MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

Surface Problems in Plasma Physics and Fusion Research*

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IPP 9/4 Februar 1972

*Based on a paper presented at a seminar at Institut für Technische Physik der KFA Jülich, November 1971

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract

An outline is presented of plasma-wall interaction. A few of the relevant surface-physics effects are discussed. It is pointed out that desorption and backscattering are of importance for plasma-physics experiments, while for a steay-rate fusion reactor probably sputtering and backscattering will be the most important surface effects.

Introduction

The most important technological objective of plasma physics is controlled thermonuclear fusion. The main interest at present is the reaction between D and T:

$$D+T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1.\ MeV)$$

If the energy of the α particles, which it is hoped can be used for heating the plasma, is sufficient to cover the bremsstrahlung losses and heat the freshly supplied fuel, it should be possible to construct a continuously operating reactor. Without allowance for synchrotron radiation this yields a condition for the product of the particle density and confinement time. The energy balance is

$$\frac{1}{4}\, n_i^{\,2} \langle\sigma v\rangle\, E^* = b n_i^{\,2} T^{1/2} + 3kTm_i/\tau$$

from which follows:

$$n_i\tau = 3kT/\left\{\frac{1}{4}\langle\sigma v\rangle\, E^* - bT^{1/2}\right\} \qquad (1)$$

where E^* is the α energy used for heating the plasma, $\langle\sigma v\rangle$ the value of $\sigma\cdot v$ averaged over the temperature, and $bn_iT^{1/2}$ the power radiated per unit volume by bremsstrahlung. This is a special form of the Lawson criterion (according to MILLS [1]). Fig. 1 gives a graphic representation of the resulting $n\tau$ as a function of T (with $E^* = 3.5$ MeV). Suitable methods have therefore to be found to heat a deuterium-tritium mixture to about 20 keV and confine it with magnetic fields so as to achieve an $n_i\tau$ of a few 10^{14} sec cm^{-3}.

A plasma is not so well confined by its magnetic field, however, that the interaction with the surrounding material walls can be neglected. In fact, the plasma emits electromagnetic radiation, fast neutrals due to charge exchange, ions and electrons owing to the finite value of the particle confinement time, neutrons and α particles in the event of fusion reactions and possibly impurity ions.

The effects of this bombardment of the wall include particle emission from the wall, viz. sputtering, backscattering, and desorption, emission of secondary ions and electrons, and vaporization in the event of overheating. The emitted particles are largely neutral and can thus advance to the plasma boundary without being affected by the magnetic field. Here they lead to charge exchange losses or, if ionized, to enhanced radiation. This is because radiation strongly increases with the atomic number Z. The reaction of the wall on the plasma is thus due to surface processes, and hence the plasma physicist's interest in surface physics.

The points treated in this report are as follows:

1. Description of the plasma-wall interaction
2. Some individual processes occurring on the surface
3. Plasma-wall interaction in a possible fusion reactor.

Description of plasma-wall interaction

The theoretical description of the plasma-wall interaction is a very complex and as yet unsolved problem. The basic principle can be explained, however, by means of a radically simplified model (according to BEHRISCH and HEILAND [2]). It is thereby assumend that the plasma and wall are separated by a vacuum. All particles in this "vacuum" are of the same type; the particle density is n, and the mean velocity if $\bar{v}$. If ionization processes occurring in the neutral gas as a result of, for example, radiation from the plasma are now neglected (see, however, [3,4]) the following particle balance can be made:

$$\frac{dN}{dt} = \rho\Phi_p \cdot F + \alpha F + \Gamma - S - \frac{1}{4} n\bar{v}F^{*}\gamma \tag{2}$$

where the notation is as follows:

- N ... total number of neutrals in the gas
- ρ ... re-emission coefficient of the wall, giving the number of particles emitted from the wall per particle impinging from the plasma
- Φ_p ... particle flux from the plasma (at the wall)
- α ... number of atoms emitted from the wall per unit area without the effects of particle radiation, e.g. by photodesorption or diffusion from the interior. α may be negative if gas diffuses into the wall.
- Γ ... inflow from divertors and injection systems
- S ... pump capacity (particles/sec)
- F ... surface area of wall
- F^{*} ... surface area of plasma
- γ ... probability that the impinging particle either is ionized or undergoes charge exchange in the plasma

The individual sum terms on the right-hand side of eq. (2), in order, are: inflow of particles due to re-emission, to diffusion out of the wall, and to inflow from the injection apertures and divertors, and loss of particles to pumps and to the plasma.

The particle flux from the plasma is caused by charge exchange and diffusion:

$$\Phi_p = \frac{1}{4} n\bar{v} \frac{F^{*}}{F} \eta + \Phi_{Diff.} \tag{3}$$

where η is the probability of emission of a fast neutral when a gas atom impinges on the plasma boundary.

Furthermore, one has (assuming high vacuum):

$$S = \frac{1}{4} n\bar{v}\delta F Ho \tag{4}$$

where δ is the fraction of the surface area available for pumping and Ho is the Ho-factor describing the deviation of the pump from the ideal case. It is only the steady state that concerns us here, i.e. $\frac{dN}{dt} = 0$.
Substituting eqs. (3) and (4) in eq. (2) yields:

$$n = \frac{\rho\Phi_{Diff} + \alpha + \Gamma/F}{\frac{\bar{v}}{4}\left\{\frac{F^{*}}{F}(\gamma - \eta\rho) + \delta Ho\right\}} \tag{5}$$

This only gives a steady state if the denominator is greater than zero. As $\delta Ho \ll 1$ and $\frac{F^{*}}{F}$ is smaller than 1 but of the same order, this practically means that:

$$(\gamma - \eta\rho) > 0 \tag{6}$$

γ and η are governed by the plasma density and cross sections. The inequality (6) is thus a condition for the wall re-emission coefficient ρ. As $\eta \leq \gamma \leq 1$, it follows that $\rho < 1$ satisfies the inequality (6) in any case. If $\rho > 1$, a more exact analysis is required (*).

(*) Note: Condition (6) and eq. (5) as the stationary components of the solution are also obtained with the time dependent calculation of Behrisch and Heiland [2] if the source terms are taken into account. If allowance is made for transients, then one should also consider the time variation of α and ρ, which may under certain circumstances vary over a fairly long period until the surface achieves a steady state.

The factor ρ as introduced here is a very summary quantity: it gives the number of particles emitted from the wall per incident particle, averaged over all types of particles, all energies, and all angles. Further discussion of ρ is therefore not worthwhile. It is the individual processes contributing to ρ that should be investigated in defined experiments in order to explain the physics of the plasma-wall interaction with respect to the surface. To complete the picture in terms of the plasma, it is also necessary to know the particle fluxes in respect of energy and angle of incidence and to determine the radiation load on the wall. For this purpose balance equations of the same type as eq. (2) have to be formulated for all types of particles, with due allowance for the influence of particles emitted by the wall on the composition and temperature of the plasma. The systems of equations then quickly become very complex and the computing time correspondingly long. Since, moreover, these effects are of minor importance for short-lived or cold plasmas, not very much has been done so far in this field (see, however, [5]). Since it has become possible, however, to confine hot plasmas for longer periods, e.g. in the tokamak, the discussion of such recycling has gained importance (see, for example [6]).

Discussion of the individual processes

As already stated, the metal wall we have in mind (although one class of plasma experiments is conducted in quartz vessels) is bombarded by photons, electrons, ions,neutral atoms, and neutrons. Only a few of the many processes conceivable here [7] are singled out.

A very important process is sputtering since it also erodes the wall. The usual method of measuring the sputtering yields by bombardment with the various hydrogen ions does not work. This consists in determining how much weight the sample loses after ion bombardment. Large quantities of hydrogen, however, are sometimes trapped in metals. Furthermore, the sputtering yields are so small that the sample sometimes even becomes heavier during the sputtering process. YONTS [8] therefore uses the apparatus sketched in Fig. 2. The ion beam passes through a mass separator and strikes the sample. Part of the sputtered material is collected on a microscope glass. The light transmission through the glass is then measured. The apparatus is calibrated by means of sputtering with helium. Little helium is collected, and so it is legitimate here to measure the loss of weight to determine the absolute value of the sputtering yield s. YONTS obtains $s = 4x10^{-3}$ for sputtering of niobium at $1100^{\circ}C$ by 20 keV D^+.

Another method is used by SUMMERS, FREEMAN and DALY [9]. They vacuum coat a zirconium base with a thin niobium film. The secondary ions are analysed in a mass spectrometer and the dose is measured until a zirconium signal appears in the mass spectrometer. The onset of the signal is not too sharp, but an accuracy of 50% for the sputtering yield is sufficient for estimating the wall erosion. Results for $D^+ \rightarrow$ Nb are shown in Fig.3. The measured values are smaller than predicted by the two theories used for comparison, but comparable with YONT's value.

The same paper [9] contains measurements of the self-sputtering of niobium (by the usual weight loss method). The results are presented in Fig. 4. Two points should be noted here: s grows here with increasing energy, the maximum being above 80 keV in agreement with theoretical predictions. The rise of the curve in the preceding case was just the opposite, the maximum being below 10 keV. Furthermore, the absolute value of s for Nb $\rightarrow$ Nb is more than two orders of magnitude larger than for D $\rightarrow$ Nb, and so slight contamination of the plasma with wall material is already sufficient to cause an appreciable increase of sputtering.

The erosion of thin films is also used by BEHRISCH and WEISSMANN [10] to measure the sputtering yield. They measure the thickness of the film by means of the energy spectrum of the backscattered ions. These measurements were recently described in a seminar [11], and are therefore not dealt with in detail here.

To estimate the wall erosion it is sufficient to know the sputtering yield. If, however, one wants to know how far the sputtered particles penetrate the plasma, their charge and energy have to be determined. These particles are largely neutral, and so measuring the energy distribution presents problems.

Sputtering is caused by transfer of momentum from bombarding ions to metal atoms, thus touching off a collision sequence. The theoretical treatment of such a sequence without allowance for single crystal effects yields a E^{-2} distribution [12]. This is confirmed by the few measurements available. Figure 5 shows a measurement made by M.W. THOMPSON [13]. Here polycrystalline gold was bombarded with 43 keV Ar^+. The maximum possible energy E_{max} is calculated by the binary collision rule to be:

$$E/E_o = \frac{4M_1 M_2}{(M_1+M_2)^2}$$

For example in the figure it is 23 keV. In the case of 20 keV deuterium and helium on Nb it is 1.65 and 3.2 keV respectively. No measurements have yet been made, however, to determine whether the energy distribution of the sputtered particles due to bombardment with light ions is also $1/E^2$. Neither has the maximum of the energy distribution for bombardment by light ions been determined. In the use of Argon bombardment it is at 1 to 5 eV [14]. In any case in a reactor we may expect to have sputtered particles with energies up to a few hundred eV which can penetrate a few millimetres into the fusion plasma until they are ionized.

Not only do the ions injected into the metal cause sputtering, some of them are backscattered after collision with the metal atoms. A measurement of the energy distribution of protons after bombardment of Nb is shown in Fig. 6 [15]. The top curve is the sum of ions and neutral particles, while the bottom curve represents only the neutrals. The energy distribution of neutrals between a few hundred eV and 10 keV still has to be measured. In this energy range semiconductor counters can no longer be used and post-ionization is not very effective. This one example will again suffice because this point has also been treated in the already quoted paper of BEHRISCH [11], as also have the single crystal effects and the application of these effects to examine the radiation damage caused by the ions.

Also of interest in sputtering investigations is how the surface of a sputtered material looks. A large number of such investigations with a resolution of a few hundred to a thousand Å are described in the literature (e.g. [16, 17]. We made use of the higher resolution of the field emission microscope [18]. The system is differentially pumped and an ion beam (rare gas, energies 300 eV to 5 keV) is focused through a hole in the fluorescent screen onto the field emission tip. The tip is cooled with LN_2 and can be heated to any temperature required with an electronically controlled heating current. The partial pressure of adsorbable gases is below 10^{-11} torr. Observation and bombardment take place alternately, i.e. during bombardment there is no imaging field on the tip.

Figure 7 shows the result obtained when niobium was bombarded with Ar^+ [19] at different temperatures. Prior to bombardment the tip looks as shown at the bottom of the figure. At low temperatures the surface is rough all over and the differences between the individual crystal surfaces disappear. After bombardment at medium temperatures certain structures correlated with the crystal structure of the base are obtained. In the case of body-centered cubic metals the <111> zone always shows up bright. Finally, at high temperatures the surface, on the scale observed here, remains unchanged. Observations of a whole series of metals with high melting points show as a rule [18]: Bombardment below 0.1 T_m produces general roughness, between 0.1 and 0.3 T_m the surface structure described are obtained, and above 0.3 T_m the surface remains perfect. Figure 8 shows how the roughness propagates as a function of the bombardment dose. The variation of the FE current at constant voltage thereby serves as a measure of the change in structure. Up to 10^{15} ions/cm^2 the variation of the surface structure is pronounced, while afterwards hardly any change can be observed in the FE pattern. Similar experiments with the field ion microscope (but with less well defined ion beams [20] show that the roughness does in fact represent the production of atomic surface disorder. Despite these marked changes in the atomic structure of the surface it seems from the literature that the sputtering yields are largely independent of temperature. The surface structure thus apparently has no essential influence on the propagation of the avalanches leading to sputtering (see, however, [17]).

Another subject that should be discussed is desorption due to ion bombardment. This effect is generally used for cleaning surfaces, but hardly any exact investigations on yields, etc. have been made. Now this is an important process in the context of this report because in plasma apparatus it is generally not possible to subject all surfaces to rigorous UHV cleaning. Surface layers on the wall can thus be expected in pulsed plasma experiments and possibly in the start phase of a reactor as well. At Culham McCRACKEN [21] used D^+ of 15 keV to bombard Mo that had been chemically cleaned and then baked for 24 h at 250°C. He found an initial desorption of approx. 5 gas atoms (mainly hydrogen and CO) per incident ion. After about 2×10^{15} ions/cm^2 the yield had dropped to half and continued to decrease. This is thus a case where the wall emission assumes critical values.

Another investigation deals with the desorption of nitrogen adsorbed on W bombarded with low-energy argon (WINTERS [22]). Here, too, appreciable desorption rates are found down to very low ion energies (Fig. 9). The desorption becomes quite enormous, however, if layers of condensed hydrogen are bombarded with D^+ (5 keV). ERENTS and McCRACKEN [23] found values between 10^4 and 10^5. For us this means that the plasma ought not to "see" any cryogenic surfaces unless a notable sorption on these surfaces can be prevented.

The plasma wall interaction in a fusion reactor

We now turn our attention to the wall problem expected in a future fusion reactor. On the assumption that plasma confinement and heating can be satisfactorily solved, there are various D-T reactor concepts that can be developed. These different proposals lead to similar problems with the wall, and so the stationary toroidal reactor is taken as an example. (The pulsed reactor does, however, involve additional problems owing to the high thermal load during the pulse). A power of up to 13 MW/m^2 has to be transmitted through the wall, but only 1.5 MW of this in the form of heat, the greater part of the power being transported by the neutrons, whose energy has to be converted into heat in the blanket. Working temperatures of about 900 to 1000°C are needed for the wall to obtain a high thermodynamic efficiency. The vacuum wall therefore has to meet the following requirements: Good mechanical properties up to 1000°C, good machinability, good thermal conductivity, low vapour pressure up to 1000°C, resistance to corrosion by the cooling agent, and, finally, small neutron capture cross section together with a large cross section for (n, 2n) reaction. The neutron reactions should not, however, yield secondary products with long half-times.

For this purpose the only suitable materials are the metals with high melting points and alloys of these. Consideration of the neutron cross sections leaves us primarily with molybdenum and niobium. As Mo is difficult to machine and Nb becomes quite strongly activated, consideration is also given to vanadium and possibly to types of steel with very good high-temperature characteristics, but then working temperatures of about 700°C have to suffice.

First, however, let us return to eq. (6). In a fusion plasma one has $\gamma = 1$, the plasma is dense for incoming neutrals. Comparison between the reaction rates for ionization and charge exchange also shows that about two-thirds of all incoming hydrogen particles undergoes charge exchange [2]. About half of this again will have the right direction of flight to leave the plasma, i.e. $\eta \approx 1/3$. Equation (6) is thus satisfied if $\rho<3$. It is presumed that under reactor conditions in steady state operation the walls are clean and saturated with hydrogen, so that one gets $\rho \approx 1$. No trouble is therefore anticipated from this quarter, with one exception: if the wall contains large quantities of hydrogen, as e.g. niobium, and there is a local temperature excursion, the wall emits hydrogen. As a result of charge exchange the wall bombardment increases and the process can grow. It can be estimated that with a neutral gas density of 3×10^{14} cm^{-3} in front of the wall, a wall temperature of 900°C, and a wall thickness of 1mm, a uniform temperature rise of about 10°C is sufficient to release as much hydrogen from the wall as is contained in the plasma [24]. As it is the kinetics of the process that decides whether it is really dangerous we make a rough estimate using the long term time constant of diffusion $\tau = x^2/\pi^2 D$ (x the wall thickness, D the diffusion coefficient) [25]. With the extrapolated value of D from [26] ($D = 2 \cdot 10^{-4}$ cm^2/s) we get for our example a τ of 5 sec for D in Nb or V.

We nevertheless proceed on the assumption that re-emission is uncritical. This takes us to the next problem, sputtering, which is probably caused primarily by fast neutrals due to charge exchange. For this purpose the neutral gas pressure has to be known. This is ultimately governed by the gas throughput, which in turn depends on the reactor output and the attainable relative burn-up, and by the pumping speed. The best pump for a plasma machine is the divertor, through which the "burned" plasma is removed and the impurities which are emitted from the wall and are ionized in the outer layer of the plasma are quickly extracted.

In one possible configuration, the Torsatron [27], the magnetic field is shaped in such a way that in effect there are three divertors around the torus. With respect to the vacuum this is probably about the best configuration. PREVOT [28] and GOURDON et al. [27] estimate that the neutral gas density obtained in this case is probably between a few times 10^{11} to a few times 10^{12}/cm^3. (For a more detailed discussion see Appendix A).

With $n = 10^{12}$ cm^{-3} the bombardment of the wall by particles that have undergone charge exchange is about 10^{17}/cm^2. The intense charge exchange causes the boundary layer of the plasma to cool. In the least favourable case the temperature drops to the region of a fewkeV, where the sputtering maximum for hydrogen is located. If we put the yield at 10^{-2} (extrapolated from the measurements in [9]), we get a wall erosion of 5 mm per annum and a flux of 10^{15} wall atoms per cm^2 sec to the plasma. Should this in fact happen, it might be useful to raise the neutral gas pressure until the boundary layer cools to a temperature of below 100 eV, provided that this is permissible with regard to the plasma, and that the additional thermal load on the wall due to thermal conduction remains tolerable.

Another possibility would be to reduce the power output per unit area of the wall. This would allow the gas throughput to be decreased and the neutral gas density could be lowered for the same pumping speed. Such a power decrease is also important with respect to radiation damage, magnetic field technology, and cooling problems, and perhaps fusion reactors of low output density will have to suffice for a start. (Further details on sputtering are discussed in Appendix B).

Conclusion

The foregoing remarks may have succeeded in conveying an idea of some of the surface problems encountered in plasma physics, although it has only been possible to deal with a selection of the relevant effects. By way of summary it can be stated that in plasma experiments now and in the next few years the effects of desorption, trapping and backscattering are and will continue to be of major importance, a further difficulty being that these are technical surfaces that are mostly not well defined.

For a fusion reactor it is probably sputtering and backscattering that will be the main interest, in so far as such predictions can be made at all at this stage.

APPENDIX A

An attempt is made here on the basis of eq. (5) to estimate the neutral gas density for the case of a reactor with divertor. The divertor prevents charged particles from reaching the wall, i.e. $\Phi_{diff} \approx 0$. The particle balance between the neutral particle flux to and from the divertor is allowed for by regarding it, on the one hand, as an ideal pump (Ho = 1) and, on the other, as a gas source Γ_{div}. If n_{div} is the neutral gas density in the divertor (being given by the gas throughput of the reactor and the pumping speed at the divertor chamber), it follows that

$$\Gamma_{div} = n_{div} \frac{\bar{v}}{4} \delta F$$

where δF is the size of the opening between the divertor and reactor vessel.

The gas flow from the injectors is another source. It is assumed that the amount of neutral gas there is proportional to the quantity of fuel injected, and thus

$$\Gamma_{inj} = c \cdot \frac{2R}{f} \cdot F$$

where $\frac{2R}{f}$ is the gas throughput per unit area (f the burn-up, R the number of fusion reactions/ unit wall surface and c is the fraction of the fuel injected as "cold gas").

For α we make the following ansatz (according to [29])

$$\alpha = BR$$

where B is the breeding rate. This is the maximum value that α can assume in genuinely stationary operation if the diffusion and desorption of impurities can be neglected, but allowance is made for the tritium produced in the blanket diffusing through the wall into the reactor.

With the abbreviation $\frac{F^*}{F}(1-\eta)+\delta = A$ eq. (5) then reads

$$n = \frac{2cR}{f} \cdot \frac{4}{\bar{v} A} + \frac{n_{div}}{A} + \frac{4BR}{\bar{v} A} \tag{A1}$$

where the sum terms give the inflow from injectors and from the divertor and diffusion of the bred tritium through the wall.

Let, for example, the total power throughput per unit area of the first wall be 13 MW/cm^2. If the energy per reaction is 22.4 MeV, it follows that $R = 3.6 \times 10^{14}$ cm^{-2} sec. Let also $f = 3 \times 10^{-2}$, $\frac{F^*}{F} = 0.7$; $\bar{v} = 2.8 \times 10^5$ cm sec^{-1} (D-T mixture, 1000°K); $\eta = \frac{1}{3}$, $\rho = 1$, $B \approx 1$ and $c = 10^{-2}$ (1% of the injected fuel ends up as neutral gas) and according to Prevot [21] in the case of the Torsatron reactor, let

$$n_{div} = 3 \times 10^{12} \ cm^{-3}; \quad \delta = 0.15.$$

It then follows that

$$n = (0.06 + 7.3 + 0.09)\ 10^{11}/cm^3$$

i.e. the inflow from the divertor makes the major contribution (on the above assumptions).

Allowance should, of course, be made in the reactor for the fact that n is space dependent and has its maximum near the injection and divertor openings.

No allowance is made, on the other hand, for the fact that the neutral gas backstreaming from the divertor might already be ionized in the fairly dense plasma flow in the divertor slit.

APPENDIX B

On estimating the sputtering in a fusion reactor

The particle fluxes to the wall that are required for calculating the sputtering are usually estimated in the literature with one of two approximations. It is assumed either that the total particle throughput of the reactor is uniformly distributed over the wall, and that the incident ions have an energy of 20 keV [e.g 30], or that only the charge exchange leads to wall bombardment. For the calculation in the main part of the report it was the latter approximation that was used since the other is completely fictitious: either the reactor has a divertor, so that the charged particles are conveyed to it and the wall is mainly impinged upon by the charge exchange neutrals, or no divertor is present, with the result that a relatively high pressure results between the plasma and wall owing to the limited pumping speed [28] and charge exchange again becomes dominant.*

Let us make another estimate [32]. In the stationary reactor the power transported to the wall by particle bombardment has to be covered by the α-particle heating. It can thus at most be equal to the α-particle power minus the bremsstrahlung. Thus, if the power density in the reactor plasma and the ratio of the plasma volume to the surface area of the first wall is given, an upper limit of the power transmitted to the wall by particle bombardment is known. The thickness of the layer eroded by sputtering (provided eroded atoms are not redeposited on the wall) is given by

$$\Delta x = \Phi s \frac{m}{\rho} \Delta t$$

where
- Φ ... particle flux to wall
- s ... sputtering yield
- m ... mass of the wall atoms
- ρ ... density of the wall material
- Δt ... time

Since $m/\rho = v_{at}$ = atomic volume

and $\Phi E = P$ (E the particle energy, P the power transmitted to the wall by particle bombardment per unit area),
the thickness loss is then $\Delta x = P \frac{s}{E} v_{at} \Delta t$

In Fig. 10 the experimental values of s for bombardment of Nb with light ions and normal incidence is plotted as a function of E. As only measurements at high energies are available for deuterium on niobium, we have extrapolated the curve with a constant factor to the He-Nb curve for want of better data. According to this extrapolation we would thus expect a maximum $\frac{s}{E}$ of 5×10^{-3}/keV.

As an example, we then use this to calculate Δx for a reactor with the following data: total wall load 1300 W/cm^2, reaction energy 22.5 MeV, α energy 3.5 MeV, and hence α-power/area ...200 W/cm^2. If 50 W is allowed for radiation losses [33], we are left with 150 W/cm^2 as the upper limit for p. With $v_{at} = 1.8 \times 10^{-23}$ cm^3 it follows that

$$\Delta x = 2.6 \text{ cm/year.}$$

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*The gas between plasma and wall may be ionized ([3, 4]), but this should not basically alter the above conclusion. In this case the "outer plasma" is in contact with the wall, where it is neutralized. The resulting influx of neutrals from the wall again leads to charge-exchange losses of the plasma. The "outer plasma" might effect the energy distribution of the particles hitting the wall, but this at present is unknown for either case.

No allowance has been made for the fact that part of the wall bombardment is due to tritium and small amounts of He and impurities, and that the angle of incidence is not always perpendicular. Taking these effects into account will increase Δx, but probably by 20 to 50% only.

This wall erosion is so great that even one-tenth of it would be prohibitive for a fusion reactor. Another very serious impediment is the slow decrease of $\frac{S}{E}$ towards low energies. This means that only when the boundary layer has cooled to below 100 eV, other things being equal, is there a pronounced reduction of sputtering.

It is concluded that since energy considerations reveal an intolerably high upper limit for the wall erosion more detailed studies are necessary. For this purpose we need more data on the sputtering yields in the energy range from a few eV to 10 keV and a knowledge of the particle fluxes from a fusion plasma and their energy spectra.

Acknowledgements

I would like to acknowledge the many useful discussions that I had with Dr. G. Haas, Dr. W. Heiland and Dr. B.M.U. Scherzer in preparing this paper. I have also to thank them and Dr. R. Behrisch, Dr. G.M. McCracken and Dr. H. Schulze-Schüler for the permission to use unpublished work.

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Figure Captions

Fig. 1 Lawson-criterium for the case of stationary reactor with α-particle heating (after [1])

Fig. 2 Apparatus for measuring sputtering yields for deuterium (after [8])

Fig. 3 Sputtering yields for bombardment of Nb with D^+ at normal incidence (after [9])
(a) Phase theory
(b) Goldman and Simon theory
(c) Experimental
Δ Yont's value [8]

Fig. 4 Sputtering yields for bombardment of Nb with Nb^+ at normal incidence (after [9])

Fig. 5 Energy distribution of Au, sputtered by Ar^+ of 43 keV (after [13])
lower curve .... experimental values
upper curve .... E^{-2}-line for comparison

Fig. 6 Energy distribution of protons backscattered from polycristalline Nb (after [15])
Primary energy: 150 keV
(a) ... charged and neutral particles
(b) ... neutral particles alone

Fig. 7 FEM-pictures of Nb-tips after Ar^+-bombardment

Fig. 8 Ar^+-bombardment of Nb
Change in field emission current at constant voltage as a function of dose.
Tip-Temperature 100^oK

Fig. 9 Sputtering yields of N adsorbed on W for bombardment with Ar^+ (after [22])

Fig. 10 Sputtering yield per unit energy transmitted as a function of energy for the bombardment of Nb by light ions
a ... Rosenberg and Wehner [31]
b ... Summers, Freeman, Daly [9]

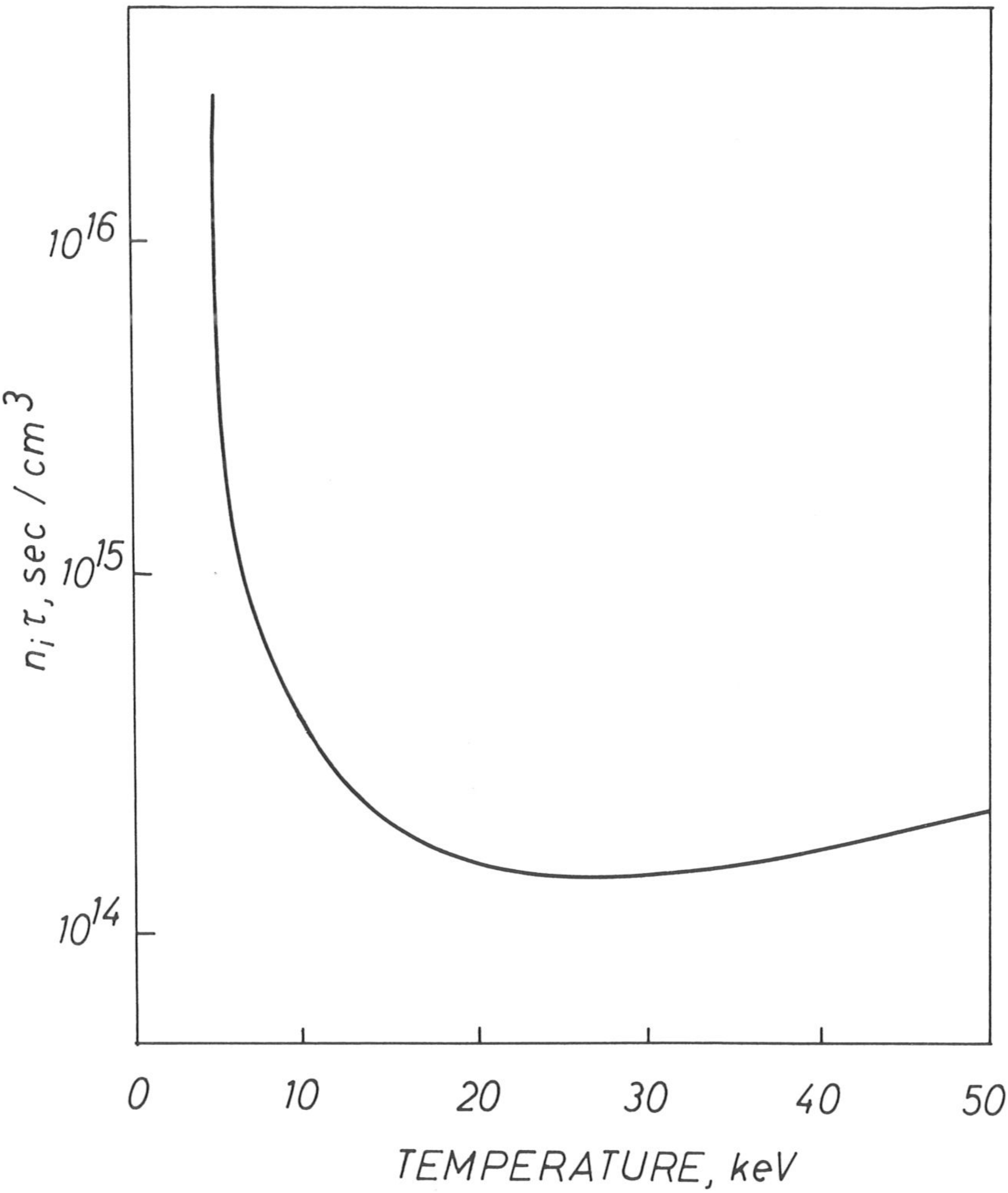


Fig. 1

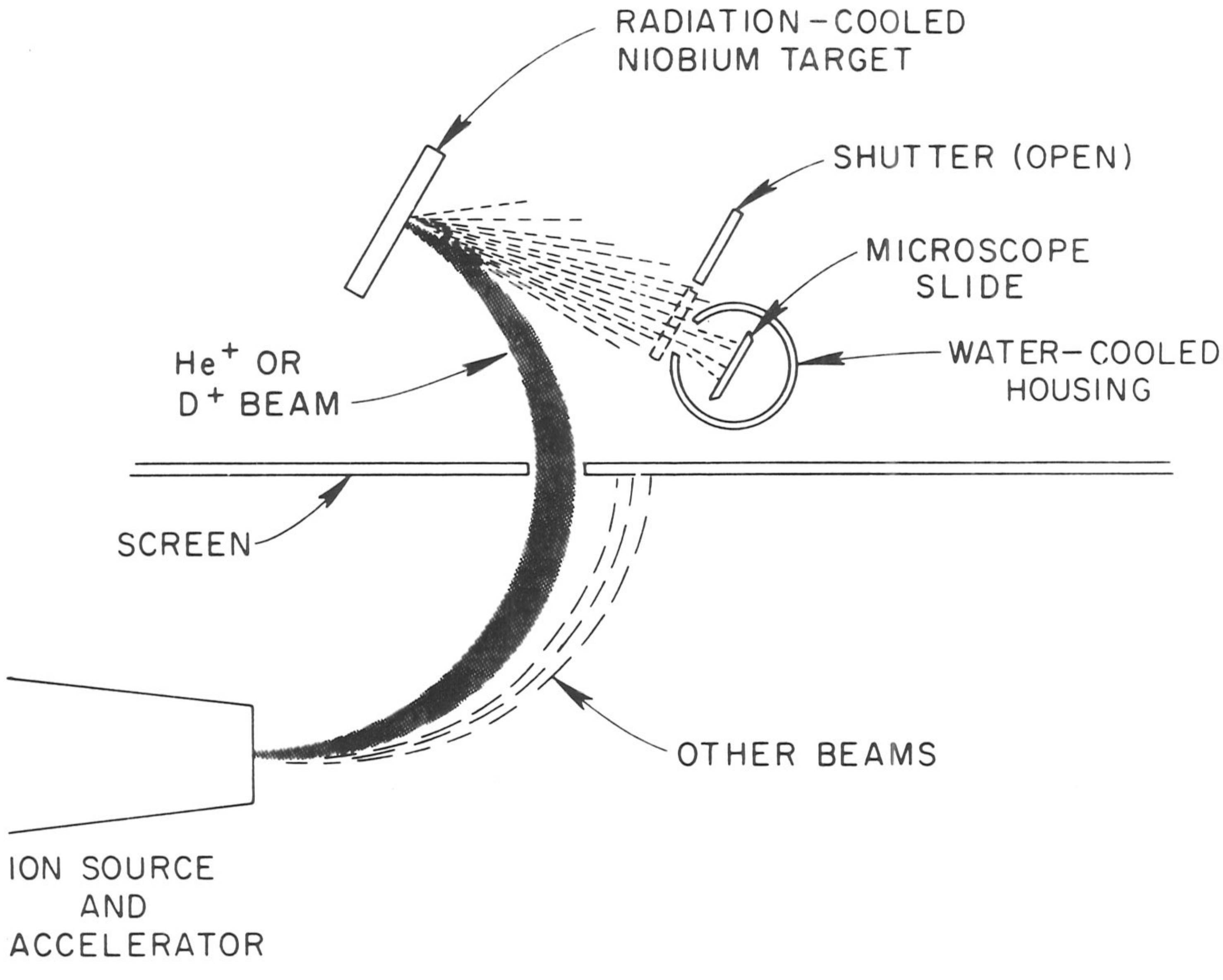
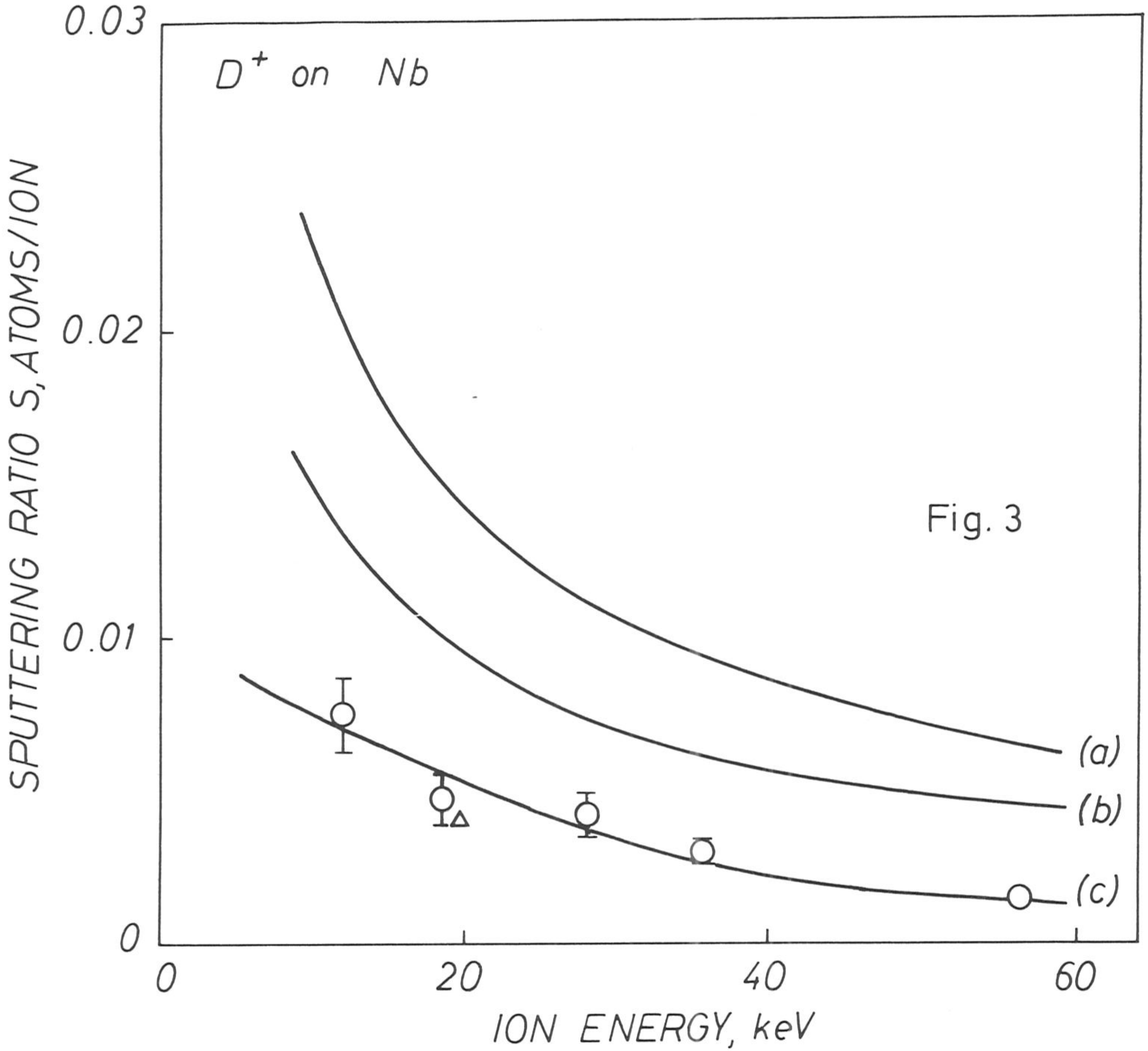
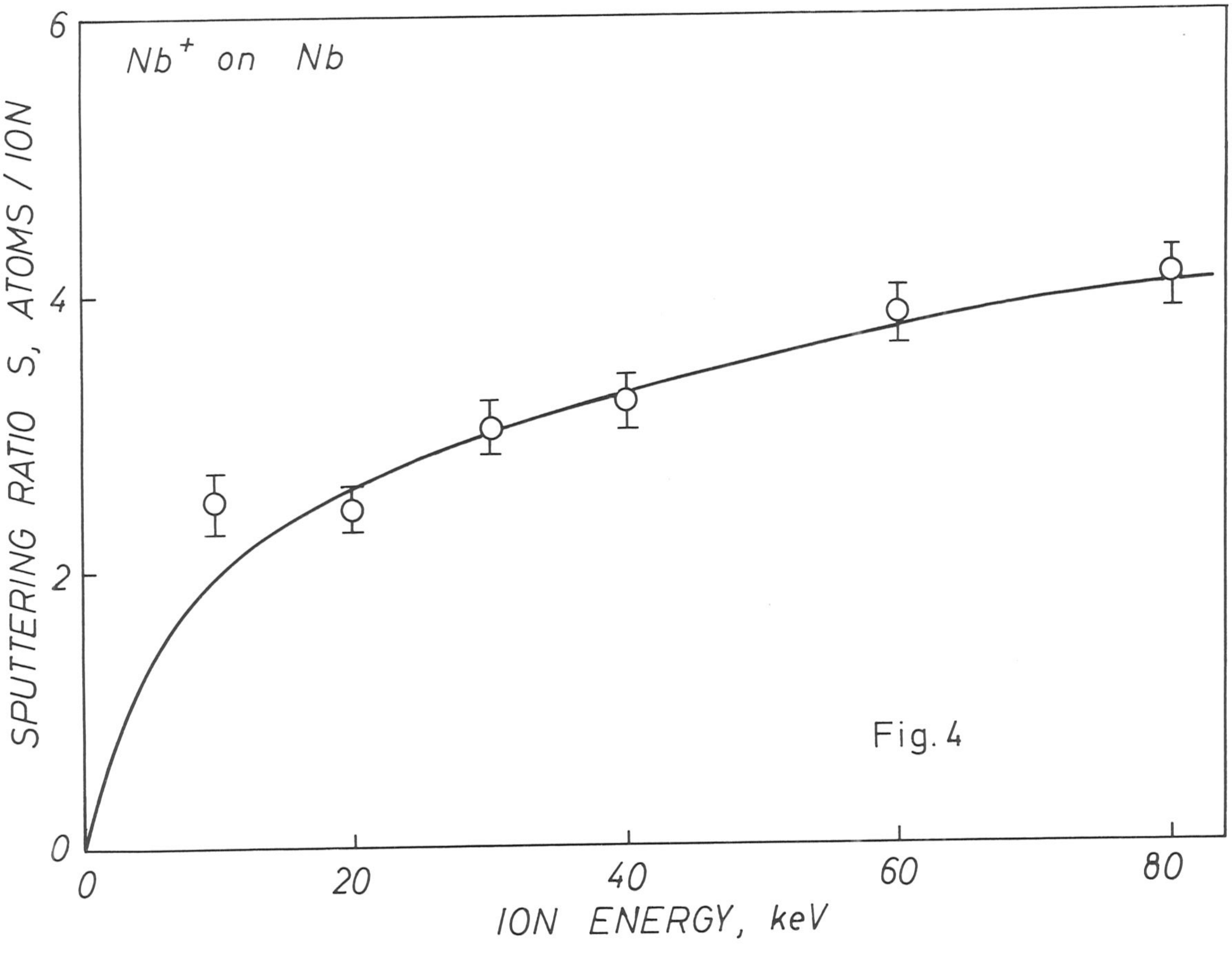


Fig.2 Schematic of indirect method of measuring sputtering ratio within calutron unit.



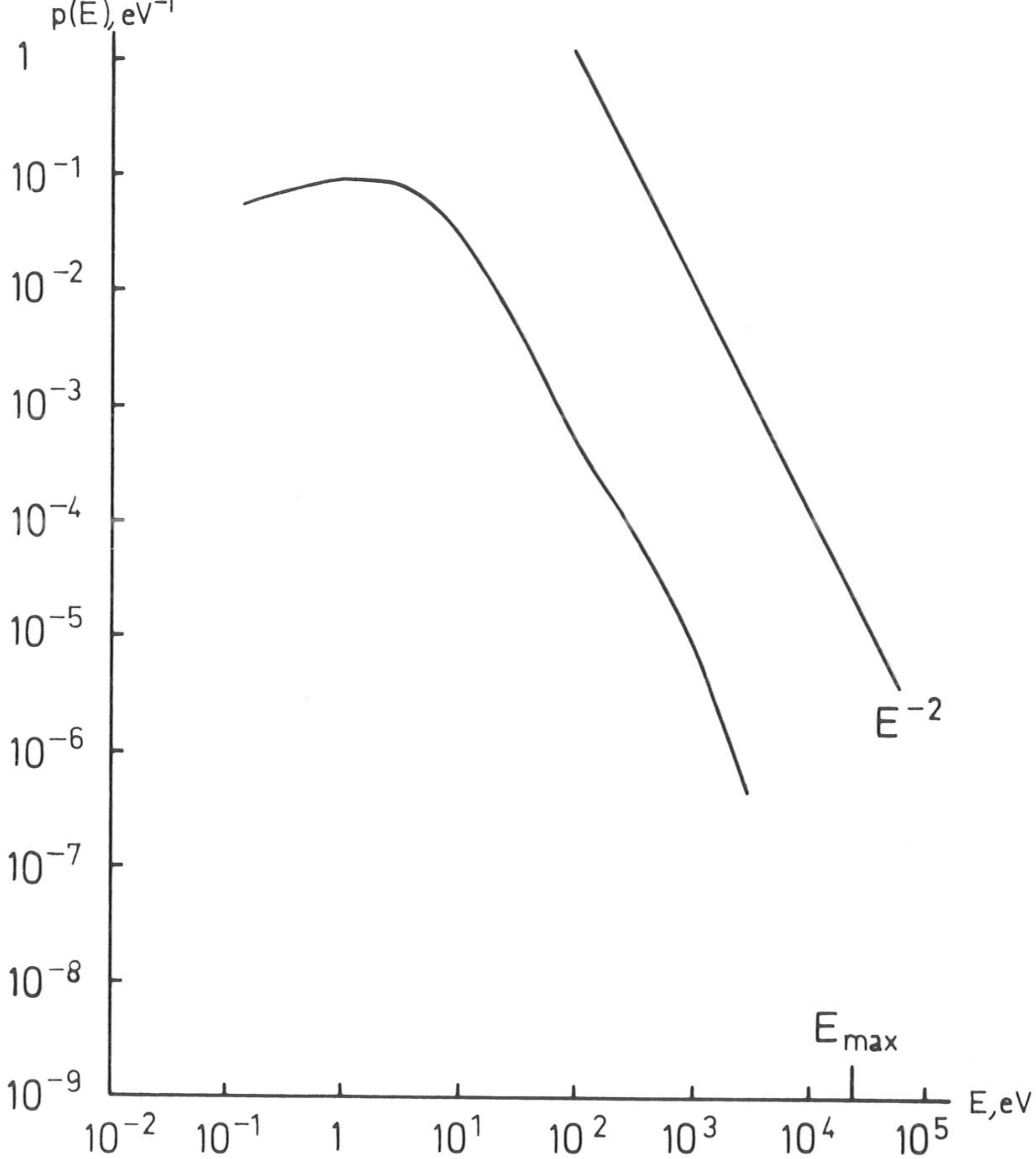
D+ on Nb
SPUTTERING RATIO S, ATOMS/ION
0.03
0.02
0.01
0
0
20
40
60
ION ENERGY, keV
(a)
(b)
(c)

Fig. 3



6
4
2
0
Nb$^+$ on Nb
SPUTTERING RATIO S, ATOMS / ION
0
20
40
60
80
ION ENERGY, keV

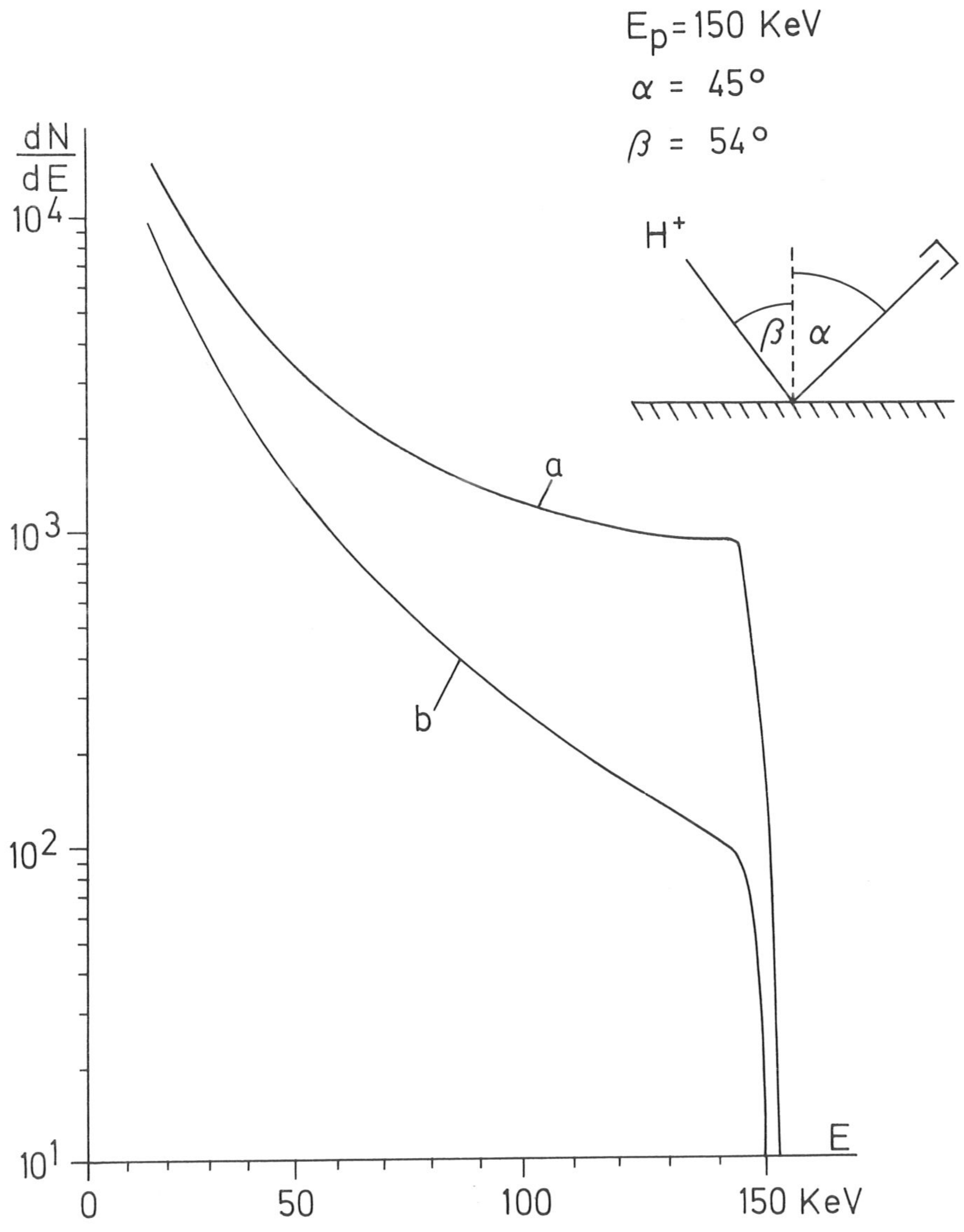
Fig. 4



Energieverteilung des abgestäubten Au bei Beschuß mit 41 KeV Ar^+

[M.W. THOMPSON, Phil. Mag. 18, 377 (1968)]

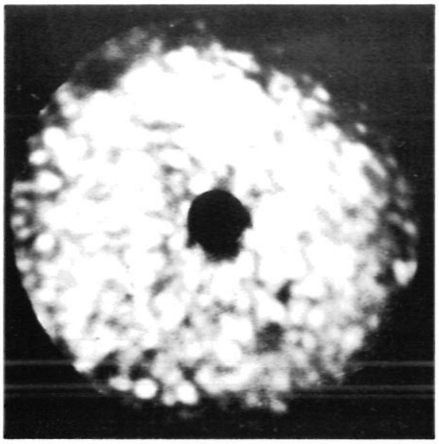
Fig. 5



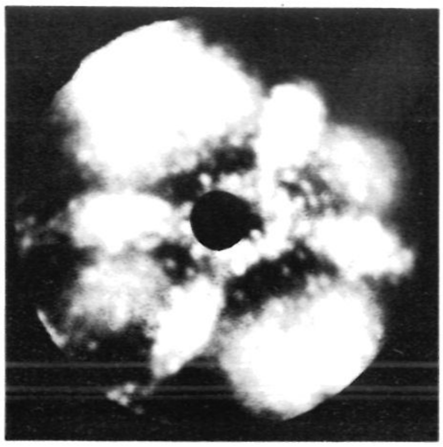
$E_p = 150$ KeV
$\alpha = 45°$
$\beta = 54°$
H⁺
β
α
dN/dE
10^4
10^3
10^2
10^1
a
b
E
0
50
100
150 KeV

Fig. 6

$2{,}5\cdot10^{15}/cm^2$ of 2KeV Ar^+ — Nb at different temperatures

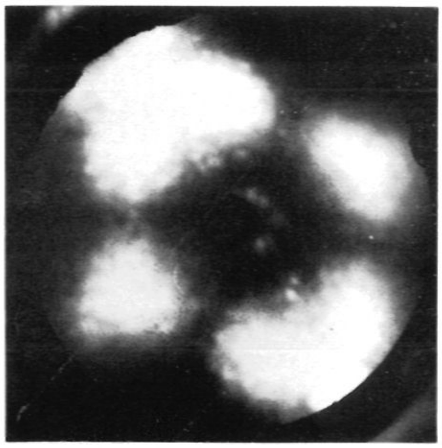


100° K

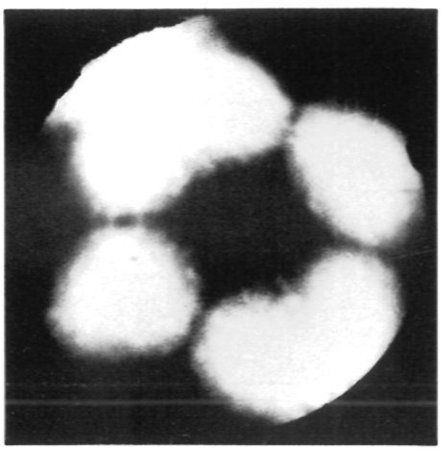


450°K

560°K

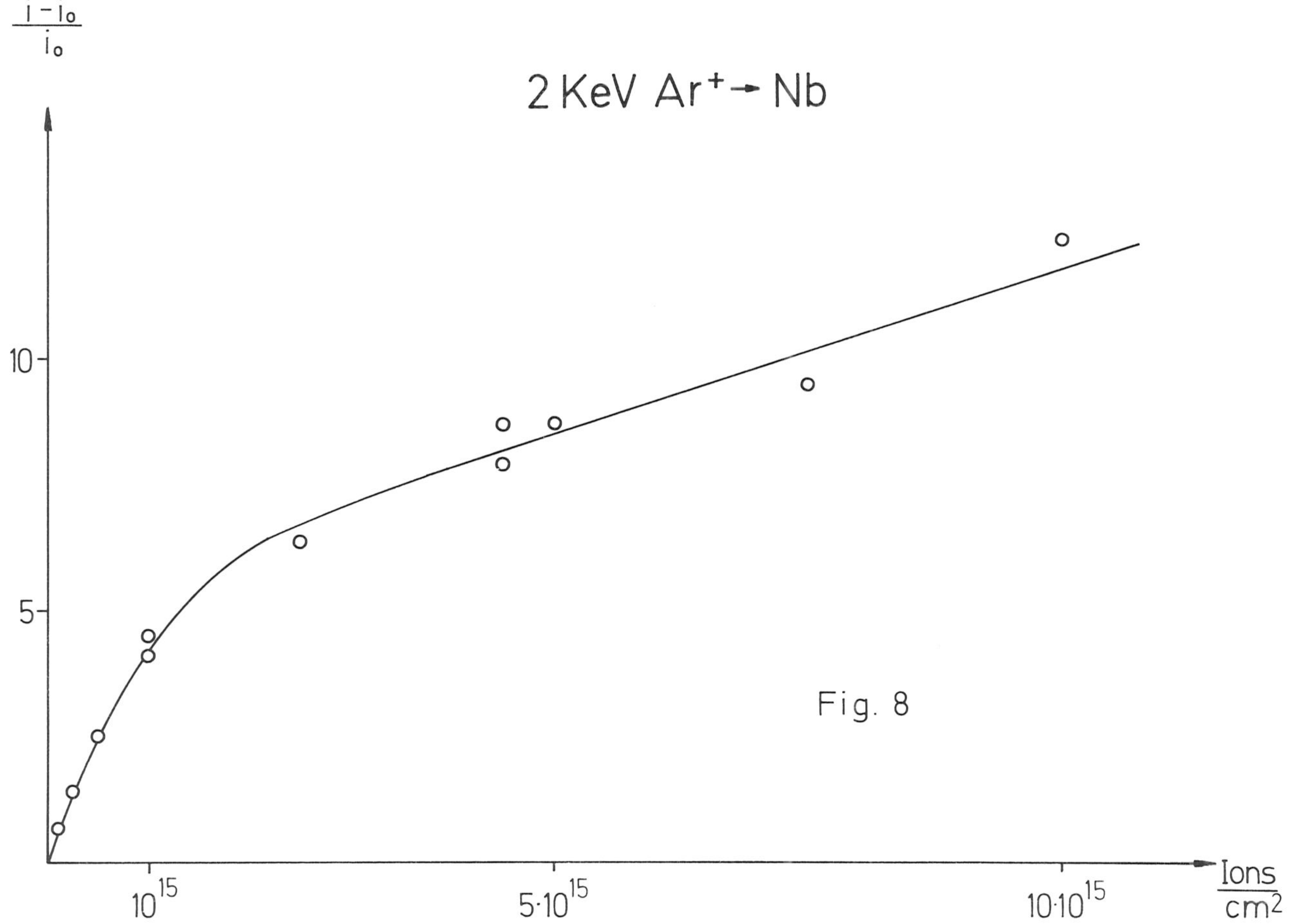


670°K



780°K

Fig. 7



$\frac{i - i_0}{i_0}$
2 KeV $Ar^+ \rightarrow Nb$
10
5
10^{15}
$5 \cdot 10^{15}$
$10 \cdot 10^{15}$
$\frac{Ions}{cm^2}$

Fig. 8

SPUTTERING OF NITROGEN WITH Ar^+

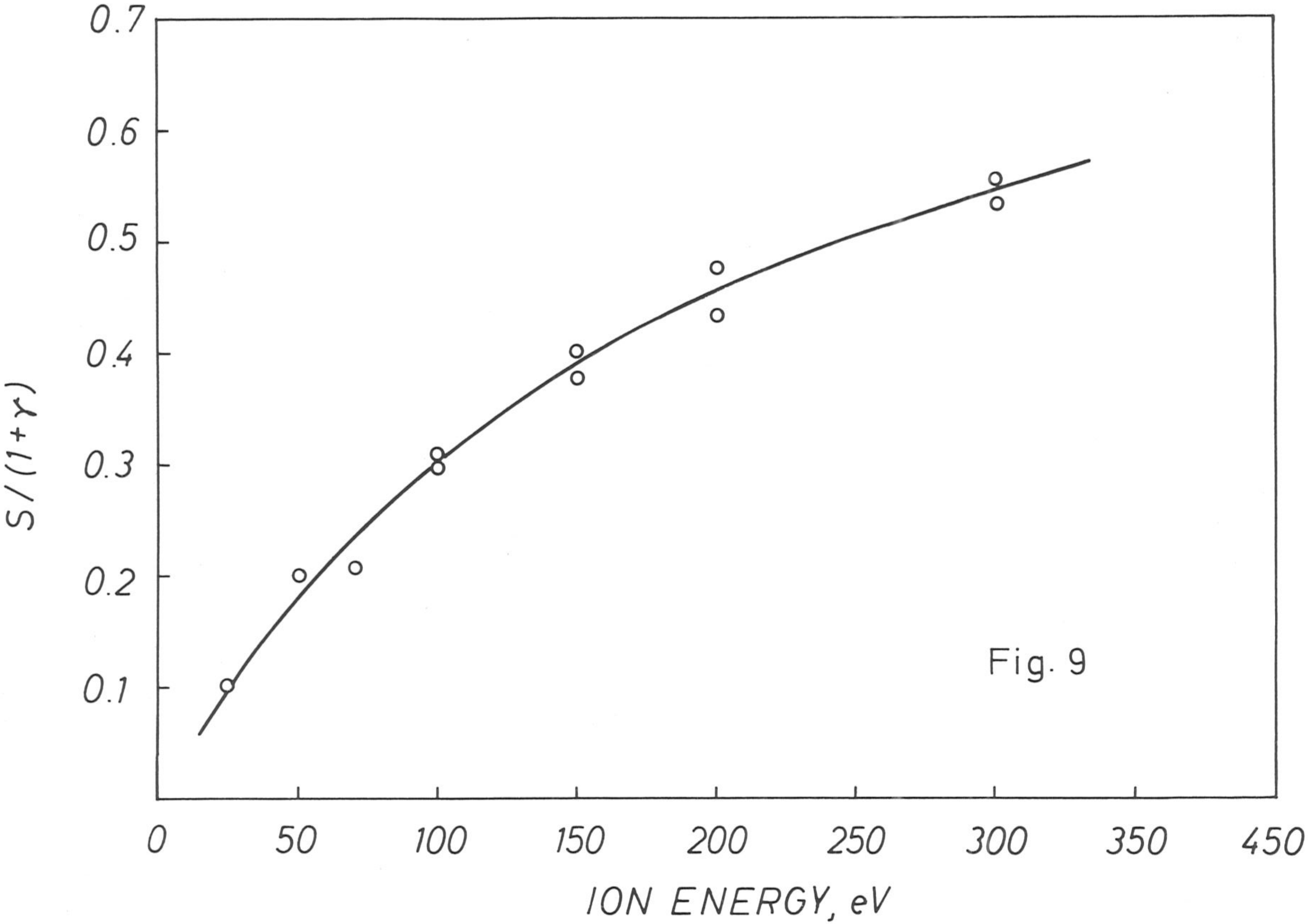


Fig. 9

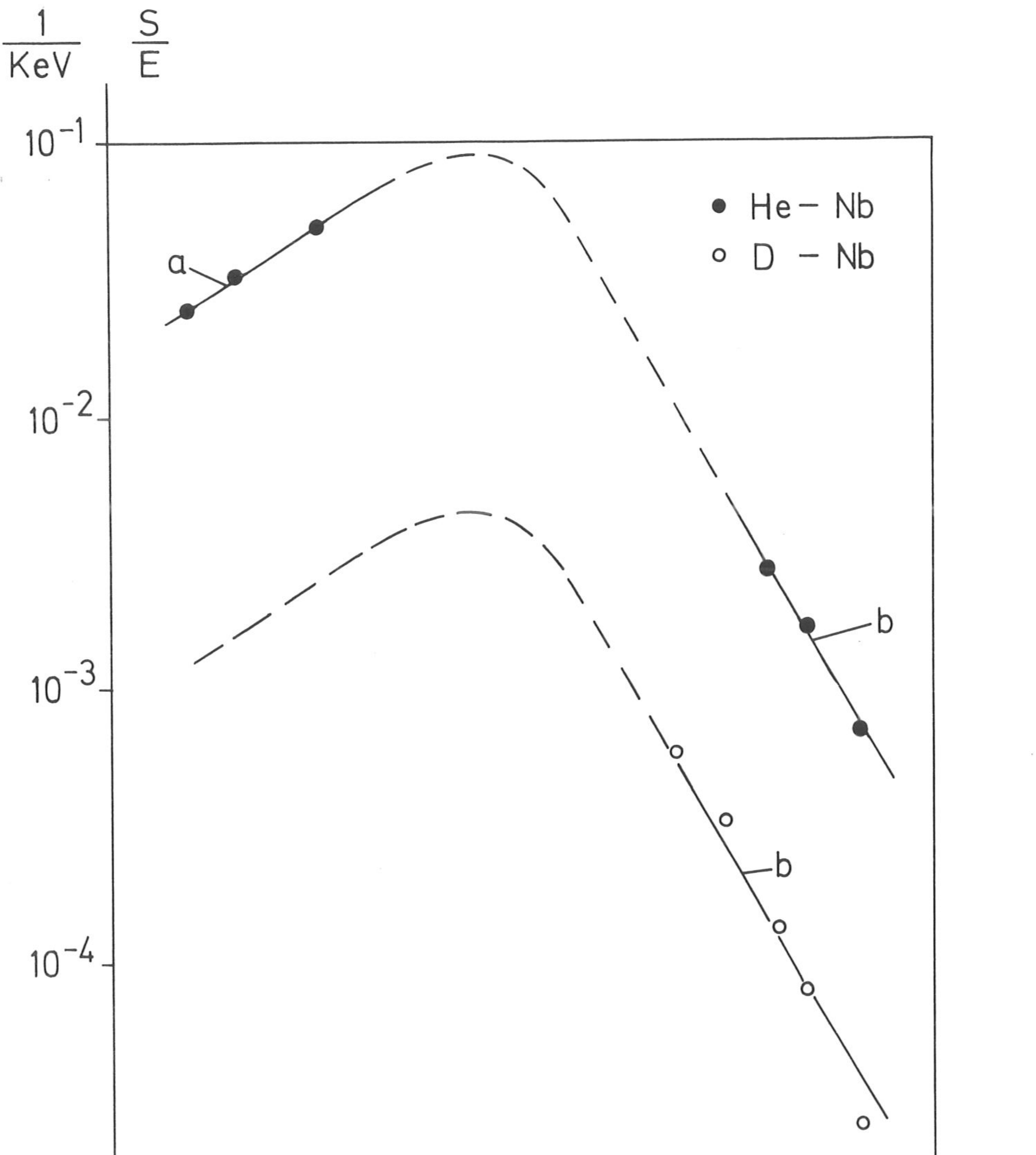


Fig. 10