
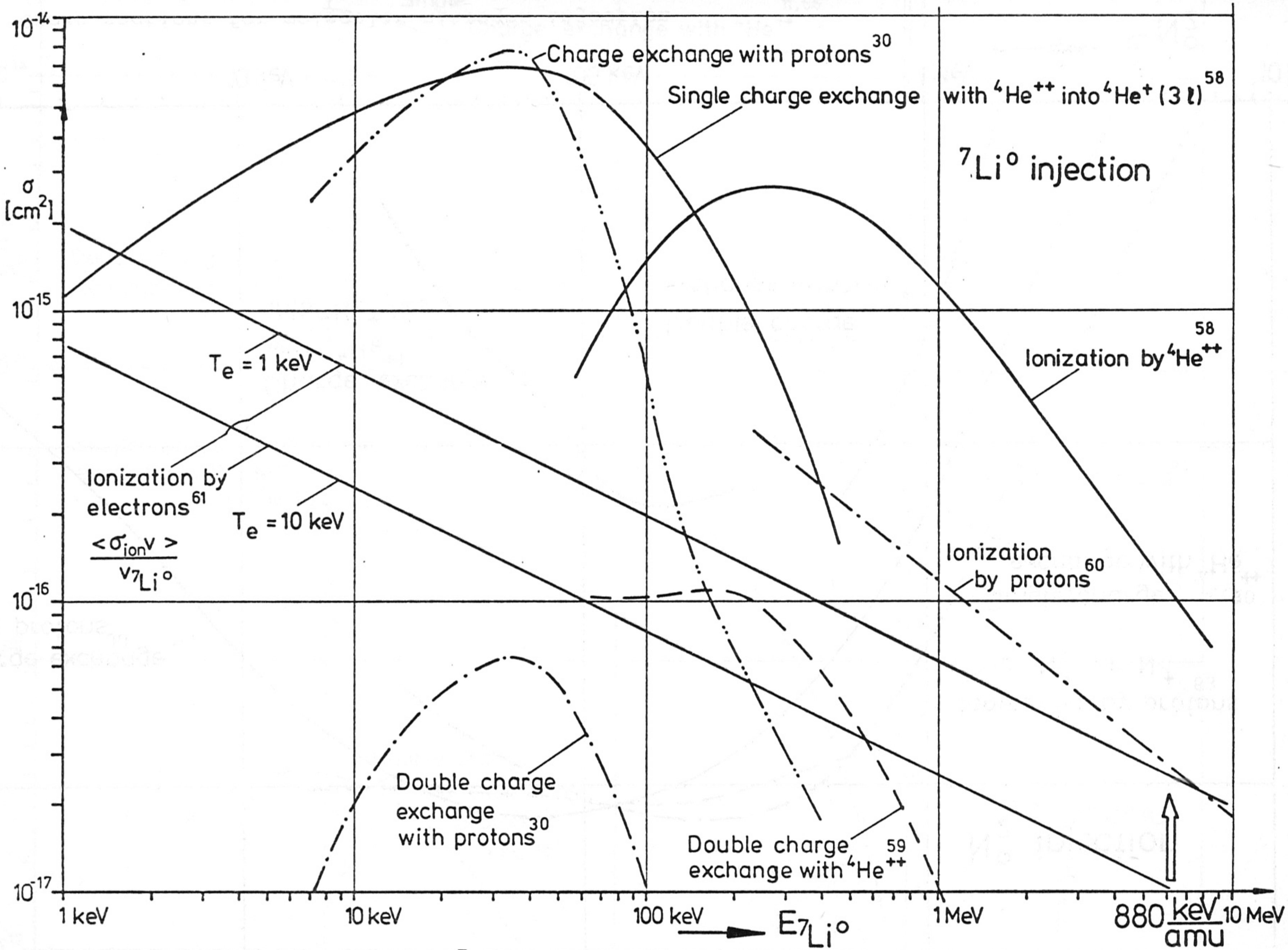
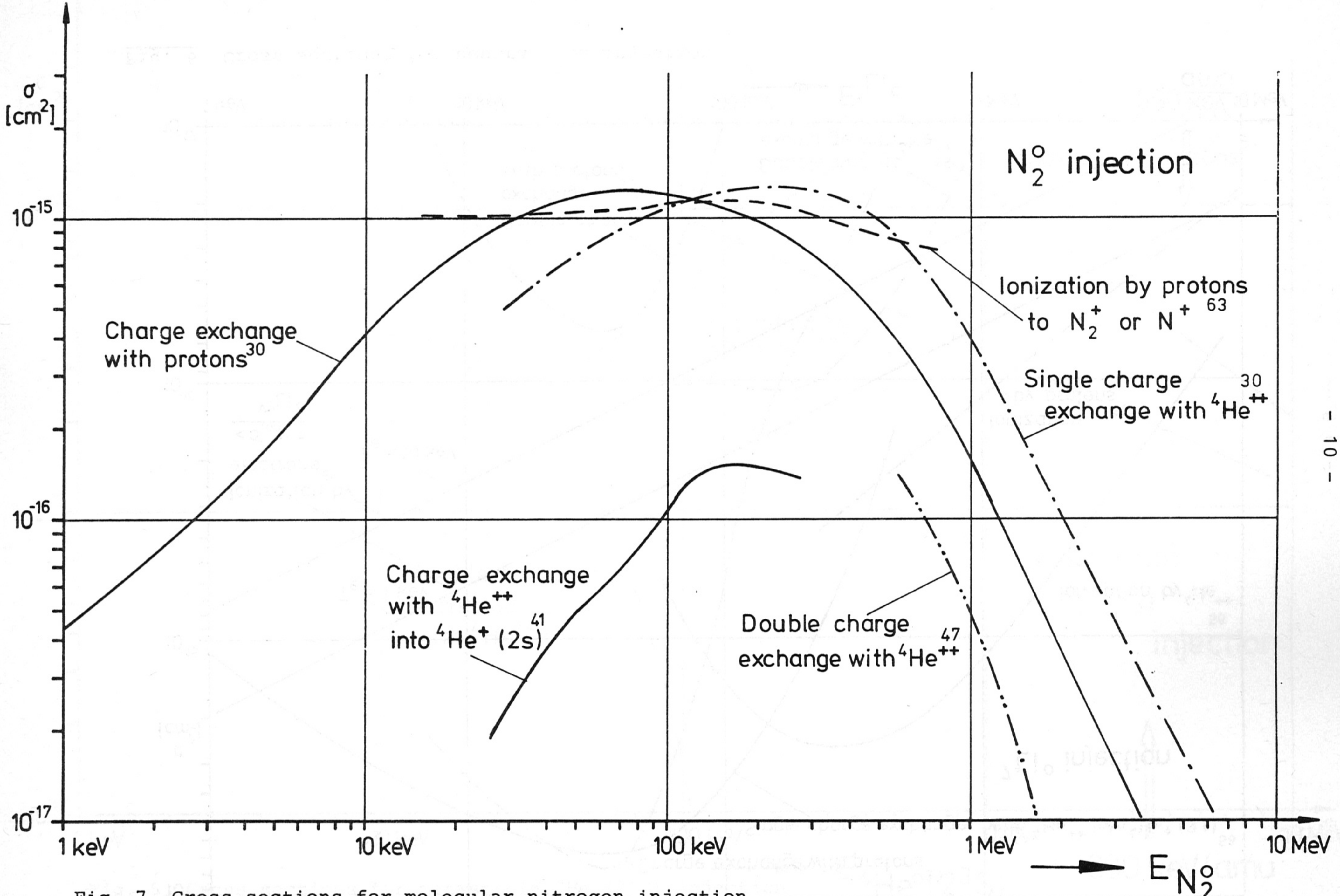


Fig. 5 Cross sections for metastable ^{4}He (2^3S) injection



<u>Fig. 6</u> Cross sections for neutral ^{7}Li injection



<u>Fig. 7</u> Cross sections for molecular nitrogen injection

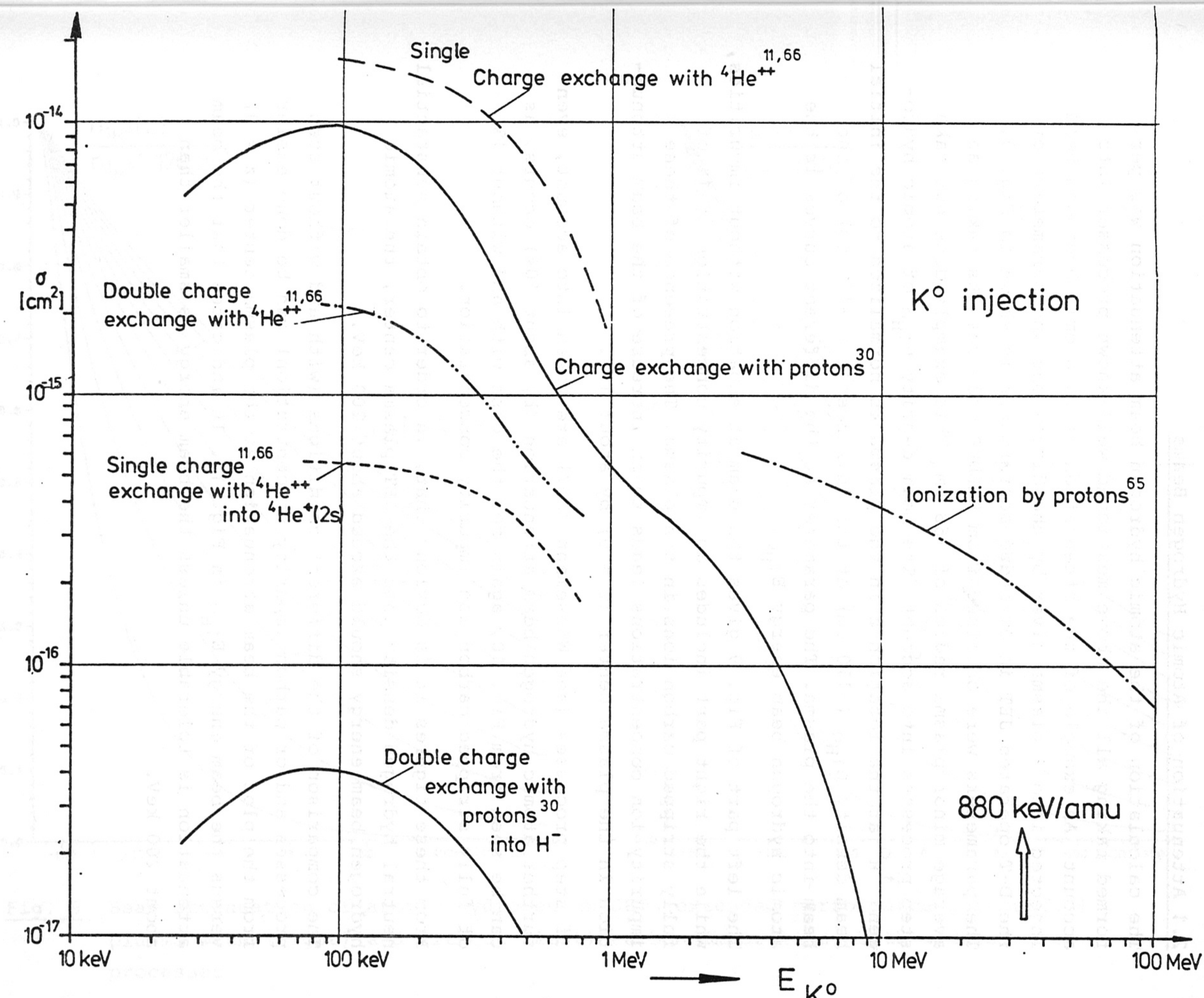


Fig. 8 Cross sections for neutral potassium injection

2.1 Attenuation of Atomic Hydrogen Beams

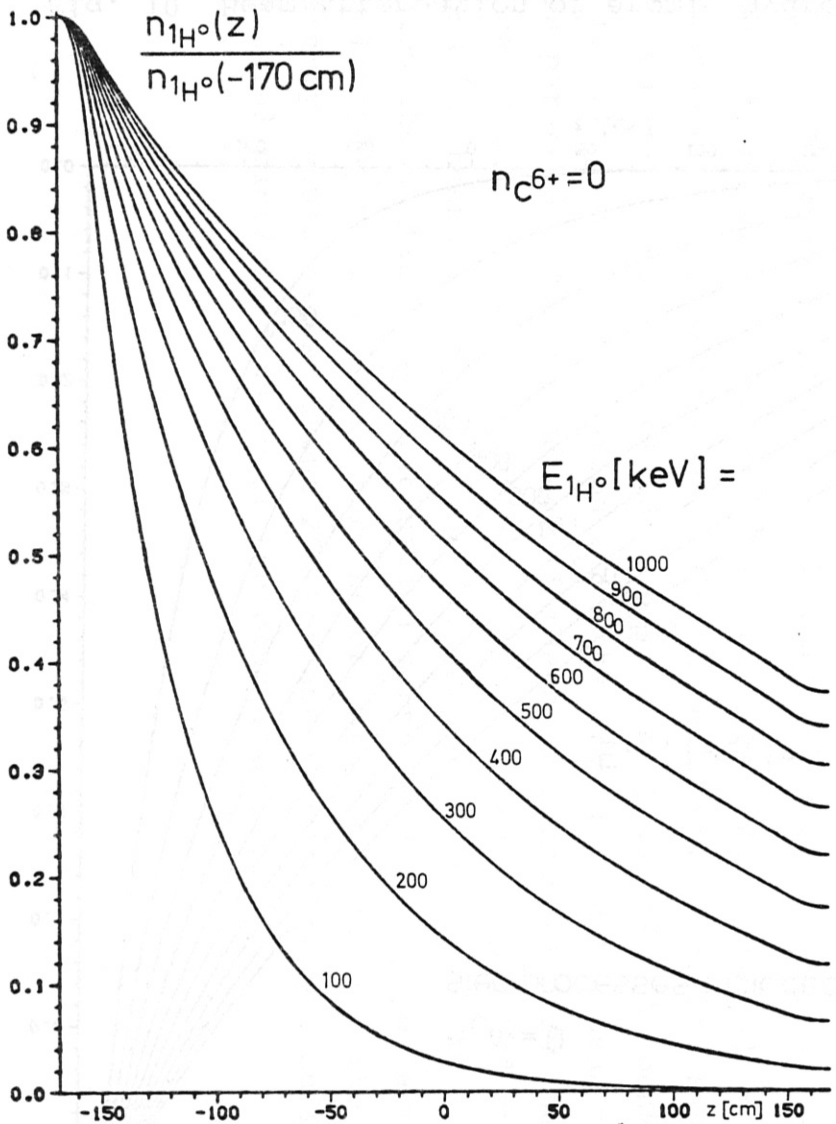
The calculation of the atomic hydrogen beam attenuation was performed taking all the above mentioned well-known processes into account. An example of the attenuation of an atomic hydrogen beam injected into a plasma given by the dimensions and parameters of the D-T operated JET in extended performance is shown in Fig. 9. The parameters were obtained from BALDUR code results taking an average minor plasma radius of 168 cm. This example does not take step processes into account. The beam density $n_{^1H^o}$ of atomic hydrogen $^1H^o$ at the location z in the plasma is normalized to the initial beam density $n_{^1H^o}$ (-170 cm) at the entrance (Z = -170 cm) of the beam into the plasma. The parameter at the different curves is the atomic hydrogen beam energy $E_{^1H^o}$.

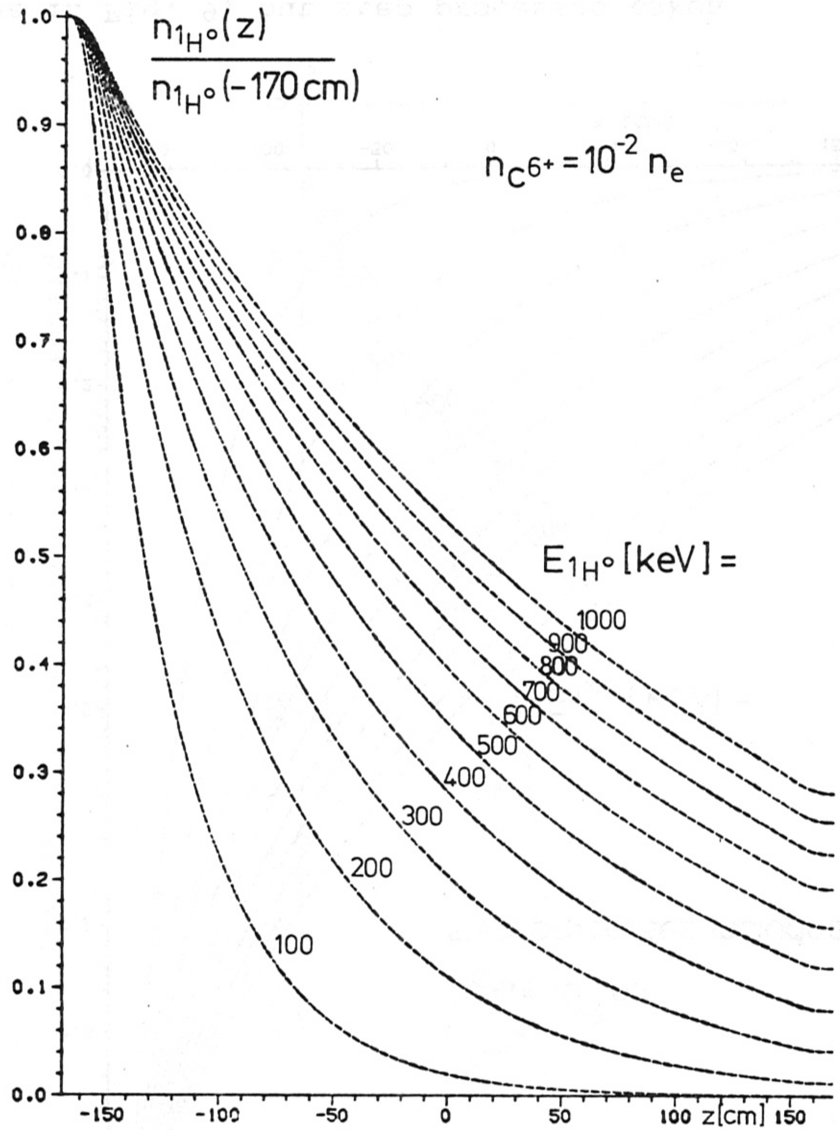
The left part of Fig. 9 gives the beam attenuation without impurities, while the right part includes an impurity concentration of 1% of fully stripped carbon ions in the plasma. The presence of these impurity ion concentrations leads to an increase of the beam attenuation in the plasma center (z = 0) by about 15%.

If step processes (see Wiesemann /20/) are taken into account, even further atomic hydrogen beam attenuation (by about 10%) occurs, as can be seen from Fig. 10, again for the case with and without 1% of fully stripped carbon ion impurity concentration.

From these figures it is obvious that, in order to obtain substantial neutral hydrogen density into the JET plasma center, the atomic hydrogen beam energy should exceed about 200 keV.

The comparison of the different conditions (with and without step processes and/or carbon impurity concentration) can be done easier from the plot of the beam attenuation at the plasma center (z = 0) versus the beam energy $E_{^1H^o}$ in Fig. 11. It indicates that the beam attenuation is tolerable unless the beam energy is smaller than about 200 keV.





<u>Fig. 9</u> Beam attenuation of atomic hydrogen in JET (extended performance parameters) plasma with (right) and without (left) carbon impurities, both without step processes

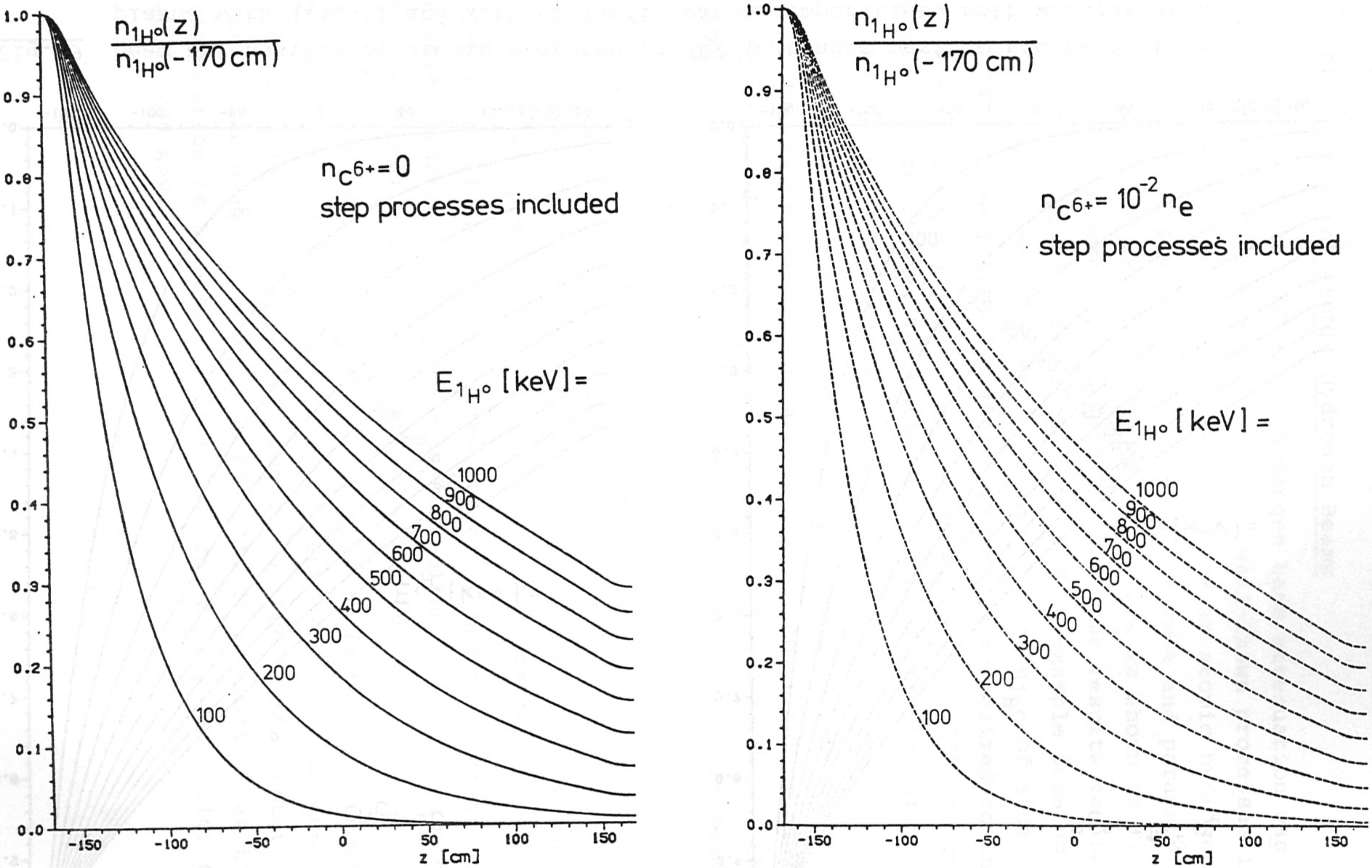


Fig. 10 Beam attenuation of atomic hydrogen, as in Fig. 9, but step processes taken into account

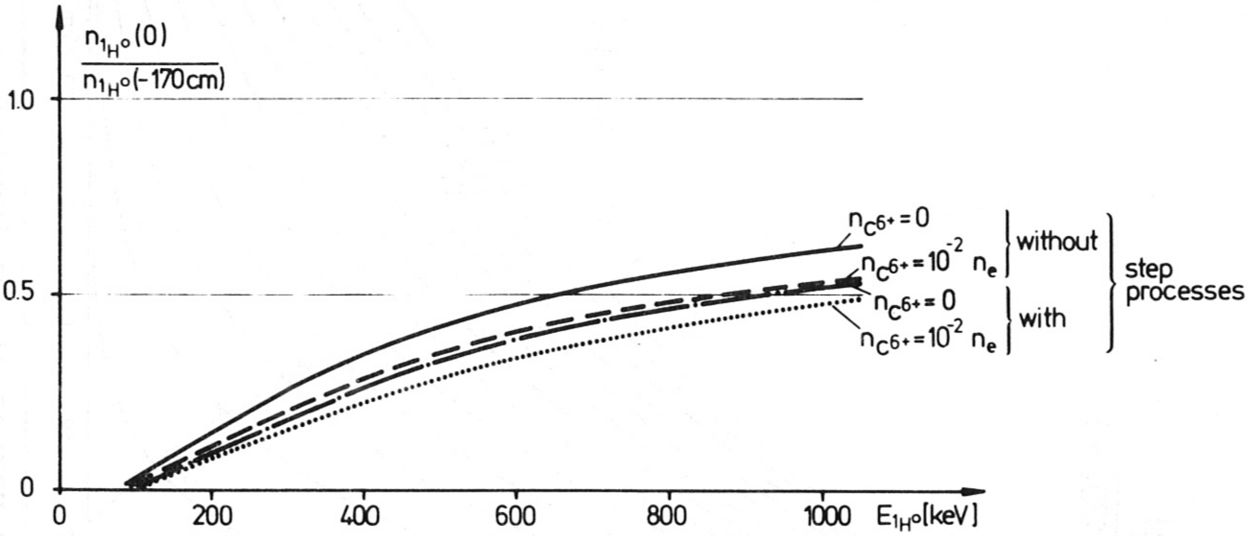


Fig. 11 Atomic hydrogen beam attenuation at JET plasma center versus beam energy for different conditions.

2.2 Attenuation of Helium and Lithium Beams

The attenuation of neutral $^3He^o$ and $^7Li^o$ beams injected into a plasma of the same parameters looks relatively similar. Fig. 12 gives the attenuation of $^3He^o$ beams (left) and of $^7Li^o$ beams (right) versus the location z in the plasma with the beam energy as parameter. The dependence of the beam attenuation in the plasma center ($z = 0$) on the neutral particle energy is plotted for ^3He and ^7Li beams in Figs. 13 and 14, respectively. In first approximation the neutral beam attenuation versus the energy per amu looks relatively similar. Also for ^3He or ^7Li beam injection the particle energy should exceed about 200 keV/amu in order to get sufficient neutral particle density at the plasma center.

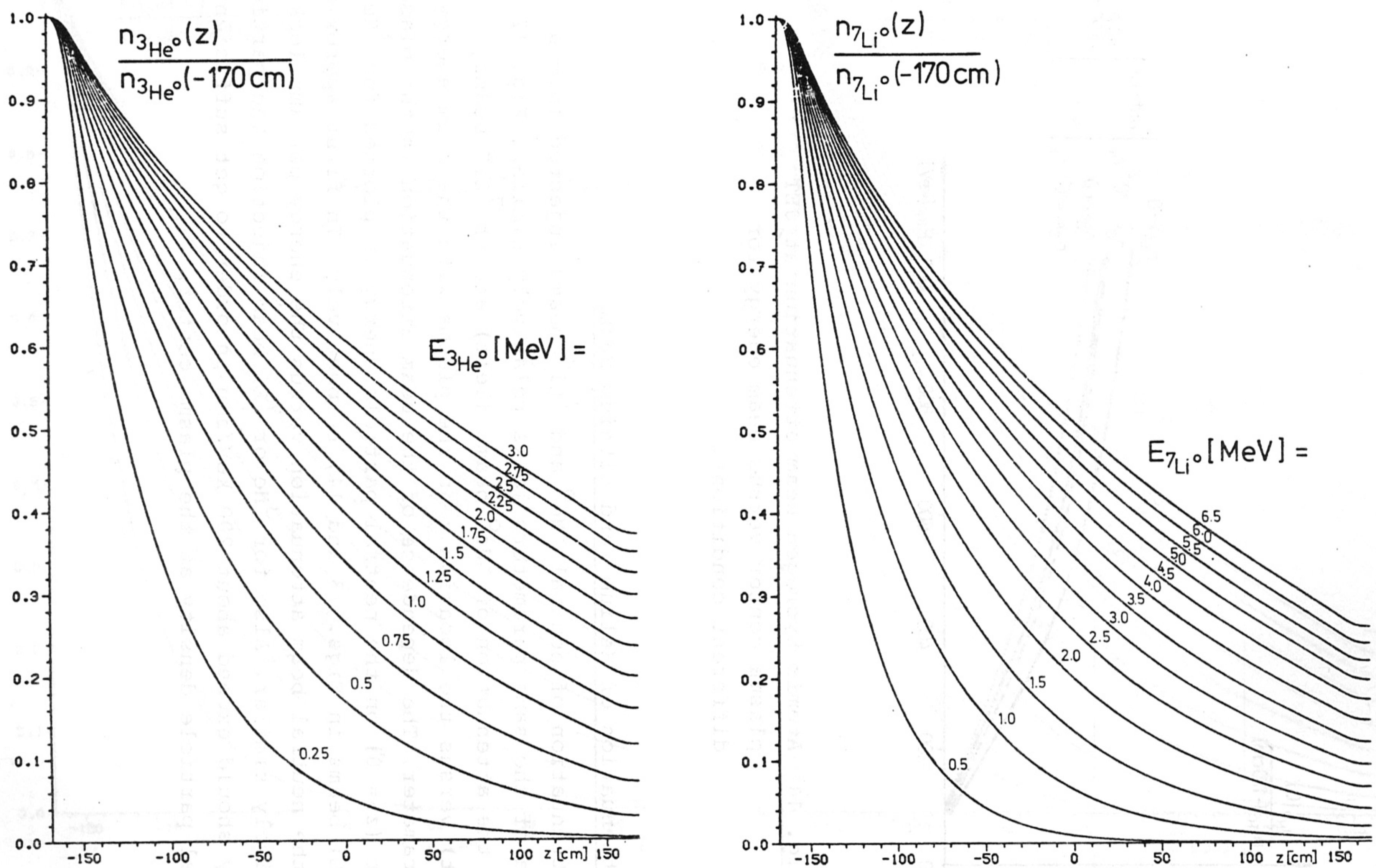


Fig. 12 Neutral ^{3}He (left) and ^{7}Li (right) beam attenuation versus plasma location z for different beam energies

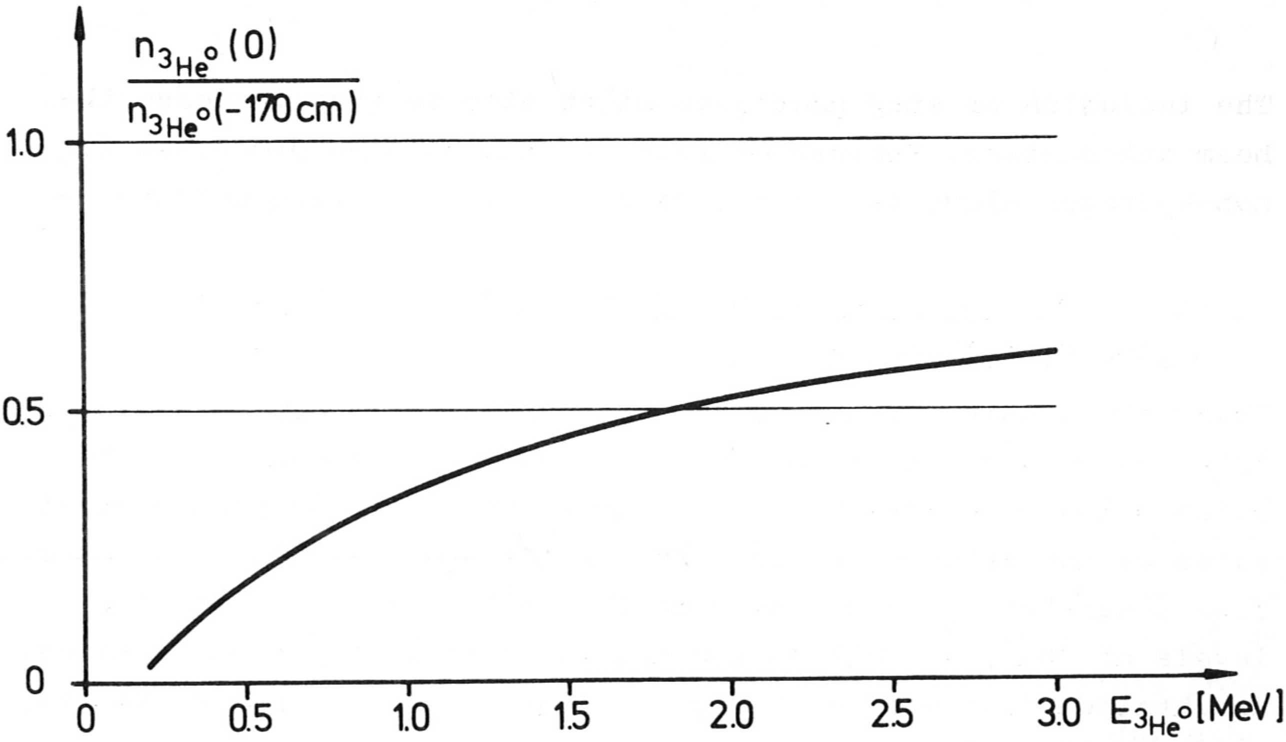


Fig. 13 Helium-3 beam attenuation at JET plasma center versus beam energy

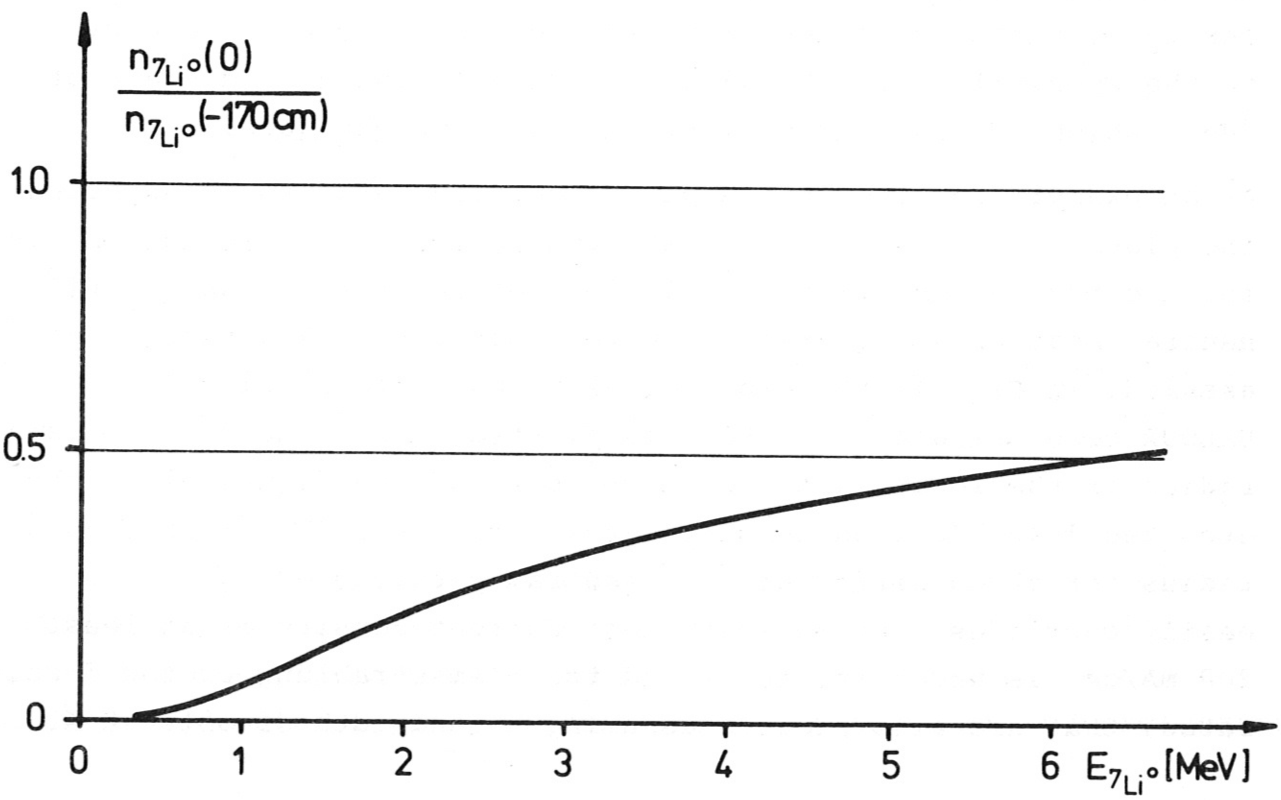


Fig. 14 Lithium beam attenuation at JET plasma center versus beam energy

The inclusion of step processes might also further increase the beam attenuation. Because of lack of data on step processes for non-hydrogen elements the relevant calculations were omitted.

3. Estimate of Expected Photon Density Rates and Neutral Helium Density Rates

Using the density values of the neutral particles as obtained from the parameters of the injected neutral beams and from the attenuation calculations of chapter 2, the expected photon density rates of the relevant helium ion (He II) spectral lines, as obtained from single charge exchange with the alpha particles into excited levels of $^4He^+$, as well as the neutral helium $^4He^o$ density rates, as obtained from double charge exchange with the alpha particles, can be estimated.

Concerning the spectroscopic measurements of helium ion lines West et al. /14/ pointed to the fact that the transition from the 3s and the 3d levels of $^4He^+$ to its 2p level is advantageous for this measurement, because the relevant spectral line at 1640 Å can be measured using normal incidence spectroscopy in contrast to the spectral lines at 256 Å and 304 Å to the ground state of $^4He^+$, which afford grazing incidence (VUV) techniques.

As an example for the 1640 Å photon density rates to be expected the plasma parameters of JET extended performance were chosen (as for the beam attenuation calculations of chapter 2), and a $^7Li^o$ neutral beam of an equivalent current density of 200 mA/cm^2 was assumed. In Fig. 15 the expected alpha particle density (from BALDUR code calculations /67/) is plotted versus the minor plasma radius in the lower part. The upper part of the figure gives the expected 1640 Å photon density rates versus the JET minor plasma radius for three different $^7Li^o$ neutral particle energies. One easily concludes that an equivalent current density of at least 200 mA/cm^2 is necessary to exceed the bremsstrahlung photon density rates, that are also plotted assuming a bandwidth of only 10 Å.

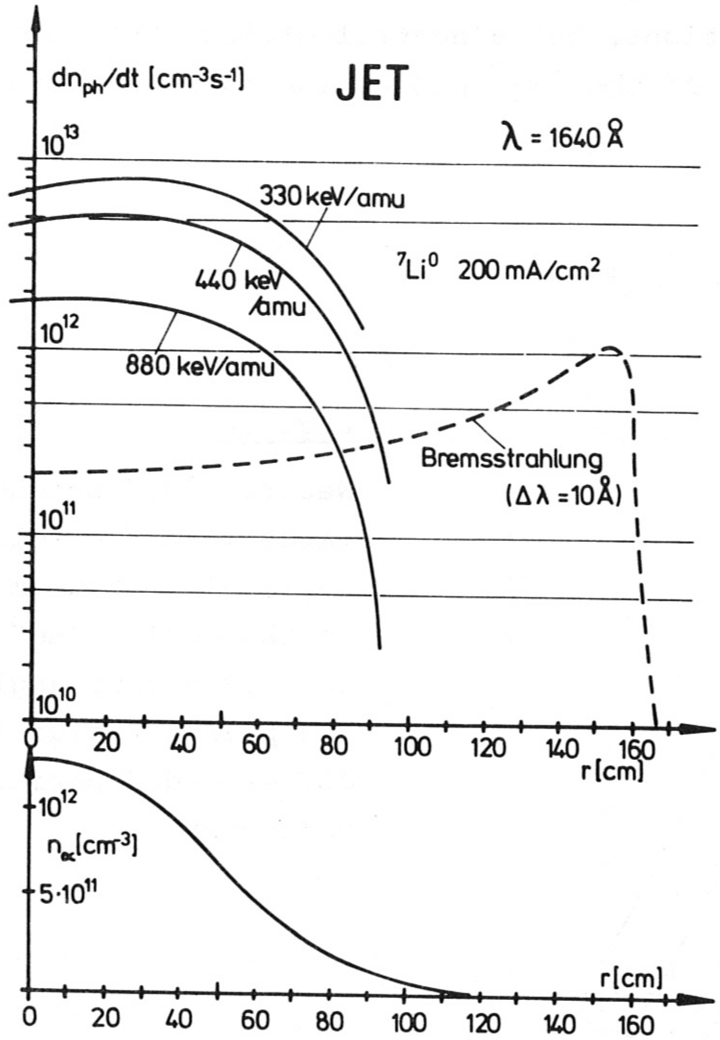
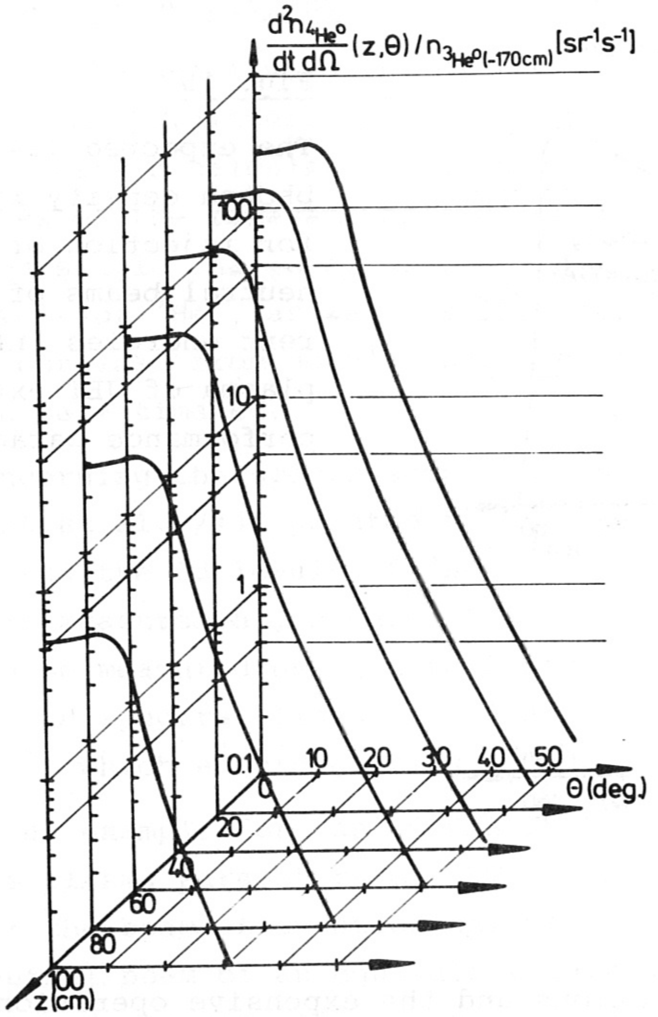


Fig. 15

The expected 1640 Å photon density rates for injection of $^7Li^o$ neutral beams of different energies into a plasma of JET extended performance parameters

Due to the technological implications and the expensive operation of stationary neutral $^7Li^o$ beams of such high current densities the application of pulsed beam technology seems appropriate for this application /68/.

The double charge exchange process of injected neutral particles with the alpha particles in the plasma leads to $^4He^o$ neutrals that leave the plasma unaffected by the magnetic field and can be diagnosed outside /10/. As an example for the expected production rate of $^4He^o$ into the solid angle element we chose again JET extended performance conditions, but a neutral doping $^3He^o$ beam. Fig. 16 gives a plot of the $^4He^o$ production rate into the



<u>Fig. 16</u>

Neutral $^4He^o$ production rates into the solid angle element normalized to the doping $^3He^o$ beam density versus angle Θ and plasma radius z for JET extended performance parameters

solid angle element normalized to the doping $^3He^o$ beam density as function of the angle Θ from the direction of the incoming neutral beam and of the radius z as location in the plasma.

Similar to the case of spectroscopic measurements applying the single charge exchange processes, the doping beam current density should also be in the range above about 100 mA/cm^2 for double charge exchanged alpha particle diagnostics. Moreover the emittance of these doping beams should be less than about 100 mrad cm.

Fig. 17 gives a very rough sketch of a possible application of the alpha particle diagnostics on JET, using neutral doping beams. The neutral beam would be injected vertically through the JET plasma using top and bottom vertical diagnostic ports. The measurements of double charge exchanged alpha particles could be performed under a small angle Θ against the neutral beam direction by neutral particle diagnostics, e.g. on top of a vertical diagnostic flange, while the Doppler shifted decay photons from the single charge exchanged alpha particles could be measured through one of the horizontal ports and/or through the vertical ports.

For the ZEPHYR ignition experiment design /17/ injection of the neutral beams through horizontal ports and observation through horizontal and vertical ports was proposed /69/.

4. Conclusions

Alpha particle diagnostics applying neutral doping beams for single and double charge exchange as proposed by Post et al. /10/ seems feasible for plasma parameters and dimensions as foreseen for JET extended performance. It turns out, however, that for the energies of the doping beams the step processes have to be taken into account for the attenuation calculations. In order to obtain photon density rates clearly above the bremsstrahlungs level and neutral production rates above to noise level, respectively, the neutral doping beam current densities should be beyond 200 mA/cm^2, and the particle energy should exceed 200 keV/amu.

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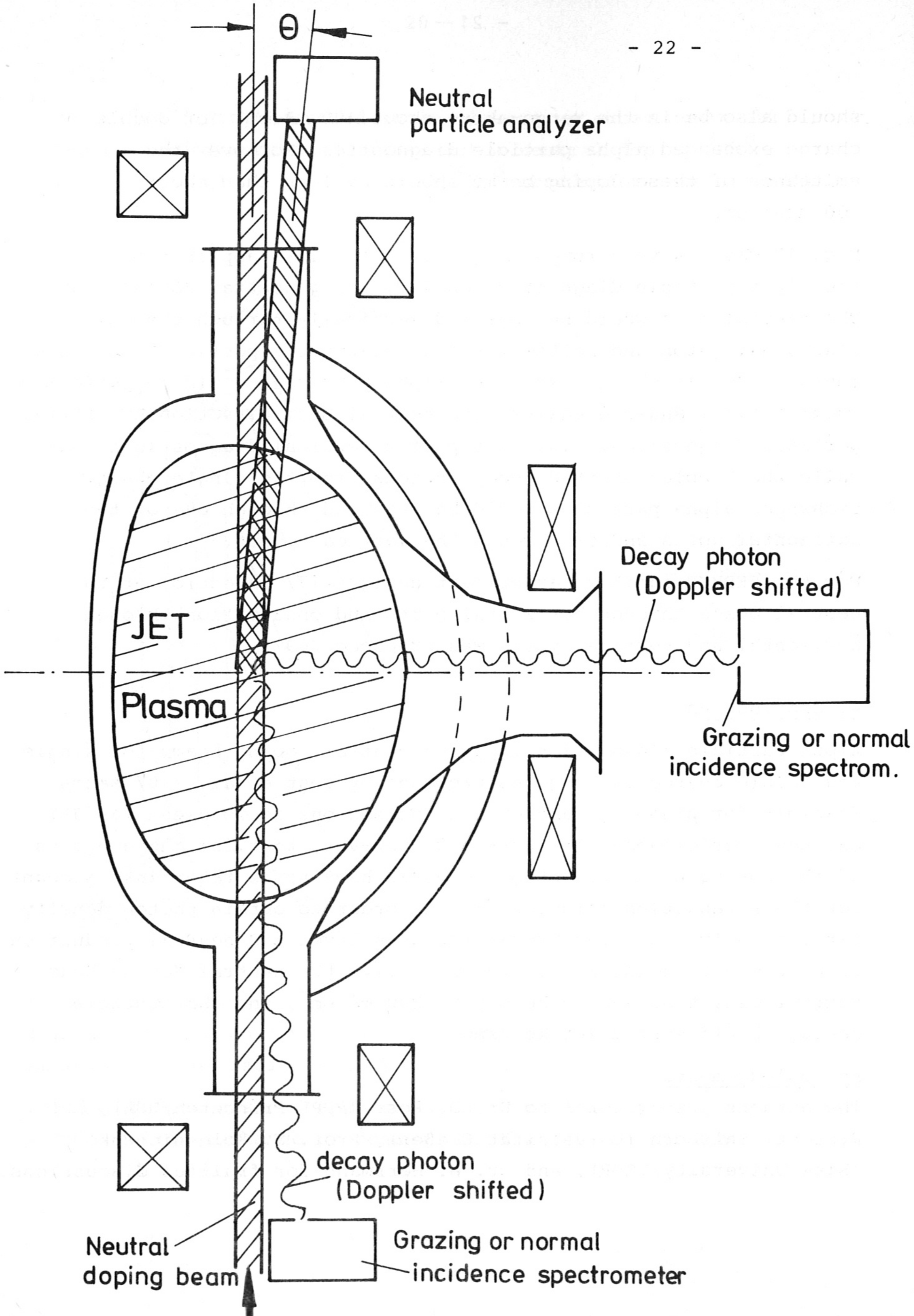

Fig. 17 Rough sketch of a possible application of alpha particle diagnostics on JET

References

/1/ D.G. Lominadze, A.B. Mikhajlovskij, W.M. Tang: Sov. J. Plasma Phys. 2, 286 (1976)

/2/ A.B. Mikhajlovskij: Sov. Phys. J.E.T.P. 41, 890 (1976)

/3/ D.J. Sigmar, H.C. Chan: Nucl. Fusion 18, 1569 (1978)

/4/ Y.I. Kolesnichenko: Nucl. Fusion 20, 727 (1980) (Review Paper on "The Role of Alpha Particles in Tokamak Reactors" with extended bibliography)

/5/ D. Pfirsch: In "Theory of Magnetically Confined Plasmas", ed. by B. Coppi et al., p. 383, Pergamon Press Oxford and New York 1979

/6/ J.G. Cordey, R.J. Goldston, D.R. Mikkelsen: Nucl. Fusion 21, 581 (1981)

/7/ T.D. Kaladze, A.B. Mikhajlovskij: Kurchatov Institute Moscow, Report IAE 2679 (1976)

/8/ H.W. Drawin: In "Atomic and Molecular Processes in Controlled Thermonuclear Fusion" (eds. M.R.C. McDowell, A.M. Ferendici), Plenum Press, New York and London, p. 471-485 (1980)

/9/ K.H. Burrell: Bull. Am. Phys. Soc. 24, 767 (1979)

/10/ D.E. Post, D.R. Mikkelsen, R.A. Hulse, L.D. Stewart, J.C. Weisheit: Princeton Plasma Physics Laboratory Report PPPL-1592 (October 1979), Journal of Fusion Energy 1, 129 (1981)

/11/ L.R. Grisham, D.E. Post, J.R. Weisheit, H.P. Eubank, D.R. Mikkelsen, L.D. Stewart: Princeton Plasma Physics Laboratory Report PPPL-1661 (May 1980)

/12/ J. Weisheit, L. Grisham, R. Hulse, D. Mikkelsen, D. Post, L. Stewart: Top. Conf. on High Temperature Plasma Diagnostics of the APS, Los Angeles, March 1980, paper E16

/13/ L. Grisham, H. Eubank, D. Post. L. Stewart: Top. Conf. on High Temperature Plasma Diagnostics of the APS, Los Angeles, March 1980, paper E15

/14/ W.P. West, E.S. Ensberg, K.H. Burrell: Third Top. Conf. on High Temperature Plasma Diagnostics of the APS, Los Angeles, March 1980, paper E17

/15/ D.E. Post: Physica Scripta 23, 123 (1981)

/16/ D.E. Post, L.R. Grisham, D.R. Mikkelsen, J. Weisheit: Third Top. Conf. of the APS Atomic Processes in High Temperature Plasmas, 27, Louisiana State University, Bato Rouge, Feb. 1981

/17/ Investigation for the ZEPHYR Ignition and Burn Experiment, Internal ZEPHYR Report No. 32 (1980);
C. Andelfinger, M. Kaufmann, W. Köppendörfer, K. Lackner and the ZEPHYR team: Z.Naturforsch. 37a 912 (1982)

/18/ M.L. Watkins, T.E. Stringer, A. Gibson, W.G.F. Core: Proc. 8th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-38/W-3, Brussels, 1-10 July 1980

/19/ G. Magyar, P.E. Stott: JET Diagnostic Memo 1 (19.10.1979), unpublished

/20/ K. Wiesemann: Proc. Vth ESCAMPIG, Dubrovnik 1980, Report SFB-80-05-068, Ruhr-Universität Bochum (Sept. 1980)

/21/ V.V. Afrosimov, M.P. Petrov, V.A. Sadovnikov: J.E.T.P. Lett. 18, 300 (1973)

/22/ A.M. Kudryavtsev, A.F. Sorokin: J.E.T.P. Lett. 18, 2-6 (1973)

/23/ A.C. Riviere: In "Neutral Injection Heating of Toroidal Reactors", Culham Report CLM-R112, p. A2-1 (1971)

/24/ W.L. Fife, R.F. Stebbings, D.G. Hummer, R.T. Brackman: Phys. Rev. 119, 663 (1960)

/25/ H.B. Gilbody, J.V. Ireland: Proc. Roy. Soc. 277A, 137 (1964)

/26/ J.W. Hooper, E.W. McDaniel, D.W. Martin, D.S. Harmer: Phys. Rev. 121, 1123 (1961)

/27/ V.A. Balyaev, B.G. Brezhniev, E.M. Erastov: Proc. Vth Int. Conf. on the Physics of Electronic and Atomic Collisions, Leningrad, Publishing House NAUKA, p. 156 (1967)

/28/ H.B. Gilbody, G. Ryding: Proc. Roy. Soc. 291A, 438 (1966)

/29/ C.F. Barnett, H.K. Reynolds: Phys. Rev. 109, 355 (1958)

/30/ C.F. Barnett, J.A. Ray, E. Ricci, M.I. Wilker, E.W. McDaniel, E.W. Thomas, H.B. Gilbody: Report ORNL-5206, Vol. I, Oak Ridge (1977)

/31/ Equipe TFR: Nucl. Fusion 18, 647 (1978)

/32/ R.E. Olson, A.Salop: Phys. Rev. A16, 531 (1977)

/33/ E. Salzborn: Nagoya Seminar on Atomic Processes in Fusion Plasmas, Nagoya/Japan, Sept. 1979

/34/ W.L. Fite, A.C.H.Smith, R.F.Stebbings: Proc. Roy. Soc. London A 268, 527 (1962)

/35/ J.E. Bayfield, G.A. Khayrallah: Phys. Rev. A 12, 869 (1975)

/36/ M.B. Shah, H.B. Gilbody: J. Phys. B7, 630 (1974)

/37/ M.B. Shah, H.B. Gilbody: J. Phys. B11, 121 (1978)

/38/ B.H. Bransden, C.W. Newby, C.J. Noble: J. Phys. B13, 4245 (1980)

/39/ D. Belkić, R. Gayet: J. Phys. B10, 1911 (1977)

/40/ M.F.A. Harrison: Phys. Reports 37 (2), 59 (1978)

/41/ J.E. Bayfield, G.A. Khayrallah: Phys. Rev. A11, 920 and 930 (1975)

/42/ A.S. Schlachter: private communication in ref. 11

/43/ S.K. Allison: Phys. Rev. 109, 76 (1958)

/44/ S.K. Allison, J. Cuevas, P.G. Murphy: Phys. Rev. 102, 1041 (1956)

/45/ R.A. Baragiola, I.B. Nemirovsky: Nucl. Instr. and Meth. 110, 511 (1973)

/46/ P. Hvelplund, J. Heinemeier, E.H. Pedersen, F.R. Simpson: 9th Int. Conf. Atomic and Electron Collisions 185, Seattle, Wash (1975)

/47/ L.I. Pivovar, M.T. Novikov, V.M. Tubaev: Sov. Phys.-JETP 15, 1035 (1962)

/48/ L.I. Pivovar, V.M. Tubaev, M.T. Novilov: Sov. Phys. - JETP 14, 20 (1962)

/49/ M.B. Shah, H.B. Gilbody: J. Phys. B7, 256 (1974)

/50/ V.V. Afrosimov, G.A. Leiko, Yu.A. Mamaev, M.M. Panov, N.V. Fedorenko: Sov. Phys.-JETP 35, 1070 (1972)

/51/ R. Browning, H.B. Gilbody: J. Phys. B1, 1149 (1968)

/52/ Estimate, corresponding to ${}^{1}H^{o}$

/53/ H.W. Drawin: "Collision and Transport Cross-sections", Report CEA Fontenay-aux-Roses EUR-CEA-FC-383 (Mars 1966)

/54/ B.H. Bransden, L.T.Sin Fai Lam: Proc. Phys. Soc. (London) 87, 653 (1966)

/55/ E. Speth: 2nd Joint Grenoble-Varenna Int. Symp. on Heating in Toroidal Plasmas, Como, Sept. 3-12, 1980

/56/ R.K. Janev: Phys. Lett. 83A, 5 (1981)

/57/ Estimate from electron collisional ionization coefficient of He (2^3S) in Fig. 15 of ref. 53 and from proton collision according to ref. 30

/58/ E.J. Shipsey, L.T. Redmon, J.C. Browne, R.E. Olson: Phys. Rev. A18, 1961 (1978)

/59/ R.E. Olson: Private communication in ref. 11

/60/ Estimate with equ. 34 in Fig. 16 in ref. 53

/61/ Calculated from data in refs. 30 and 62 applying the Gryzinski formula

/62/ R. Jalin, R. Hagemann, R. Botter: J. Chem. Phys. 59, 952 (1973)

/63/ R. Browning, H.B. Gilbody: J. Phys. B1, 1149 (1968)

/64/ W. Lotz: Institut für Plasmaphysik, Garching, Report IPP 1/47 (April 1966)

/65/ Calculation from electron ionization cross-section for $K \rightarrow K^+$ according to ref. 64

/66/ M.B. Shah, H.B. Gilbody: J. Phys. B7, 637 (1974)

/67/ J. Neuhauser: private communication

/68/ U. Schumacher: Proc. 1982 Int. Conf. on Plasma Physics, Göteborg (Sweden), 356 (1982)

/69/ H.-U. Fahrbach, H. Röhr, U. Schumacher, J. Sommer: Max-Planck-Institut für Plasmaphysik, Garching, Internal ZEPHYR Report No. 28 (August 1980)

Appendix A

Approximations for the electron ionization rates ("averaged electron ionization term")

In contrast to the ions the plasma electrons cannot be regarded to be at rest compared to the speed of the injected neutrals having kinetic energies up to 880 keV per nucleon. (The velocity amounts of 1 keV electrons and 880 keV per nucleon neutral particles are comparable). Hence the contribution of the plasma electrons to the attenuation of the neutral particle beam in the plasma is given by the "averaged electron ionization term" /A1, A2/

$$\text{(a1)} \quad \frac{\langle \sigma_{ion}(v_e) \cdot v_e \rangle}{v_p} = \frac{1}{v_p} \int_{E_{ion}}^{\infty} f(E_e) \cdot \frac{1}{2} \cdot \int_{0}^{\pi} \sigma_{ion}(E_c) \cdot \left(v_e^2 + v_p^2 - 2 v_e v_p \cos\phi\right)^{1/2} \sin\phi \, d\phi \, dE_e ,$$

where v_e and E_e are the electron velocity and kinetic energy, respectively, v_p the neutral particle velocity, and ϕ the angle enclosed by the electron and neutral particle velocity vector. E_{ion} is the ionization energy.
The electron velocity is given by

$$v_e = c \cdot \left[1 - \frac{1}{(1 + E_e/m_o c^2)^2}\right]^{1/2}$$

with the electron rest mass m_o and the speed of light c, or numerically

$$v_e\,[\text{cm/sec}] = 2.9979 \times 10^{10} \left[1 - (1 + 1.957 \times 10^{-3} \cdot E_e\,[\text{keV}])^{-2}\right]^{1/2}$$

The relative velocity v_c is

$$v_c = \left(v_e^2 + v_p^2 - 2 v_e v_p \cos\phi\right)^{1/2}$$

and the corresponding kinetic energy of the electron

$$E_c\,[\text{keV}] = 511.03\,(\gamma_c - 1)$$

with

$$\gamma_c = \left\{1 - \left(\frac{v}{c}\right)^2\right\}^{-1/2}$$

and c = 2.9979 x 10^{10} cm/sec.
The distribution function $f(E_e)$ is always assumed to be a Maxwellian one.
$\sigma_{ion}(E_c)$ is the ionization cross section as a function of the electron energy E_c.
For neutral hydrogen $^1H^o$ we used for the ionization cross section the Gryzinski /A3/ formula

$$\sigma_{ion}(E_c)[cm^2] \simeq 3.568 \times 10^{-16} \cdot g(x)$$

with

$$g(x) = \frac{1}{x}\left(\frac{x-1}{x+1}\right)^{3/2}\left[1 + \frac{2}{3}\left(1 - \frac{1}{2x}\right)\ln\left(2.7 + \sqrt{x-1}\right)\right]$$

and

$$x = 73.5 \cdot E_c[keV].$$

The particle velocity is v_{1H^o} [cm/sec] = 4.3775 x 10^7 $(E_{1H^o}\ [keV])^{1/2}$

The "averaged electron ionization term"

$$\frac{\langle \sigma_{ion}(v_e) \cdot v_e \rangle}{v_{1H^o}}$$

for atomic hydrogen beams of energy E_{1H^o} injected into a plasma of electron temperature T_e, calculated from equation (a1) is plotted in Figs.(A1)and(A2)as function of E_{1H^o} and T_e, respectively, as to be found elsewhere /A.1, A.4, A.11/.

For further easier numerical procedures we approximate the "averaged electron ionization term" for atomic hydrogen beams by

$$\frac{\langle \sigma_{ion}(v_e) \cdot v_e \rangle}{v_{1H^o}}[cm^2] \simeq 5.3 \times 10^{-16} \cdot \left(T_e[keV]\right)^{-0.4} \cdot \left(E_{1H^o}[keV]\right)^{-0.5}.$$

For neutral helium $^3He^o$ we approximated the given electron ionization cross section /A.5, A.6/ similarly by

$$\sigma_{ion}(E_c)[cm^2] \simeq 2.208 \times 10^{-16} \cdot g(x)$$

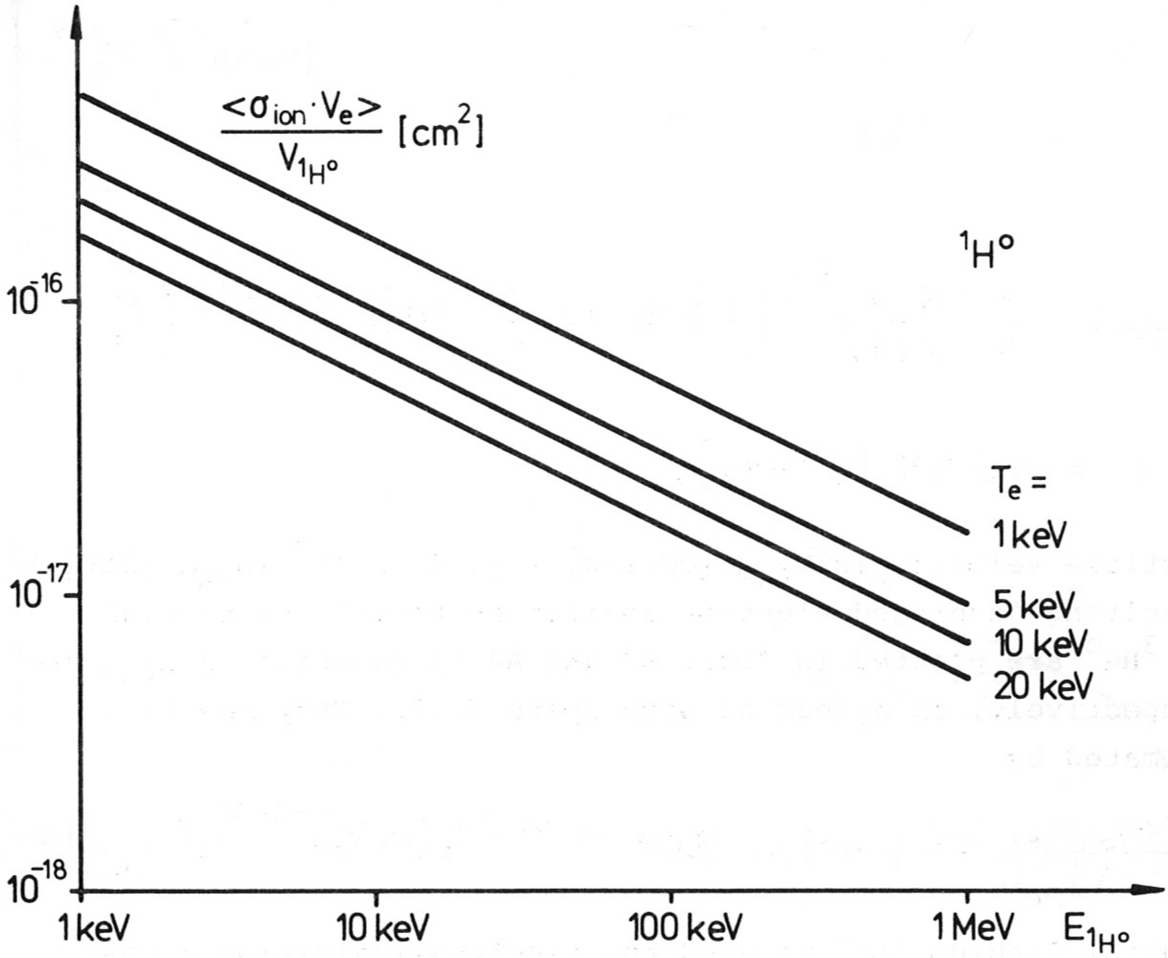

Fig. A1 "Averaged electron ionization term" for neutral hydrogen as function of beam energy $E_{1_{H^o}}$ for different electron temperatures

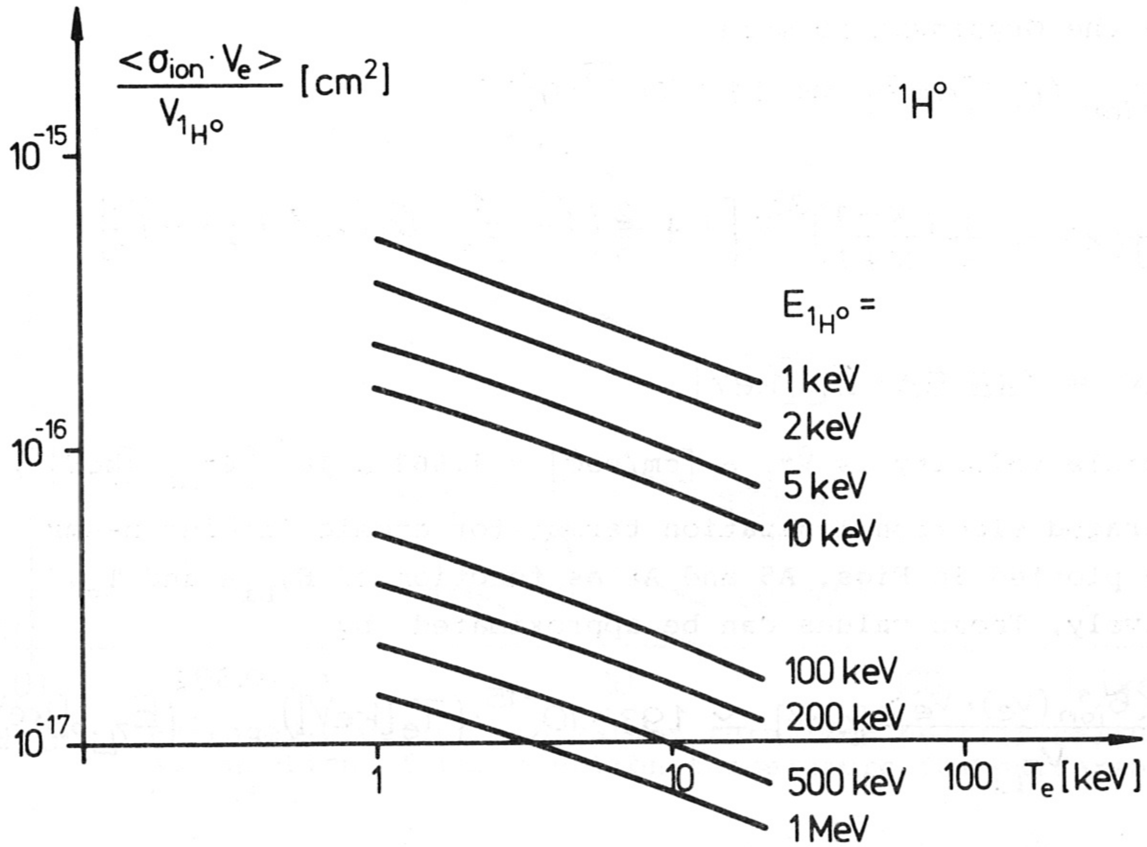

Fig. A2 "Averaged electron ionization term" for neutral hydrogen as function of the electron temperature for different beam energy $E_{1_{H^o}}$

with

$$g(x) = \frac{1}{x}\left(\frac{x-1}{x+1}\right)^{3/2}\left[1+\frac{2}{3}\left(1-\frac{1}{2x}\right)\ln\left(2.7+\sqrt{x-1}\right)\right]$$

and

$$x = 40.68 \cdot E_c\,[\text{keV}].$$

The particle velocity is $V_{^3H^o}$ [cm/sec] = 2.527 x 10^7 ($E_{^3H^o}$ [keV] $)^{1/2}$
The resulting "averaged electron ionization terms" for neutral helium $^3He^o$ are plotted in Figs. A3 and A4 as function of $E_{^3H^o}$ and T_e, respectively, in agreement with Speth /A.7/. They may be approximated by

$$\frac{\langle \sigma_{ion}(v_e)\cdot v_e\rangle}{v_{^3He^o}}\,[\text{cm}^2] \simeq 9.0\times 10^{-16}\cdot\left(T_e[\text{keV}]\right)^{-0.36}\cdot\left(E_{^3He^o}[\text{keV}]\right)^{-0.5}.$$

For <u>neutral lithium</u> $^7Li^o$ we used the electron ionization cross-section of Jalin et al. /A.6, A.8/ which is lower by a factor of about 2 (but more correct) than the values given before /A.9, A.10/. With some degree of uncertainty these values are approximated by the Gryzinski formula

$$\sigma_{ion}(E_c)\,[\text{cm}^2] \simeq 1.1\times 10^{-15}\cdot g(x)$$

with

$$g(x) = \frac{1}{x}\left(\frac{x-1}{x+1}\right)^{3/2}\left[1+\frac{2}{3}\left(1-\frac{1}{2x}\right)\ln\left(2.7+\sqrt{x-1}\right)\right]$$

and

$$x = 185.53\cdot E_c\,[\text{keV}].$$

The particle velocity is $V_{^7Li^o}$ [cm/sec] = 1.662 x 10^7 $\left(E_{^7Li^o}\,[\text{keV}]\right)^{1/2}$

The "averaged electron ionization terms" for atomic lithium beams $^7Li^o$ are plotted in Figs. A5 and A6 as function of $E_{^7Li^o}$ and T_e, respectively, These values can be approximated by

$$\frac{\langle \sigma_{ion}(v_e)\cdot v_e\rangle}{v_{^7Li^o}}\,[\text{cm}^2] \simeq 1.93\times 10^{-15}\cdot\left(T_e[\text{keV}]\right)^{-0.392}\cdot\left(E_{^7Li^o}[\text{keV}]\right)^{-0.5}.$$

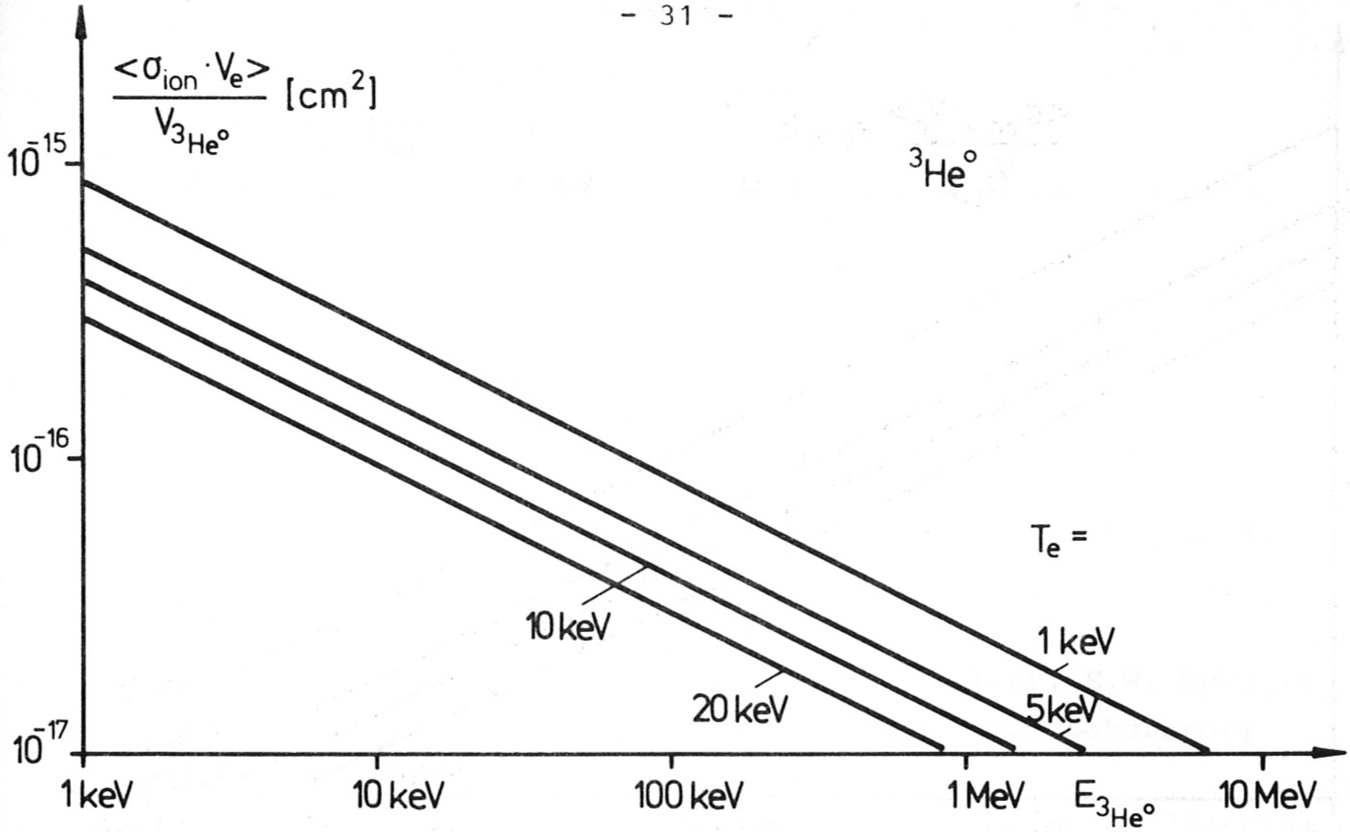

Fig. A3 "Averaged electron ionization terms" for neutral helium $^3He^o$ as function of beam energy for different electron temperatures

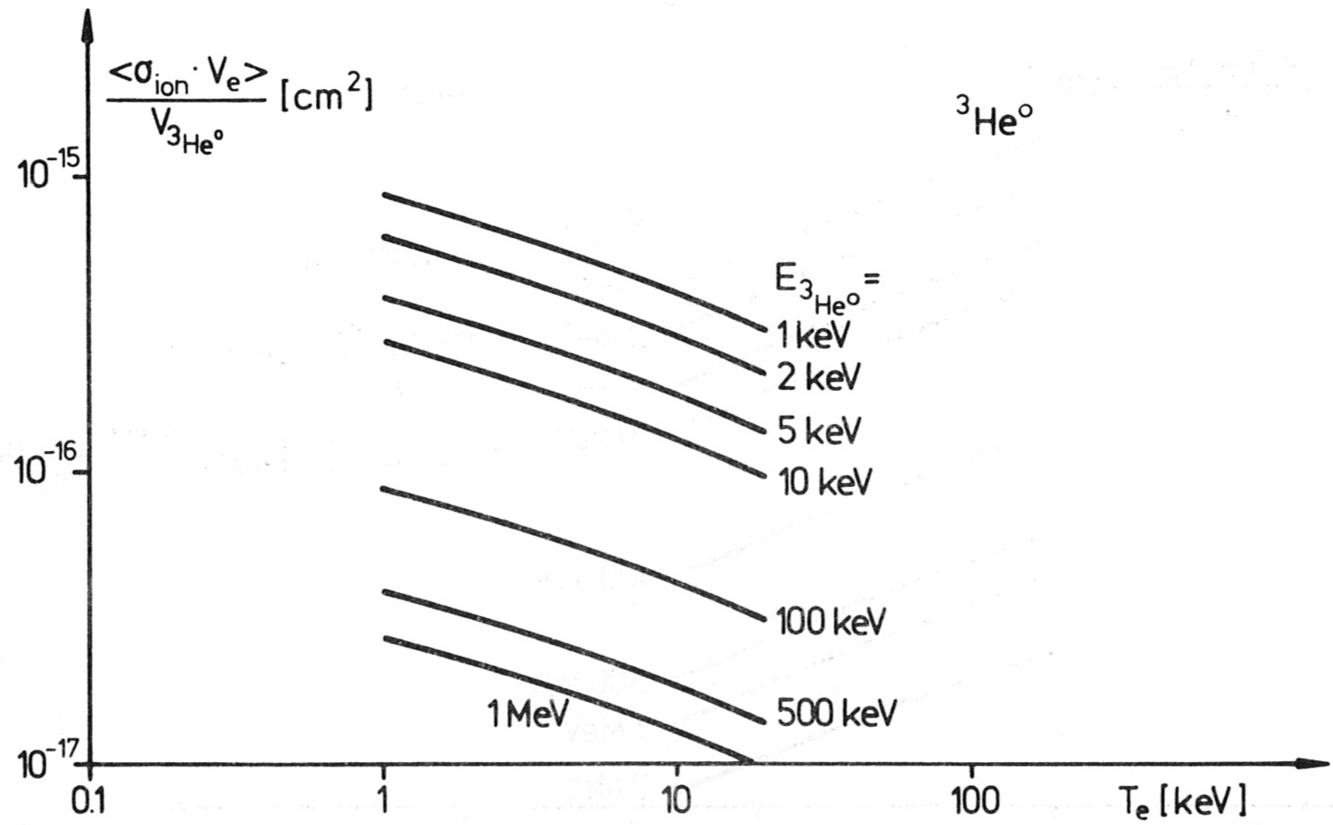

Fig. A4 "Averaged electron ionization term" for neutral helium $^3He^o$ as function of the electron temperature for different beam energies

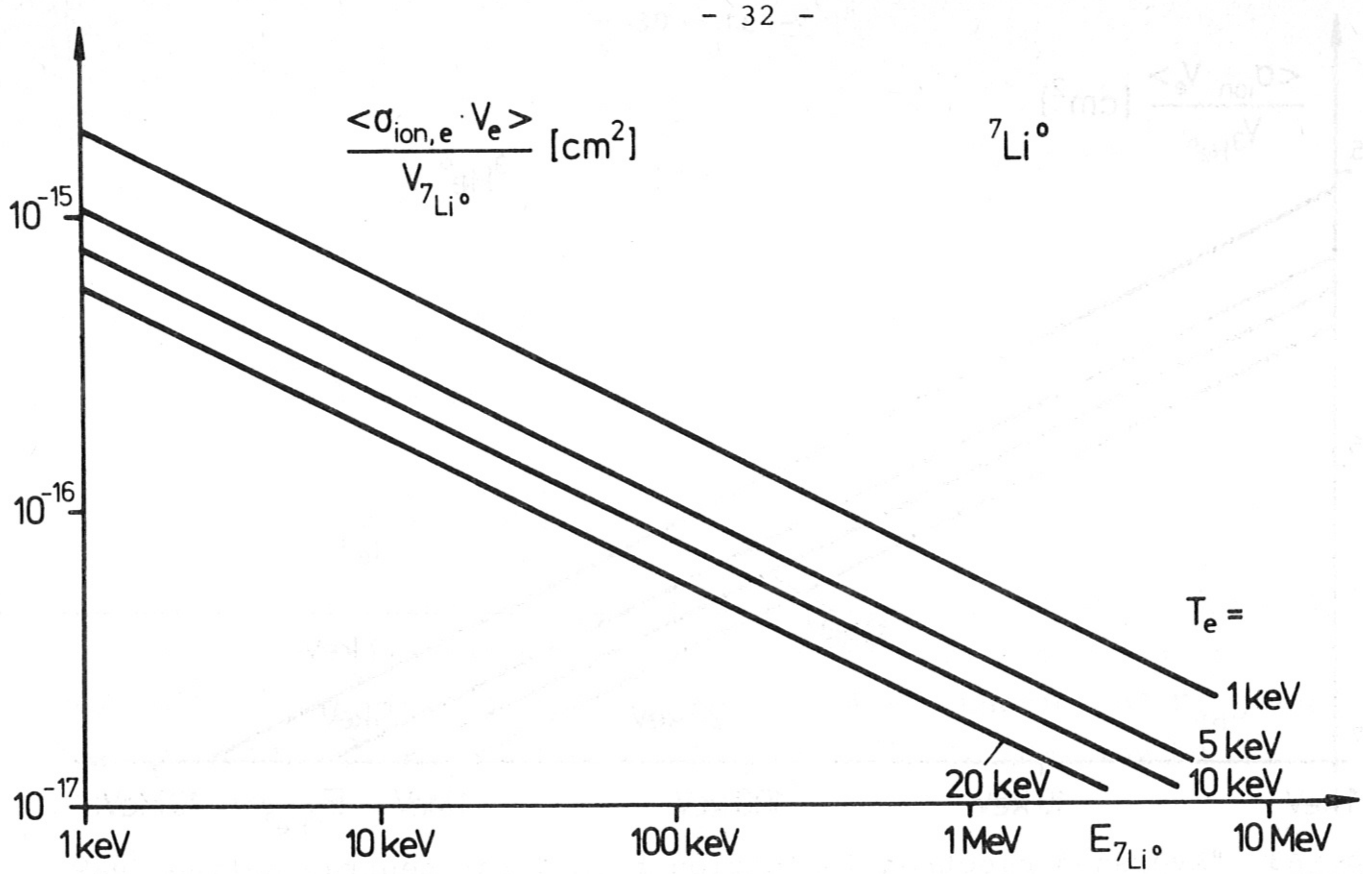

Fig. A5 "Averaged electron ionization term" for neutral lithium $^7Li^o$ as function of **beam energy** for **different** electron temperatures

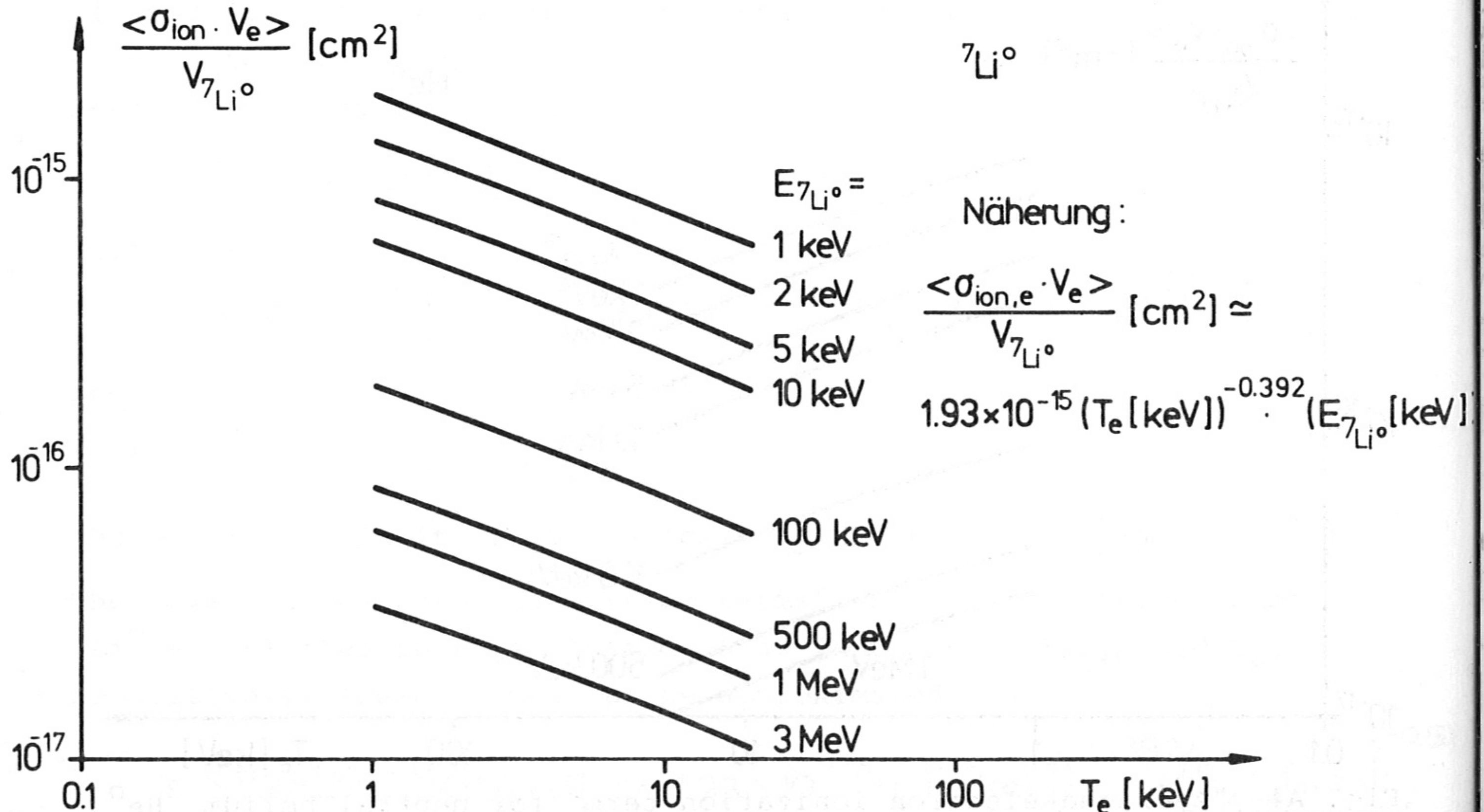

Fig. A6 "Averaged electron ionization term" for neutral lithium $^7Li^o$ as function of electron temperature for different beam energies

References to Appendix A:

/A.1/ M.F.A. Harrison: "Atomic and Molecular Processes in Fusion Research", Phys. Report 37(2), 59 (1978)

/A.2/ A.C. Riviere: "Neutral Injection Heating of Toroidal Reactors", Culham Report CLM-R112, A2-1 (1971)

/A.3/ M. Gryzinski: "Atomic Collision Processes", ed. by M.R.C. McDowell (North-Holland Publishing Company, Amsterdam 1964), pp. 226-236

/A.4/ Equipe TFR: "Tokamak Plasma Diagnostics", Nucl. Fusion 18,5, 647 (1978)

/A.5/ R.E. Fox: J. Chem. Phys. 35, 1379 (1961)

/A.6/ C.F. Barnett, J.A. Ray, E. Ricci, M.A. Wilker, E.W. McDaniel, E.W. Thomas, H.B. Gilbody: Oak Ridge National Laboratory Report ORNL-5206 (1977)

/A.7/ E. Speth: 2nd Joint Grenoble-Varenna Int. Symp. on "Heating in Toroidal Plasmas", Como. Sept.3 -12, 1980

/A.8/ R. Jalin, R. Hagemann, R. Botter: J. Chem. Phys. 59, 952 (1973)

/A.9/ R.H. McFarland, J.D. Kinney: Phys. Rev. 137, A 1058 (1965)

/A.10/H.W. Drawin: "Collision and Transport Cross-Sections", Fontenay-aux-Roses Report EUR-CEA-FC-383 (1967)

/A.11/D.R. Sweetman: Nucl. Fus. 13, 157 (1973)

Appendix B

Approximations for the alpha particle ionization plus charge exchange rates ("averaged alpha particle ionization plus charge exchange term")

The contribution of the alpha particles in a thermonuclear plasma to the attenuation of an injected neutral beam is not negligible. The velocity of the alpha particles (born with a speed of about 1.3×10^9 cm/sec or 3.52 MeV kinetic energy) is of the order of the velocity of the injected neutral particles, which is the essence of the diagnostic method. Hence the ionization plus charge exchange rate of the neutral atom beam by the alpha particles ("averaged alpha particle ionization plus charge exchange term") is given (similarly to equ. (a1) by

$$\text{(b1)} \quad \frac{\langle \sigma_{ion+cx}(v_{c,\alpha}) \cdot v_{c,\alpha} \rangle}{v_p} = \frac{1}{v_p} \int_0^{3.52\,\text{MeV}} f(E_\alpha) \cdot \frac{1}{2} \int_0^{\pi} \{\sigma_{ion+cx}\}(E_{c,\alpha}) \cdot v_{c,\alpha} \sin\phi \, d\phi \, dE_\alpha ,$$

where $v_{c,\alpha}$ is the relative velocity between the alpha particle (with the velocity v_α and energy E_α)and the neutral particle (velocity v_p),

$$v_{c,\alpha} = (v_\alpha^2 + v_p^2 - 2 v_\alpha v_p \cos\phi)^{1/2}$$

and the corresponding neutral particle kinetic energy

$E_{c,\alpha}$ [keV] $= 5.22 \times 10^{-16} \cdot A \cdot (v_{c,\alpha}$ [cm/sec] $)^2$, with A the atomic weight.

Because the alpha particle contribution to the neutral beam attenuation is not dominant for the parameters of the envisaged experiments it might be justified to use the classical alpha particle energy distribution function /B.1/, as obtained (in isotropic form) from the usual Fokker-Planck equation /B.2/ and, moreover, to neglect its spatial dependence. It is approximated by

$$f(E_\alpha)\,[\text{keV}^{-1}] \simeq 1.39 \times 10^{-3} \{ \exp(-0.01192 \cdot E_{\alpha[\text{keV}]}^{0.7}) + 0.7 \cdot \sin(3.93 \times 10^{-3} E_\alpha\,[\text{keV}]) \cdot \exp(-6.5 \times 10^{-3} \cdot E_\alpha\,[\text{keV}]) \}$$

where

$$E_\alpha\ [\mathrm{keV}] = 2.087 \times 10^{-15} \cdot (v_\alpha\ [\mathrm{cm/sec}])^2.$$

$\{\sigma_{ion+cx}\}(E_{c,\alpha})$ is the sum of the ionization and charge exchange cross section as a function of the neutral particle kinetic energy $E_{c,\alpha}$.

For neutral hydrogen $^1H^o$ we used the single charge exchange cross section with alpha particles ($^4He^{++}$) as given by several authors /B.1, B.3, B.4, B.5/ and combined it with the cross section for atomic hydrogen ionization by alpha particles /B.4, B.6/ to be roughly approximated by

$$\{\sigma_{ion+cx}\}(E_{c,\alpha})\ [\mathrm{cm}^2] \simeq \begin{cases} 1.7 \times 10^{-16}\ (E_{c,\alpha}[\mathrm{keV}])^{0.6} & \text{for } E_{c,\alpha} \leq 15 \text{ keV} \\ 3.48\times10^{-14}\ (E_{c,\alpha}[\mathrm{keV}])^{-0.715} & \text{for } E_{c,\alpha} > 15 \text{ keV} \end{cases}$$

Applying equ. (b1) we obtain the "averaged alpha particle ionization plus charge exchange term" for hydrogen, which is approximated by

$$\frac{\langle\sigma_{ion+cx} \cdot v_{c,\alpha}\rangle}{v_{1_H o}}\ [\mathrm{cm}^2] \simeq \begin{cases} 1.12\times10^{-14}\ (E_{1_H o}\ [\mathrm{keV}])^{-0.486} & \text{for } E_{1_H o} < 50 \text{ keV} \\ 1.71\times10^{-14}\ (E_{1_H o}\ [\mathrm{keV}])^{-0.594} & \text{for } 50 < E_{1_H o}[\mathrm{keV}] < 300 \\ 2.69\times10^{-14}\ (E_{1_H o}\ [\mathrm{keV}])^{-0.679} & \text{for } E_{1_H o} > 300 \text{ keV.} \end{cases}$$

For neutral helium $^2He^o$ we combined the single charge exchange cross section with alpha particles ($^4He^{++}$) /B.3, B.7, B.8/ and the ionization cross section /B.3, B.9/ by alpha particles and used for this the approximation

$$\left\{\sigma_{ion+cx}\right\}(E_{c,\alpha})\left[cm^2\right] \simeq \begin{cases} 2x10^{-16}(E_{^3He^o}[keV])^{0.075} & \text{for } E_{^3He^o} \leq 20 \text{ keV} \\ 6.4x10^{-16}(E_{^3He^o}[keV])^{0.455} & \text{for } 20 < E_{^3He^o}[keV] < 100 \\ 5.0x10^{-16} & \text{for } 100 \leq E_{^3He^o}[keV] \leq 200 \\ 3.5x10^{-14}(E_{^3He^o}[keV])^{-0.785} & \text{for } E_{^3He^o} > 200 \text{ keV} \end{cases}$$

Using equ. (b1) the "averaged alpha particle ionization plus charge exchange term" for $^3He^o$ is approximated by

$$\frac{\langle\sigma_{ion+cx} \cdot v_{c,\alpha}\rangle}{v_{^3He^o}}\left[cm^2\right] \simeq \begin{cases} 4.36x10^{-15}(E_{^3He^o}[keV])^{-0.421} & \text{for } E_{^3He^o} < 17 \text{ keV} \\ 1.24x10^{-15} & \text{for } 17 \leq E_{^3He^o}[keV] \leq 150 \\ 1.47x10^{-13}(E_{^3He^o}[keV])^{-0.96} & \text{for } E_{^3He^o} > 150 \text{ keV.} \end{cases}$$

For neutral lithium $^7Li^o$ the published data for the single charge exchange cross section with alpha particles ($^4He^{++}$) plus those for the ionization cross section by alpha particles /B.10/ were approximated by

$$\left\{\sigma_{ion+cx}\right\}(E_{c,\alpha})\left[cm^2\right] \simeq \begin{cases} 1.33x10^{-15}(E_{^7Li^o}[keV])^{0.48} & \text{for } E_{^7Li^o} \leq 40 \text{ keV} \\ 5.1x10^{-14}(E_{^7Li^o}[keV])^{-0.5} & \text{for } 40 < E_{^7Li^o}[keV] < 600 \\ 7.37x10^{-12}(E_{^7Li^o}[keV])^{-1.26} & \text{for } E_{^7Li^o} \geq 600 \text{ keV,} \end{cases}$$

resulting after application of equ. (b1) in the approximation for the "averaged alpha particle ionization plus charge exchange term" for $^7Li^o$:

$$\frac{\langle\sigma_{ion+cx} \cdot v_{c,\alpha}\rangle}{v_{^7Li^o}}\left[cm^2\right] \simeq \begin{cases} 4.3x10^{-14} & \text{for } E_{^7Li^o} > 40 \text{ keV} \\ 1.31x10^{-12}(E_{^7Li^o}[keV])^{-0.926} & \text{for } 40 < E_{^7Li^o}[keV] < 750 \\ 5.31x10^{-11}(E_{^7Li^o}[keV])^{-1.49} & \text{for } E_{^7Li^o} \geq 750 \text{ keV.} \end{cases}$$

References to Appendix B:

/B.1/ 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", Princeton University Plasma Physics Laboratory Report PPPL-1592 (1979)

/B.2/ J.G. Cordey, W.G.F. Core: Phys. Fluids 17, 1626 (1974)

/B.3/ C.F. Barnett, J.A. Ray, E. Ricci, M.I.Wilker, E.W. McDaniel, E.W. Thomas, H.B. Gilbody: Oak Ridge National Laboratory Report ORNL-5206 (1977)

/B.4/ R.E. Olson, A.Salop: Phys. Rev. A16, 531 (1977)

/B.5/ M.B. Shah, H.B. Gilbody: J. Phys. B.:Atom.Molec. Phys. 11, 121 (1978)

/B.6/ E. Salzborn: Nagoya Seminar on Atomic Processes in Fusion Plasmas, Nagoya/Japan, 6./7. April 1979

/B7/ L.I. Pivovar, M.T. Novikov, V.M. Tubaev: Sov. Phys. JETP 15, 1035 (1962)

/B8/ J.E. Bayfield, G.A. Khayrallah: Phys. Rev. A11, 920+930 (1975)

/B9/ E. Speth: 2nd Joint Grenoble-Varenna Int. Symp. on Heating in Toroidal Plasmas, Como, Sept. 3-12, 1980

/B10/E.J. Shipsey, L.T. Redmon, J.C. Browne, R.E. Olson: Phys. Rev. A18, 1961 (1978)