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PARTICLE-IMPACT INDUCED ELECTRON EJECTION FROM SURFACES

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SUMMARY

We seek to consolidate data on particle induced electron emission from surfaces into a predictive algorithm, useful for modelling plasma-surface interactions in fusion devices. The available data base is found to be fragmentary with very limited coverage of light particle (H, D, He, atoms and ions) impact on metals in the energy regime from zero to a few keV. Standard theoretical techniques suggest that particle induced electron emission scales with electronic stopping power. Standard tabulations of such stopping powers are found to be quite misleading at low energies (E < 10 keV/amu)

On a purely empirical basis we propose a simple correction term which, in association with tabulated stopping powers, permits a representation of electron emission. This is found to provide a satisfactory model for gold targets which is the sole case for which there is good low energy data.

In Appendix I we present parameters for modelling the cases of D^+ impact on candidate plasma facing materials Be, C and W as well as the benchmark case of Au.

In Appendix II the coefficients for reflection, re-emission, sputtering and electron emission are presented graphically and in tabular form for D^+ impact on Be, C, Au and W at energies from zero to 10 keV. Coefficients are calculated from predictive algorithms.

A. INTRODUCTION

We review the various mechanisms whereby electrons might be ejected from plasma facing component surfaces by impact of heavy particles or by impact of (primary) electrons. For the present purposes it is convenient to divide the subject into three categories.

(a) Electron emission induced by light particle impact; hydrogen and helium atoms and ions representing fuel and ash.
(b) Electron emission induced by heavy multiply ionized particles representing impurities from the plasma core.
(c) Secondary electron emission due to primary electron impact representing electrons emerging from the sheath.

The parameter of interest is the electron emission coefficient; total number of electrons ejected for each particle (electron, ion or neutral) incident. This coefficient varies with incident angle and energy; it may be expressed differentially in energy and angle of the emergent electrons For the present purposes we restrict ourselves to target materials which are conductors, polycrystalline, and candidates for plasma facing components. Incident particle energies range from zero to 10s of keV; higher energies are not important for a fusion device.

Much of the current research activity in the field of electron emission involves detailed studies of energy and angular distribution of electrons ejected from single crystal materials. The objective is the elucidation of the structure of the material. This important field is not covered in the present review.

Electron ejection occurs through two general processes, kinetic and potential emission

Kinetic emission relates to the transfer of projectile kinetic energy to an electron in the target through a collision. In many respects this is similar to ionization or excitation in a gas phase collision. Some of the excited electrons migrate to the surface and if of sufficient energy to overcome the potential barrier will escape and contribute to the flux of ejected electrons

The mechanism involves collisional excitation, transport to the surface, and penetration through the potential barrier. The requirement of sufficient energy to penetrate the barrier will result in some minimum projectile threshold energy below which kinetic emission will not occur. The energy losses in the transport process will limit the depth from which ejection occurs; this will typically be tens of Angstroms. The initial excitation mechanism is the loss of kinetic energy from the projectile to electrons of the target and is expected to be intimately related to electronic stopping power The coefficient itself has a maximum value of 1 to 5 for particles on metals and about unity for electrons on metals

Potential emission occurs when the incident particle has potential energy; that is to say the particle is an ion (or less importantly an excited atom). As the surface is approached a target electron tunnels into a vacancy, a second electron is ejected by the Auger process and may, if it has sufficient energy, emerge from the surface into vacuum For multiply charged heavy particles with very high potential energy there may be transfer of many electrons to the projectile followed by a complex "peeling off" of outer electrons leading to a very large ejection coefficient. Potential ejection occurs independently of kinetic energy There is therefore no threshold. As impact velocity increases, interaction time decreases, and potential ejection will decrease Potential ejection will depend on the electronic structure of the projectile and of the target Quite clearly potential ejection will not occur for electron or netural particle impact Typical ejection coefficients for proton and helium ion impact are of the order a few electrons for ten to a hundred particles incident; for multiply ionized projectiles the coefficients can be many tens of electrons per particle incident

Potential emission occurs immediately before the projectile eneters the surface and will be related to surface electronic band structure Kinetic emission occurs after the projectile enters the surface, due to energy losses during transport those electrons which escape have emanated from a region only 10s of Angstroms from the surface and they must surmount the potential barrier at the surface in order to escape Thus both mechanisms are very surface sensitive. Experimental observation will be much influenced by surface topography, impurities, and past sample history An ideal (i.e. reproducible) experiment is performed on an optically flat, atomically clean, pure polycrystalline surface These are not conditions anticipated at the

limiter of a fusion device which is likely to be rough, damaged, and coated with deposits

The electrons ejected by the two separate mechanisms of potential and kinetic emission cannot be separately distinguished except perhaps through detailed analysis of their energy distributions. Thus for a fusion device related situation it is the sum of the two processes which is important. For a review of phenomena occuring at a plasma facing component it is convenient to divide the discussion into the three categories introduced at the start of this section

First we consider (Section B) impact of light ions, H^+ and He^+ (and their atoms) At the lowest energies, for ion impact, there is only potential emission with a coefficient much less than unity. This remains constant until the threshold energy for kinetic emission is reached, generally at a few 100s of eV/amu, whereupon total coefficient rises, maximising in the region of 100 keV/amu and then declining The energy dependence is observed to closely mirror the electronic stopping power Except below and close to threshold the kinetic emission dominates and potential emission can often be neglected. Neutral atom impact gives only kinetic emission, starting with the distinct energy threshold and thereafter behaving in a similar fashion to the ion induced emission There is a signficant data base for this kind of process but generally at impact energies above a few keV and therefore often higher than the particle temperatures expected at a limiter surface

Multiply charged heavy ions (Section C) have large emissions dominated by the potential process A general rule of thumb is that for every 80 to 100 eV of potential energy, one electron is ejected Coefficients may decline as energy is increased (and interaction time decreased) Again there is a theshold for onset of kinetic emission generally at a few 100s of eV/amu, beyond which the emission coefficient is the sum of both processes This subject is a comparatively recent and active research field. Emphasis is on understanding the process rather than tabulating coefficients and on the study of cases where the projectile has the very highest potential energy (i e heavy particles in very high states of ionization). There is little or no information on species which are likely to be impurities in a plasma and at best one can only interpolate from experiments using rare gas ions

Finally there is ejection by electron impact (Section D), a purely kinetic process There will possibly be a threshold but since both projectile and target are electrons that threshold is probably the surface work function Coefficients maximise in the region of one keV impact energy and have values at the maximum of around unity There is a considerable amount of past research in the field driven by design of electron multiplier devices and vacuum tubes Current activity in the field is very limited

B. PARTICLE INDUCED ELECTRON EMISSION

1. INTRODUCTION

We consider here emission from metals induced by H^+ and He^+ impact and by the impact of their atoms Ejection of electrons involves two mechanisms termed potential and kinetic Electrons ejected by both kinetic and potential mechanisms are of low energy and cannot be distinguished The models for each process are inherently different and it is the sum of the two processes which is of importance Recognising that there are two contributing processes we can write the total emission coefficient as

$$\gamma = \gamma_p + \gamma_k \qquad (1)$$

where γ_p is the potential emission coefficient and γ_k is the kinetic emission coefficient An example of the behaviour for H^+ on a gold target is given on Fig 1 drawn from the experimental data by Lakits et al [La90i] and by Baragiola et al , [Ba79] At lowest energy the coefficient is independent of energy and small at 0 02, this is the potential emission At about 300 eV the kinetic process commences with a distinct threshold, coefficient rises rapidly At energies above the threshold the coefficient is the sum of the kinetic and potential processes, the potential component being constant eventually becomes an insignificant contribution The corresponding behaviour for He^+ on Au is shown on Fig 3 The potential emission here is higher, the threshold for kinetic emission occurs at 1 2 keV or 0 3 keV/amu, the same value as for H^+ The total emission coefficient rises with incidence energy to peak in the region of a few hundreds of keV/amu

In Table I we list the main sources of experimental information There is only a limited body of data available with most work having been concentrated on the noble metals and at high incidence energies. The body of information related to impact in the 1 to 1000 ev/amu energy region, encompassing the potential emission, kinetic threshold and near threshold energy dependence of kinetic emission, is almost entirely limited to a single study by Lakits et al [La90i, La90ii] for a gold target.

The underlying understanding of the two mechanisms and the formulations which might be used to represent them will be considered first followed by a discussion of the available data sets and the algebraic representation of the coefficients for scaling purposes.

2. POTENTIAL EMISSION

Light ion potential ejection (as well as potential ejection by singly and doubly charged heavy particles) proceeds by an Auger transition with one electron being captured by the projectile and a second target electron being ejected. An obvious requirement is that the projectile ionization potential exceeds twice the material work function.

The probability of an Auger transition changes with distance between projectile and surface, and is related to the wave functions of the electrons involved. The probability that an electron excited by the Auger process will be ejected into vacuum is related to the angular distributions of those electrons and to reflection at the surface barrier. Kishinevsky [Ki73] has modelled the potential emission mechanism assuming a jellium band structure for the target material to provide an estimate of the emission coefficient given by

$$\gamma_p = \frac{0.2}{E_F} (0.8 E_i - 2\phi) \qquad (2)$$

here ϕ is the work function, E_F the Fermi energy of the material and E_i the ionization energy of the incident particle The equation is said to be valid in the range $3\phi<E_i<2(E_F + \phi)$ and for other conditions needs to be modified. This is at best a rough estimate and for a practical case the emission will be strongly influenced by the details of the number density of occupied states close to the Fermi level. Baragiola et al.,[Ba79ii] have collected a number of experimental

observations for singly charged rare gas ions on various metals and found that the alternative equation (with E_i and ϕ in eV)

$$\gamma_p = 0.032\ (0.78E_i - 2\phi) \qquad \textbf{(2b)}$$

fits the data somewhat better than the Kishinevsky formula of Eq (2) Both formulae show a linear dependence on E_i and on ϕ. Eq (2) shows a dependence on Fermi energy, but since this is approximately 5 eV for most materials it is not innapropriate to replace it with a constant as in Eq (2b) Either Eq (2) or (2b) could be used for purposes of estimation.

The work of Lakits et al., [La90i] for H^+ and He^+ impact on Au shown in Figs 1 and 2 gives a clear measure of γ_p from studies below the kinetic threshold For H^+ the experimental value is 0.02 compared with a prediction from Eq (2) of 0.019. For He^+ experiment gives 0.15 and Eq (2) gives 0.27. The agreement for H^+ impact seems satisfactory and that for He^+ unsatisfactory. One may also draw some information from the work of Baragiola et al [Ba79] for He^+ impact on a variety of metals just above the apparent kinetic threshold Measured coefficients, which include not only γ_p but also a small γ_k contribution, are lower than predictions of γ_p by as much as a factor of two

Experimental measurements of γ_p for H^+ and He^+ are almost non-existent. Predictions are sometimes performed by Eq. (2) but there is little test of its validity and for He^+ impact on gold it appears to predict values twice those observed

Neutral atoms in their ground state will obviously not exhibit potential emission, their potential emission coefficient is zero D^+ and T^+ will have the same coefficients as for H^+ since the electronic structure is the same Excited atoms may exhibit potential emission, there is little information on the matter and it will not be pursued here.

3. KINETIC EMISSION

(a) A General Theoretical Model of Kinetic Emission

Two approaches to the theoretical understanding can be recognised and are well described in the review of Schou [Sc88]. The semi-empirical approach is to consider the contributing processes of excitation, transport and barrier penetration as three separate mechanisms. There are also transport theories based on concepts borrowed from neutron transport theory. Much of the theoretical work is driven by the experimental observation that kinetic electron emission is proportional to electronic stopping power. The theories are often designed to confirm this rather than to evaluate electron emission coefficients from first principles. To illustrate the features of the problem and the broad assumptions made in its solution we shall briefly lay out the approach of the semi-empirical model following the descriptions of Schou [Sc88].

Let the function

$$\frac{1}{4\pi} f\,(E(x), E_0)\; dE_0\; d\Omega_0 \qquad (3)$$

be the number of excited electrons with energies Eo to Eo + dEo and directions Ω_0 to $\Omega_0 + d\Omega_0$ liberated by a primary particle with instantaneous energy E(x) in the depth interval x to x + dx. This description already involves an assumption of isotropy (which is not fully justified) The electrons are assumed to have a probability

$$\exp\left(-\frac{x}{\lambda Cos\,\Theta_0}\right) \qquad (4)$$

of arriving at the surface along a straight line trajectory from the point of excitation. Θ_0 is the angle between the electron path towards the surface and the direction and the original projectile direction into the solid. We have at this point tacitly restricted ourselves to projectiles normally incident on the surface. Combining equations (3) and (4) one can write the distribution in angles and directions of electrons arriving at the surface

$$J(E_0, \Omega_0)\ dE_0\ d\Omega_0 = \frac{1}{4\pi}\ dE_0\ d\Omega_0 \int_0^{E_{MAX}} dx\ f(E(x), E_0)\ \exp\left(-\frac{x}{\lambda(E_0)\ Cos\ \Theta}\right) \quad (5)$$

In principle one might attempt to evaluate each of the parameters and perform the integration. But to do this in a manner which gives some general result it is necessary to make further simplifying assumptions. First one argues that the escape zone is close to the surface (a few tens of angstroms) and the energy variation of the projectile over this distance is small; then E(x) can be replaced with the energy at impact on the surface E, and no longer varying in depth. It is further assumed that the majority of the electrons are at low energies so that the integration limit may be taken to infinity ($E_{MAX} = \infty$). This leads to

$$J(E_0,\ \Omega_0)\ dE_0\ d\Omega_0 = \frac{1}{4\pi}\ f(E, E_0)\ \lambda(E_0)\ Cos\ \Theta_0\ dE_0\ d\Omega_0 \quad (6)$$

Transmission through the barrier of height U is handled in a completely classical manner to relate the energy E_0 and angle Θ_0 of incidence on the surface from the material side to the energy E_1 and angle of emergence Θ_1 on the vacuum side (angles measured from the surface normal) Conservation of momentum at the interface

$$E_0\ Sine^2\ \Theta_0 = E_1\ Sine^2\ \Theta_1 \quad (7)$$

and conservation of energy

$$E_0 = E_1 + U \quad (8)$$

give the relation

$$E_0\ Cos^2\ \Theta_0 = E_1\ Cos^2\ \Theta_1 + U \quad (9)$$

Obviously the range of emergence angles Θ_1 is from zero to $\frac{\pi}{2}$ which limits the range of incidence angles (from the materials side) which will give rise to emergent electrons Integrating over the range of emergent angles one arrives at the distribution of emitted electrons

$$\frac{d\gamma(E,\ E_1)}{dE_1}\ dE_1 = \frac{1}{4}\ (1-\frac{U}{E_0})\ \lambda(E_0)\ f(E,E_0)\,dE_0 \qquad (10)$$

where for convenience we have kept the variable on the right hand side as E_0, the energy of the electron inside the material. The coefficient for kinetic ejection could now be evaluated by integrating Eq (10) over all energies inside the surface from U (the minmum electron energy required to surmount the barrier) to E_{MAX} (the maximum energy that can be collisionally transfered from the projectile to the target electron). Once again we cannot proceed without severe simplifying assumptions One assumes first that lambda $\lambda(E_0)$ is independent of the electron's energy (which must be incorrect). One then suggests that f (E, E_0), the function describing electron excitation, can be related to electronic stopping in the form

$$\int_U^{E_{MAX}} f(E,E_0)\ dE_0 = \frac{C_0}{W}\ \left|\frac{dE}{dx}\right|_e \qquad (11)$$

where W is the average energy required to produce an electron ion pair and c_0 is some constant Then the integral of Eq (10) over all internal energies could be written

$$\gamma_k(E) = \frac{1}{4}\ \lambda\ \frac{C_0}{W}\ \left|\frac{dE}{dn}\right|_e \frac{\int_U^{E_{MAX}}(1-\frac{U}{E_0})\ f(E,E_0)\ dE_0}{\int_U^{E_{MAX}} f(E,E_0)\,dE_0} \qquad (12)$$

It is then further assumed that the ratio of the two integrals will be independent of projectile energy and related only to the nature of the target and projectile so that it may be replaced by a constant. Collecting constants we arrive at

$$\gamma_k(E) = C_1\frac{\lambda}{W}\ S_e(E) \qquad (13)$$

where we have chosen to replace electronic stopping by the more convenient form S_e(E).

As Schou [Sc88] indicates this derivation is of quite doubtful validity It is hardly worth while examining in detail all the various assumptions. But the equation is very attractive in having factored the problem into the three component which we expect to be important There is the energy collisionally transfered to electrons, represented by electronic stopping and

average energy per ion pair There is the transport to the surface represented by the exponential decay length λ. There is the transmission through the barrier included in the constant c_1 λ c_1 and W are all properties of the particle-target combination and energy independent; the whole energy dependence is embodied in the electronic stopping power Thus we can further simplify matters to write

$$\gamma_k(E) = \Lambda S_e(E) \qquad (14)$$

where Λ is a constant for the target projectile combination This form has the enormously attractive feature that it actually represents experimental observations over quite broad energy ranges and for a variety of particle target combinations

Much of the relevant research in this field has been devoted to testing the validity of Eq (14) and evaluating the constant Λ for various situations Eq (14) is potentially attractive for modelling of secondary emission in plasma related situations Electronic stopping is generally thought to be a well know quantity, is available from standard numerical tabulations, and has been expressed as a function of energy in algebraic form. If Λ could be evaluated, perhaps experimentally at a single energy, then there is a very simple way of expressing kinetic electron ejection Our review of (light) particle induced electron emission coefficients will be built around examining the utility of Eq (14)

(b) A-priori Calculations

Kaneko [Ka92] has performed a calculation of kinetic electron emission from first principles including the excitation of the electrons, their transport to the surface and transmission through the surface barrier Each of these mechanisms should be included in an understanding or modelling of behaviour The results are in rather good agreement with the observations of Lakits et al [La90i, and La90ii] in the near threshold region for the case of H^+ on Au Schou [Sc88] has performed detailed calculations for H^+ on Al at moderate energies using a transport theory; again there is adequate agreement with experiment. Unfortunately the

work of Kaneko [92] and of Schou [Sc88] does not provide general formulations which might be used for interpolation and extrapolation for other cases. The proportionality to stopping power embodied in Eq (14) remains the sole formulation which offers an approach to a general modelling of kinetic emission.

(c) Testing of the General Theoretical Model

Strictly speaking the general formulation giving rise to Eq (14) has yet a further deficiency in that it neglects electron excitations caused by recoiling target nuclei. This deficiency could be accomodated by introducing a term $S_e^r(E)$ to represent excitation by recoils in the format of a stopping power so that Eq (14) is modified to

$$\gamma_k = \Lambda \, [S_e(E) + S_e^r(E)] \qquad (15)$$

This recoil contribution is only significant for heavy particle impact. It has been examined for 10 to 400 keV rare gas ion impact on Cu and Al by Holmen and Svensson [Hc81] [Sv81]. The test is quite successful in the sense that the constant Λ is indeed energy independent.

For the case of light projectile, H^+, and He^+, the primary interest here, target recoils are inefficient and the recoil contribution to electron excitation may be neglected so that the kinetic emission coefficient can be written in the original form

$$\gamma_K = \Lambda \, S_e(E) \qquad (14)$$

where S_e is the electronic stopping of the projectile in the target. This equation could provide a valuable tool for modelling coefficients over a wide range of energies and species. In principle electronic stopping is obtained from tables or standard algebraic formulations, γ_k is measured at one energy to establish the constant of proportionality Λ, and then ion induced electron emission coefficient modelled as the product of the empirical Λ and the standard expressions for stopping power We shall examine this situation separately for proton impact and then for He^+ impact.

i) Proton impact

The first step is to test validity of Eq (14) by evaluating the ratio of γ_k to tabulated electronic stoppping S_e The γ_k is an experimentally measured quantity The electronic stopping is conventionally written in units of eV/A and taken from tabulations such as that due to Anderson and Ziegler [An77] For energies above 10 keV/amu the equation is valid (see for example [Ba79, Ho81, Ha88]), Λ is independent of energy and values lie in a surprising narrow range of 0.08--0.12 A/eV for most metals. But at lower energies it appears to fail, an observation sometimes ascribed to the onset of an energy dependence in Λ. As an example we show on Fig 1 an estimate of γ_k based on Eq (14) with S_e from the tabular values [An77] and Λ obtained by normalization to coefficients at high energies (E> 30 keV/amu) where Eq (14) is expected to be valid Clearly at low energies the equation gives a serious over-estimate

Tabulated values of stopping powers at low energies are in fact extrapolations from high energy behaviour on the assumption that

$$S_e(E) = A\ E^{1/2} \qquad (16)$$

The few available experiments at low energies have shown that this relationship is not valid below 10 keV/amu [Bl80, Bl82, Ho70, Go91], the stopping power drops more rapidly For the case of gold it is possible to take the experimental values of S_e [Bl80, Bl82] again assume a constant Λ and use Eq (14) to predict γ_k from experimental rather than tabulated S_e This is also shown on Fig 1 and now the predicted coefficient is rather close to experiment. Blume et al [Bl82] recognise a number of experimental inadequacies in the measurement of S_e which might cause the quoted values to be too low, if a correction were warranted this would move the predictions of Eq (14) into even closer agreement with experiment Unfortunately we cannot make such a test for other materials as there are no other cases where there are both low energy measurements of γ_k and also of S_e But there is general theoretical evidence [Se86] that S_e does not extrapolate to low energies by Eq (16) and therefore that the tabulated values of S_e are incorrect Based on the single observation for gold we tentatively conclude that proportionality of γ_k to stopping power S_e is valid to low energies, but that tabulated stopping powers are incorrect

Even with correct stopping powers Eq (14) does not yet accomodate the empirical observation that kinetic emission has a distinct threshold; this threshold is apparent at about 300 ev/amu on Fig 1 for H^+ on Au Threshold occurs because there must be a certain minimum energy transfered from the projectile to the electron in order for that electron to escape the potential barrier Baragiola et al [Ba79] estimate this on the basis that the projectile undergoes a head on collision with a target electron which is at the Fermi velocity v_F and that the transferred energy is equal to the surface work function. On that basis the minimum projectile velocity which will eject an electron is given by

$$V_{th} = \frac{V_F}{2}\left[\left(1+\frac{2\phi}{mV_P^2}\right)^{1/2} - 1\right] \qquad (17)$$

For gold Lakits et al [La90i] calculates the threshold energy to be 315 eV/amu. This is roughly in accord with the observations shown in Fig 1. We note however that Lakits et al [La90i] detect a small kinetic component below 315 eV/amu which they tentatively ascribe to promotion of outer shell electrons. Eq (17) successfully represents the location of threshold It is not clear how the concept of a threshold will modify the relationship of γ_k to electronic stopping power.

In summary, kinetic electron emission appears to be proportional to electronic stopping down to energies of the order a few keV/amu. However the values of electronic stopping given in standard tabulations are incorrect at low energies. Eq (14) does not accomodate the notion of a distinct threshold and will need modification

ii) He^+ impact

For He^+ impact the ratio of measured kinetic emission coefficient to tabulated electronic stopping power at high impact energies (50-500 keV) is not always observed to be constant ; it is constant for Cu and Al [Ho81, Sv81] but varies with energy for Ag [Ha80]. It is not clear whether this energy dependence of the ratio is due to inadequacies in the tabulated values of stopping power or due to the failure of the proportionality involved in Eq (14). For the low energy situation of interest here we have only one set of measurements close to the threshold region to examine; again this is for gold, is shown in Fig 3, and comes from work by Lakits et al [La90i] and of Baragiola et al [Ba79]. The situation is the same as for proton impact.

Use of Eq (14) with tabulated values of electronic stoppping is inconsistent with experiment Use of Eq (14) with experimentally measured stopping powers is in better agreement with measured coefficients but the equation does not accomodate the threshold.

4. THRESHOLD FUNCTION

For impact energies above about 10 keV/amu the proportionality of kinetic emission to electronic stopping embodied in Eq (14) is well established, broadly tested and potentially valuable for modelling the coefficient. The whole of the energy dependence of the coefficient is embodied in the electronic stopping power and for this there are well established tabulations and algebraic representations Kinetic emission can therefore be modelled by taking the model for electronic stopping from a standard compendium (for example [An77], [Zi77]) and simply multiplying it by a single number obtained from experiment. But this simple procedure fails badly at energies below 10 keV/amu where the tabulated stoppping powers are wrong and where a threshold term needs to be included

There is no general theoretical basis which offers an alternative representation There is no general low energy representation of electronic stopping confirmed by experiment There is no general prediction of how the threshold modifies the proportionality term Λ. As a practical alternative approach we propose that kinetic emission be represented by

$$\gamma_K = \Lambda\, S_e(E) \left(1 - \frac{E_{th}}{E}\right)^2 \qquad (18)$$

The threshold energy E_{th} will be calculated from from Eq (6) The electronic stopping will be taken from the standard tabulations [An77] and Λ will be obtained by normalizing to experiment at a high energy (E > 10 keV/amu) Clearly the equation has the correct asymptotic dependence at high energies and gives the required distinct threshold The term $(1- E_{th}/E)^2$ represents a pragmatic correction to the asssumed constancy of Λ and a correction to the $E^{1/2}$ energy dependence of electronic stopping assumed in the tabulations of that quantity. No claim is made for a theoretical justification for the near threshold term. Evaluating Eq (18) on this basis we arrive at predicted values of kinetic emission coefficient which are plotted for

gold on figs 2 and 3. We observe remarkably good agreement with experiment suggesting that the proposed function does represent observations.

5. MODELLING ALGORITHM

For the purpose of modelling electron ejection by light particle (H^+ and He^+) impact on surfaces we propose that the emission coefficient be represented by

$$\gamma(E) = \gamma_p + \Lambda S_e(E)\, g\left(\frac{E_{th}}{E}\right) \qquad (19)$$

At energies $E < E_{th}$ the second term, kinetic emission, is dropped. The term $g(E_{th}/E)$ is a modification to accomodate near threshold behaviour; on a purely empirical basis we propose to adopt

$$g\left(\frac{E_{th}}{E}\right) = \left(1 - \frac{E_{th}}{E}\right)^2 \qquad (20)$$

For energies above 10 keV/amu this threshold term is negligible and can be replaced by unity.

i) Potential emission term γ_p

There is an inadequate data base for properly establishing γ_p In general the value is calculated by use of Eq (2) In Table II we list a few values from the literature. There is a single experimental measurement, for Au, which agrees with the prediction for H^+ impact but is half of prediction for He^+ impact.

The validity of Eq (2) requires further test against experiment and should be regarded as providing only an estimate

ii) Electronic stopping powers S_e

There are well established data bases of stopping powers We propose adoption of the set by Andersen and Ziegler [An77, Zi77] which separately list the electronic component of

stopping. Tabulated stopping powers should be expressed in the form of eV/A We recognise that the tabulated values of electronic stopping at low energies are likely to be incorrect and accomodate this by the near threshold correction term

iii) Multiplicative factor Λ

Λ has not been theoretically calculated and we must rely on experiment A proposed set of values is given as Table IV.

The value of Λ for proton impact is found from the application of Eq (14) to experimental data at impact energies above 10 keV/amu At this energy the potential emission coefficient is negligible compared with kinetic emission, the energy is far from threshold and Λ has been demonstrated to be independent of energy [Ba79, Ha88] Total emission γ is taken from experiment, electronic stopping is taken from the tabulations [An77] Values for Λ assessed in this fashion are shown in Table III The majority of the values come from analysis of data by Hippler [Hi88] at a single impact energy of 100 keV In a few cases there are a number of studies spread over a range of energies and one can check reproducibility of the results For example for H^+ on Cu there are the following values; 0.08 [Ba79], 0 09 [Ha80], 0 12 [Ro90] and 0 0771 [Ho81] The values due to Rothard et al ,[Ro90] are consistently high in all cases examined; we have chosen to reject them The remaining value agree within experimental accuracy and we quote, in Table II, the mean of the observations. Another example is for Al where there are the published values of 0.103 [Ba79], 0.11 [Ha80], 0.1 [Al80], 0.0995 [Sv81] and 0.40 [Ro90]. Again the results of Rothard et al , [Ro90] are inconsistent with the others and we choose to reject them. The remaining data agree well within experimental accuracy and we quote in Table III the mean

For He^+ impact the data base is far less extensive and there is evidence that Λ varies with energy for some target materials The reason for this variation is unclear For Al, Cu and W a constant value of Λ fits the data of Holmen and Svensson [Ho81] [Sv81] and of Baragiola et al [Ba79] We quote in Table III values for Al and Cu from the original publications [Ho81], [Sv81] where energies range from 30 to 400 keV; for W the value is our own fit to data that extend only to 40 keV [Ba 79]. For Au we quote the results of our own fit to the

detailed data of Lakits et al [La90i, La90ii] combined with the data of Baragiola et al [Ba79] which together extend from below threshold to 50 keV It is to be noted that for the few cases listed in Table III the value of Λ for He^+ impact differs from the value for H^+ only by 20% A reasonable estimate for materials not covered in Table III is to use the same value as for H^+.

iv) Threshold energy and the near threshold term

Threshold energy is estimated from Eq 6. The term $g(E_{th}/E)$ is to correct for the experimental observation that close to threshold the kinetic emission is not linearly related to the tabulated stopping power data. We have adopted a correction term shown in Eq (9). The term has no theoretical basis and is introduced as a purely empirical method for correcting known deficiencies in electronic stopping and for accomodating the notion of a distinct threshold. We have demonstrated on Figs 2 and 3 that it provides adequate agreement with detailed experiment for the case of a gold target. It agrees also with less detailed studies of H^+ and He^+ impact on targets of Li, Al, Cr, Cu and Ag performed by Baragiola et al [Ba79].

6. ISOTOPES AND NEUTRAL SPECIES

D^+ and T^+ exhibit the same electronic stopping power as equivelocity H^+ and their kinetic emission may be taken as the same as for equivelocity H^+. Potential emission will be the same as for H^+.

There are only limited studies of neutral particle impact. The potential emission will of course be zero In principle Kinetic emission should also be given by Eq (14). Experiments by Lakits et al., [La90ii] show γ for neutrals to be consistently below that for the corresponding ions. The ratios for a gold target are as follows

$$\frac{\gamma^0}{\gamma^+} = 0.83 \textit{ for hydrogen impact}$$

$$\frac{\gamma^0}{\gamma^+} = 0.9 \textit{ for helium impact.}$$

In the absence of any other information one might take these ratios as being of universal

applicability.

C. ELECTRON EMISSION BY MULTIPLY CHARGED IONS

1. INTRODUCTION

This is a subject of current active research where emphasis is on the very large emissions of electrons ejected by potential processes Coefficients as high as 250 electrons/ion have been recorded for the extreme case of low energy Th^{79+} impact on Au [Au93 ii]. For singly and doubly charged species the dominant potential ejection mechanism is Auger transitions and coefficients are small. For higher charge states the large emission coefficients are related to a complex group of mechanisms. These are not fully understood and we will only hint at the complexities involved.

A slow multiply charged ion X^{q+} ($q > 3$) approaching a surface will be accelerated by interactions with the image charge, speed increasing with decreased separation Simultaneously, image charge reduces the potential barrier seen by electrons, facilitating electron transfer The projectile-target system may be regarded as forming a transient excited complex. Electrons tunnel from the target into the higher (excited) levels of the projectile leading to partial neutralization As distance decreases further these excited levels are promoted into the vacuum contributing to a shower of stripped-off secondary electrons Continuing resonance neutralization and stripping, involving lower levels, occurs as the distance decreases and levels shift Auger transitions also contribute and become the dominant process once the projectile is inside the target itself These processes are unrelated to kinetic energy and will occur with a zero energy threshold There is however a slow decrease with increasing projectile energy as interaction time reduces and the opportunity for electron transitions decline Eventually as projectile velocities increase to exceed the threshold for kinetic emission (energies of about 100 eV/amu) that process will also contribute.

Theoretical treatment of the problem involves a modelling of all the various sequence of electron transfers as the projectile approaches the surface Such models are constructed on a case by case basis and at present lead to few generalities Experimental observations show

rather reliably that for charge states between 3 and 10 times ionized a good rule of thumb is that one electron is ejected for each 80 to 100 eV of potential energy [Ku93] It is also observed [Au93ii] that the decline of emission coefficient gamma with velocity v is roughly in accordance with

$$\gamma = \frac{Const}{\sqrt{v}} + \gamma_{\infty} \qquad (21)$$

As velocity increases the coefficient asymptotically approaches a constant value. The velocity related variation depends on charge and is small for the lower charge states

There are no published accounts of measurements directly related to a fusion scenario Some rough guidance can be achieved from the study of N^{q+} ($4 \le q \le 6$) Ne^{q+} ($5 \le q \le 10$) and Ar^{q+} ($5 \le q \le 16$) on Au by the group of Winter [Va95] [Ku93]. General reviews of current activity in the field are avaiable by the same group of authors [Au93i] [Au94].

At the present time the paucity of data in the field does not permit the assembly of a data base nor support an attempt to develop general predictive algorithms Further work on this subject should be delayed until there is evidence that the process may be important in fusion devices and that there is a data base sufficient in size to support an analysis.

2. RECOMMENDED DATA

For an ion X^{q+} with $3 \le q \le 10$ and having a kinetic energy in the range of a zero to a few hundred eV/amu it is recommended that the emission coefficient be calculated as one electron ejected for every 100 eV of internal potential energy (energy of ionization) of the incoming projectile. This is a surprisingly accurate rule of thumb consistent with all published observations It is reasonable to neglect variation with impact velocity.

For singly and doubly charged ions the potential emission can be estimated by Kishinevsky's formula given previously as Eq (2)

D. ELECTRON INDUCED ELECTRON EMISSION

1. INTRODUCTION

The flux of electrons emerging from a surface as a result of primary electron impact includes two components, the true secondaries collisionally ejected by a kinetic mechanism delta, and reflected primaries η,

$$\delta_e = \delta + \eta \qquad (22)$$

The two components can be distinguished only through their energy distributions; reflection is largely elastic and projectiles retain their incident energy while true secondary electrons emerge with a distribution of energy close to zero. We shall review the two mechanisms separately

2. REFLECTION

There is remarkably little activity in this field The only current interest relates to image formation in electron microscopes where the energies involved are much higher than are of interest to fusion In our earlier report [Th91] we listed the fragmentary data and there is nothing significant to add. It seems likely that most published information was taken under poor vacuum conditions so that the information is unreliable.

There is a rather large data set by Hungler and Kutchler [Hu79] covering energies from 3 keV to 50 keV At the lowest energy, 3 keV, the reflection coefficient varies with target nuclear charge Z roughly as

$$\eta = 0.150 \ln Z - 0.206 \quad , Z \geq 4 \qquad (23)$$

For higher energies Hunger and Kutchler [Hu79] indicate little energy variation for high Z targets and a small fall for low Z Our own previous analysis of low energy data [Th91] suggests that for most elements there is little variation of the coefficient with energy down to

the region of a few hundred eV. We suggest that Eq (22) can be used for estimates in the energy region 0.3 to 50 keV.

3. SECONDARY ELECTRON EMISSION

The kinetic process can be modelled on the same basis as proton induced electron emission. One develops the model just as in Section [B 3.a] and arrives once again at Eq (13) and (14). Reproducing Eq (14) to represent secondary electron emission

$$\delta = \Lambda \, S_e(E) \tag{24}$$

In this case the stopping power is that of the electrons of energy E, moving through a solid. The constant Λ is a property of the material, and includes the electron escape depth and the energy to produce an ion-electron pair. One might reasonably assume that Λ should be the same for electron impact as it was for protons.

In reality the situation is a little more complex. The arguments leading to Eq (24) relate to the primary electron's initial passage through the surface. If a primary electron is reflected back through the surface then there is a further opportunity to excite electrons Suszcynsky and Borovsky [Su91] estimate that as much as 50% of the total emission occurs at the exit passage of the reflected electrons. We might nevertheless retain Eq (24) as representative of yield A local density approximation calculation [Tu79] of low energy electron stopping in metals gave the following algebraic form

$$S_e(E) = C \, n_e^{-0.85} \, (E-E_F)^{2.4} \tag{25}$$

with E_F being Fermi energy and n_e electron density. Combining Eq (24) with Eq (25) we have the energy dependence of the coefficient and by single experimental measurement to fix a value of the constant one has a quantitative prediction of the energy dependent emission coefficient

There is however an even simpler algebraic representation of secondary electron emission deduced by Kollath [Ko56] on a purely empirical basis.

$$\frac{\sigma}{\delta_{MAX}} = (2.72)^2 \left(\frac{E}{E_{MAX}}\right) \exp-[2 \left(\frac{E}{E_{MAX}}\right)^2] \quad (26)$$

Here δ_{MAX} is the maximum yield and E_{MAX} is the energy at which that yield occurs. The simplicity of the equation is probably related to the fact that electron stopping varies little between materials. Past experimental studies have been analyzed to give the two constants in Eq (26) and those are often to be found in standard data handbooks [CR95] A small set of the published values are reproduced in Table IV

4. RECOMMENDED DATA

To estimate secondary electron emission it is recommended that Eq (23) be employed with coefficients from Table I or some other standard data handbook [CR95]. This is expected to be quite reliable.

If electron reflection is to be estimated then one is limited to Eq (2) with an assumption of no energy dependence. Reliability is uncertain and the equation is probably not valid at all for energies of electron impact below 300 eV

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Table I: Data Sources for H^+ and He^+ Induced Electron Emission

Reference	Projectile	Target	Energy
Lakits et al [La90i]	H^+, He^+	Au	0.1-10
Lakits et al [La90ii]	H^+, H^0, He^+	Au	1-16
Winter et al [Wi91]	H^+	Au	0 01-1 0
Baragiola et al [Ba79]	H^+, D^+, He^+	Li, Al, Cr, Cu, Ag, Au	2-50
Alonso et al [Al80]	H^+, D^+, He^+	Al	1 2-50
Ferror et al [Fe81]	H^+, D^+, He^+	Mo	0 7-60
Holmen et al [Ho81]	H^+, D^+, Cu^+	Cu	10-400
Svensson [Sv81]	H^+, D^+, Al^+	Al	10-350
Svensson [Sv82]	H^+	Al, Cu	10-400
Hasselkamp et al [Ha81]	H^+, He^+	Al, Cu, Ag, W, Au	80-1000
Hasselkamp et al [Ha73]	H^+, C^+	C	40-1000
Veje[Ve82]	H^+	Au	30-110
Hippler et al [Hi88]	H^+	Many	100
Zalm & Beckers [Za85]	H^+, He^+	Cu, Zn	5-20
Oda et al [Od92]	He^0	Ta	2-5
Zalm & Beckers [Za84]	H^+, He^+	Al, Ti, Ni, Cu, Zn, Mo, Ag, Au, Pb	5-20

Table II: Potential Ejection Coefficients γ_P for H^+ and He^+ Impact

Proj.	Target	Coeft γ_P	Theoretical or Experimental	Refc
H^+	Al	0.04	Th	[Sv81]
H^+	Cu	0.05	Th	[Ho81]
H^+	Au	0.019	Th	[La90]
H^+	Au	0.019	Ex	[La90]
He^+	Al	0 19	Th	[Sv81]
He^+	Cu	0.32	Th	[Ho81]
He^+	Au	0 27	Th	[La90]
He^+	Au	0.16	Ex	[La90]

Table III: Constants of Proportionality for Light Ion Impact. The materials dependent factor Λ in Eq. (14).

Target	Λ (eV/A^0)		Reference	
	H^+ impact	He^+ impact	H^+	He^+
Be	0.088		a	
C	0 113		b	
Mg	0.110		a	
Al	0.102	0 084	c	i
Si	0.075		a	
Ti	0 074		a	
Cr	0.068		d	
Mn	0.073		a	
Fe	0.074		a	
Co	0 085		a	
Ni	0 079		a	
Cu	0 085	0 071	e	i
Zn	0 109		a	
Ge	0 095		a	
Zr	0 069		a	
Nb	0 063		a	
Mo	0.065		a	
Ag	0 128		f	
Cd	0 100		a	
In	0 152		a	
Sn	0.138		a	
Sb	0 106		a	
Ta	0.061		a	
W	0 073	~ 0 08	g	j
Pt	0 095		a	
Au	0 12	0 16	h	h
Pb	0 127		a	

Table III Notes

(a) From a single data point at 100 keV by Hippler et al [Hi88]

(b) Average of data from Refs. [Hi88], [Ha83]

(c) Average of data from Refs. [Hi88], [Ba79], [Ha80], [Al80], [Sv81]

(d) Average of data from Refs. [Hi88], [Ba79]

(e) Average of data from Refs. [Bo79], [Ha80], [Ho81], [Hi88]

(f) Average of data from Refs. [Bo79], [Ha80], [Hi88]

(g) Average of data from Refs. [Hi88], [Ha80]

(h) By fit of model to data of Lakits et al [La90i] see Figs 2 & 3

(i) Fits by Holmen & Svennsson [Ho81, Sv81] et energies of 50-400 keV

(j) Rough estimate from data of Hasselkamp [Ha80]

Table IV: Maximum of the Secondary Electron Emission Yield, δ_{max}, and Projectile Energy at which it occurs, E_{max}, for Selected Elemental Metals and certain other Materials

Target	Z	δ_{max}	E_{max}	Refs
Be	4	0.5	200	[CR86]
C (graphite)	6	1.0	300	[CR86]
C (pocographite)	6	0 55	500	[Wo85]
Al	13	1.0	300	[CR86]
Ti	22	0 9	280	[CR86]
Fe	26	1.3	400	[CR86]
Ni	28	1.35	550	[CR86]
Mo	42	1 25	375	[CR86]
W	74	1 4	650	[CR86]
TiC		1 0	460	[Th70]
TaC		0 84	270	[Th70]
ZrC		1.25	340	[Th70]
TiN		0 95	350	[Pa79]
Stainless steel		1.22	400	[Ru82]

Data are for normal incidence For a more extensive listing, see Ref [CR95]

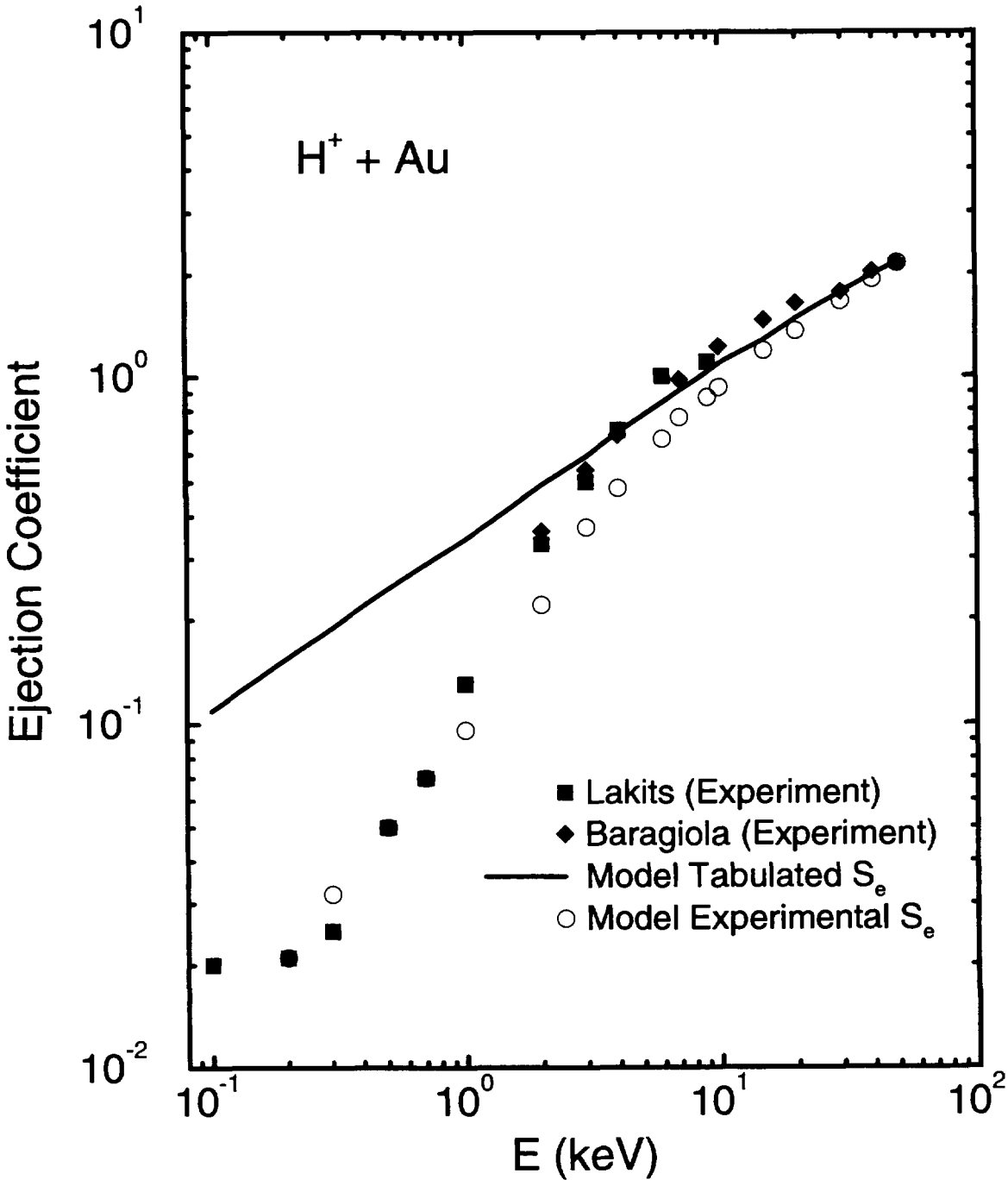

Figure. 1. Electron emission coefficient for H^+ on Au. A comparison of experimental data with predictions based on stopping power. Experimental data points are from the work of Lakits et al., [La90i], [La90ii], and from Baragiola et al [Ba79i]. Model predictions are by Eq 14 using the tabulated stopping powers of Anderson and Ziegler [Au77], and the experimental stopping power of Blume et al [Bl82].

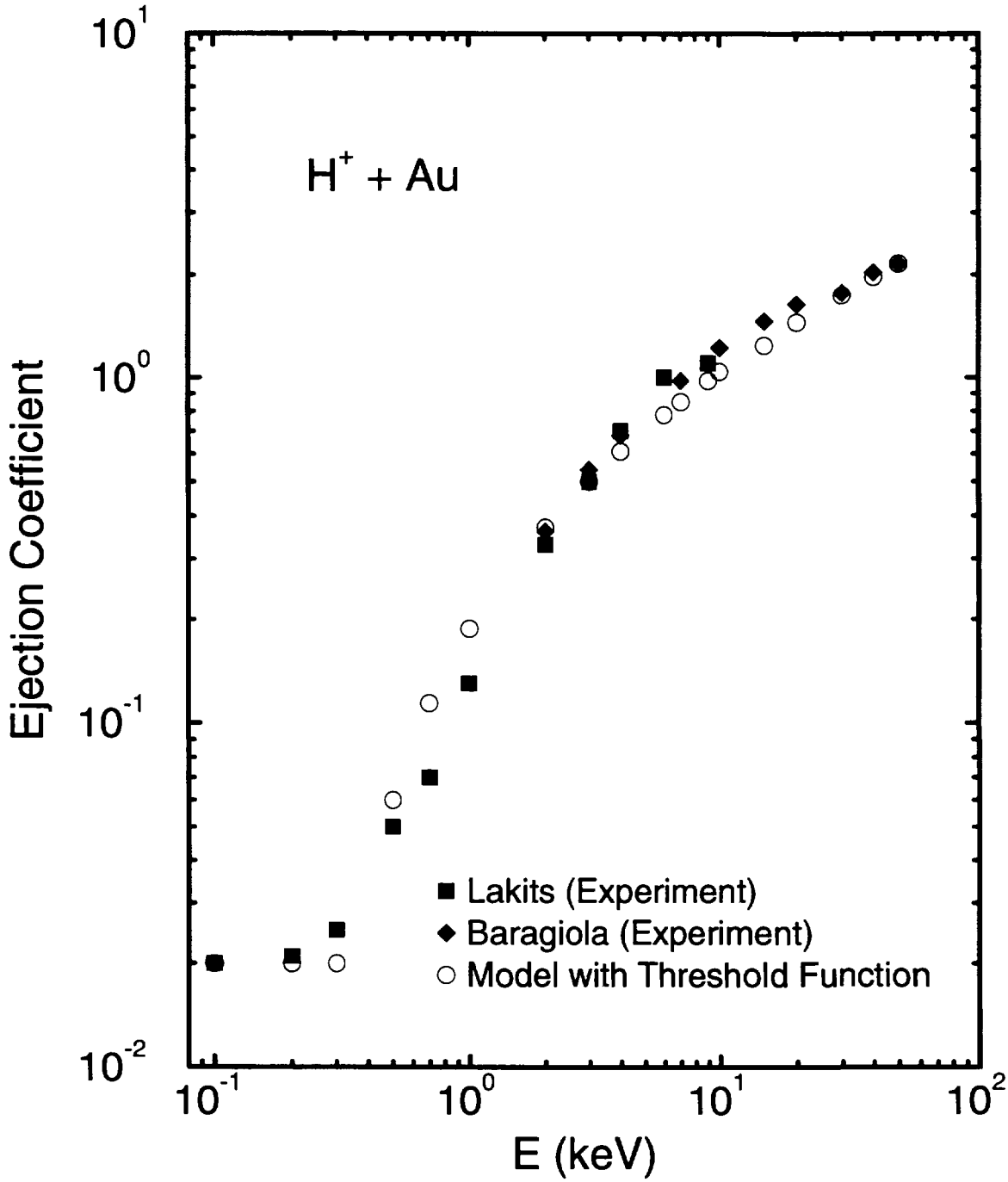

Figure: 2. Electron emission coefficient for H^+ on Au. A comparison of experimental data (Lakits et al., [La90i], [La90ii], and Baragiola et al [Ba79i] with the proposed empirical model of Eq 19.

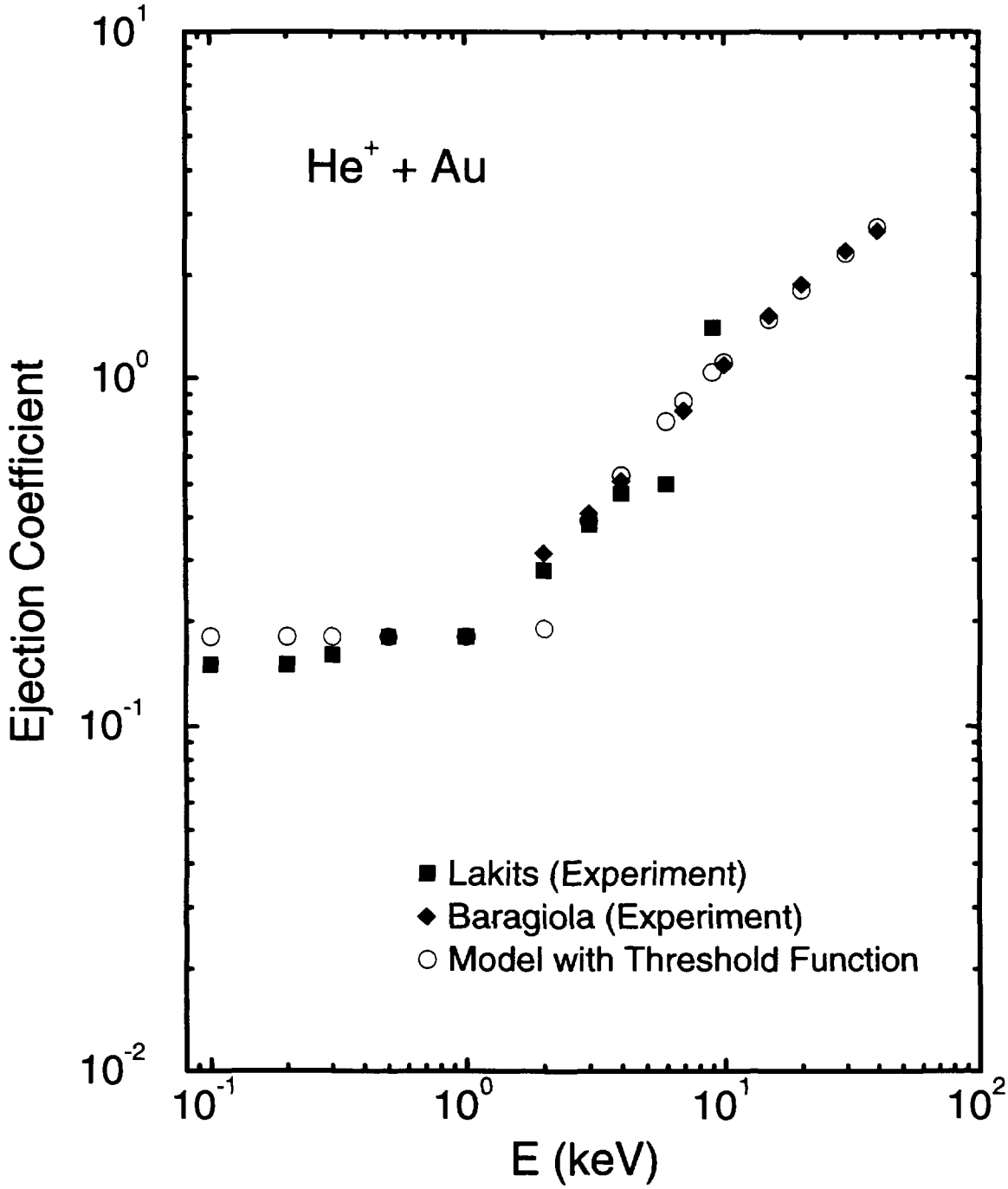

Figure: 3. Electron emission coefficient for He^+ on Au. A comparison of experimental data (Lakits et al., [La90i], [La90ii], and Baragiola et al [Ba79i] with the proposed empirical model of Eq 19.

Appendix I

Modelling Parameters for Specific Cases

Section B5 of this report gives the algorithm for estimating electron emission in terms of constants which the reader must calculate. Here we calculate out those constants for Be, C and W which are candidate plasma-facing materials and also for Au which is a case where detailed relevant data has been published. The proposed algorithm is a combination of Eq. 19 & 20 which gives

$$\gamma(E) = \gamma_p + \Lambda\, S_e(E) \left[1 - \frac{E_{th}}{E}\right]^2 \qquad \text{(A.1)}$$

Replacing stopping power by the Lindhart expression $S_e(E) = A, E^{1/2}$ (valid only to E = 10 keV and for hydrogenic species) and collecting constants we represent emission by

$$\gamma(E) = \gamma_p + C\, E^{1/2} \left[1 - \frac{E_{th}}{E}\right]^2 \Theta\ (E - E_{th}) \qquad \text{(A.2)}$$

where $\Theta\ (E - E_{th}) = 0$ when $E \leq E_{th}$ and $\Theta\ (E - E_{th}) = 1$ when $E > E_{th}$

The constants γ_P, C and E_{th}, calculated according to section B.5 are listed in Table A.I for hydrogenic ions.

The reacher is cautioned that this is a best estimate and that only for one case, H^+ + Au, is there data to confirm this estimate Part of the uncertainty arises through the choice of work function and Fermi energy which are needed to estimate γ_p and E_{th}. The numbers used in these estimates are given as a footnote to the table. The accuracy of the estimates for Be, C and W are unknown.

Equation A.2 and the data of Table A.I are valid for ions, H^+, D^+ and T^+ for neutrals, H^0, D^0, T^0 the same equations are valid except that γ_p must be taken as zero

Table A.I: Coefficients for Evaluation of γ(E) for Hydrogenic Impact at E ≤ 10 keV

Coefficients to be inserted in Eq. A 2 with E in keV

Mechanism	γ_p e/ion	C e/ion	E_{th} (keV)	Comment
H^+ + Be	6.9×10^{-2}	2.4×10^{-1}	$1\,6 \times 10^{-1}$	1
D^+ + Be	6.9×10^{-2}	$1\,7 \times 10^{-1}$	$3\,3 \times 10^{-1}$	1
T^+ + Be	$6\,9 \times 10^{-2}$	$1\,4 \times 10^{-1}$	$4\,9 \times 10^{-1}$	1
H^+ + C	$3\,9 \times 10^{-2}$	3.4×10^{-1}	$2\,3 \times 10^{-1}$	2
D^+ + C	3.9×10^{-2}	$2\,4 \times 10^{-1}$	4.5×10^{-1}	2
T^+ + C	3.9×10^{-2}	1.9×10^{-1}	$6\,8 \times 10^{-1}$	2
H^+ + Au	1.9×10^{-2}	3.4×10^{-1}	3.1×10^{-1}	3
D^+ + Au	$1\,9 \times 10^{-2}$	2.4×10^{-1}	$6\,3 \times 10^{-1}$	3
T^+ + Au	1.9×10^{-2}	$2\,0 \times 10^{-1}$	$9\,4 \times 10^{-1}$	3
H^+ + W	$6\,4 \times 10^{-2}$	2.2×10^{-1}	3.0×10^{-1}	4
D^+ + W	$6\,4 \times 10^{-2}$	$1\,6 \times 10^{-1}$	6.1×10^{-1}	4
T^+ + W	6.4×10^{-2}	$1\,3 \times 10^{-1}$	9.1×10^{-1}	4

Comments:

1. For Be we assume work function = 3.92 eV & Fermi Energy 8.85 eV. The Fermi Energy is unverified
2. For C we assume work function = 4.60 eV & Fermi Energy is 8 51 eV Work function will vary significantly with sample topology and type The Fermi Energy is unverified.
3. For Au we take work function = 5 1 eV and Fermi Energy = 7.1 eV these are reliable values from D.A. Shirley et al , Phys. Rev. B5, 4709 (1972) and U. Flech., Phys Status Solidi (a) 61, 447 (1980).
4. For W we take work function = 4 52 eV and Fermi Energy = 5.76 eV The Fermi Energy is unverified

Appendix II

Comparison of Reflection, Re-emission, Sputtering and Electron Emission

We here compare the four coefficients for mechanisms which give rise to particles ejected from surfaces. We include as materials Be, C and W which are candidates for plasma facing components. As an incident particle we consider only D^+. Incident D^+ will, in part, reflect with a significant fraction of its incident energy. The D^+ will also sputter target material and eject secondary electrons, both these species will have energy distributions peaking at a few eV That fraction of deuterium not reflected will be temporarily retained and later re-emitted as molecules Those molecules are thermally desorbed and are expected to have an energy distribution appropriate to the temperature of the target. On initial bombardment of a virgin surface re-emission is likely to be small (probably zero). With continued bombardment re-emission rises to a saturation value where every two non-reflected incident D give rise to one re-emitted D_2 We present data for that saturated condition.

We present the data as coefficients (λ) in term of the number of particles emitted (D, D_2, e or target atoms) for each D^+ incident. The coefficients for targets of Be, C, Au and W are shown in Figs AII 1, AII 2 , AII.3 and AII 4 as a function of D^+ energy from 1 to 10^4 eV The results for impact of neutral D^0 are expected to be the same except that the potential component of electron emission will be zero.

The origin of the data for the four coefficients is as follows

Reflection Reflection coefficients calculated from the fitting coefficients in E W Thomas, R K. Janev, J J Smith, "Particles Reflected from Surfaces - A Recommended Data Base. IAEA report INDC(NDS)-249 (1991)

Re-emission Coefficients for re-emission as D_2 assumed to be (1-Reflection)/2 Gives molecules out per atom in.

Sputtering Sputtering coefficient calculated from the fitting coefficients in E W Thomas, R.K. Janev, J Botero, J J Smith, Yanghui Qui, "An Evaluated Data Base for Sputtering" IAEA report INDC(NDS)-287 (1993)

Electron Emission Electron emission coefficient calculated from the data of Appendix I in the present report

Table AII.1 D^+ on Berilium - Emergent Particles and Electrons

Energy (keV)	λ_D	λ_{D_2}	λ_C	λ_e
0 100E-02	0 429E+00	0 286E-00	-	0.686E-01
0 200E-02	0.396E+00	0 302E+00	-	0 686E-01
0 500E-02	0 344E+00	0 328E+00	-	0 686E-01
0.100E-01	0 299E+00	0 351E+00	-	0.686E-01
0 200E-01	0.253E+00	0.374E+00	0 111E-02	0 686E-01
0 500E-01	0.198E+00	0 401E+00	0 172E-01	0 686E-01
0 100E+00	0.163E+00	0 419E+00	0 282E-01	0.686E-01
0.200E+00	0 132E+00	0 434E+00	0 298E-01	0.686E-01
0 500E+00	0.876E-01	0 456E+00	0 231E-01	0 830E-01
0 100E+01	0.518E-01	0.474E+00	0.168E-01	0 145E-01
0.200E+01	0.239E-01	0 488E+00	0.116E-01	0 236E+00
0 500E+01	0.641E-02	0 497E+00	0 660E-02	0 398E+00
0.100E+02	0.209E-02	0.499E+00	0 411E-03	0 568E+00
0 200E+02	0 643E-03	0.500E+00	0 247E-02	0 798E+01
0.500E+02	0 130E-03	0 500E+00	0.121E-02	0 124E+01
0.100E+03	0.379E-04	0.500E+00	0.690E-03	0.174E+01

Reflection

$$\lambda_D = \frac{a_1 \ln(a_2 E + 2.72)}{1 + a_3 E^{a_4} + a_5 E^{a_6}}$$

Re-emission

$$\lambda_{D_2} = \frac{(1-\lambda_D)}{2}$$

Sputtering

$$\lambda_{Be} = \frac{Y_o(\epsilon_L E)^{1/2} \ln(\epsilon_L E+2.72)}{1+2.06(\epsilon_L E)^{1/2}+1.57\ \epsilon_L E+8.32\ (\epsilon_L E)^{3/2}} \left[1-\left(\frac{E_{th1}}{E}\right)^{2/3}\right]\left[1-\frac{E_{th1}}{E}\right]^2$$

Electron Emission

$$\lambda_e = \gamma_p + C\sqrt{E}\left(1-\frac{E_{th2}}{E}\right)^2$$

Fitting Coefficients:

$a_1 = 0\,5173$ $a_2 = 9\,04$ $a_3 = 10\,98$ $a_4 = 0\,5719$ $a_5 = 12\,63$ $a_6 = 1\,933$

$Y_o = 0.351$ $\epsilon_L = 3.545$ $E_{th1} = 13.8 \times 10^{-3}$

$\gamma_p = 6\,86 \times 10^{-2}$ $C = 0\,1686$ $E_{th2} = 0\,326$

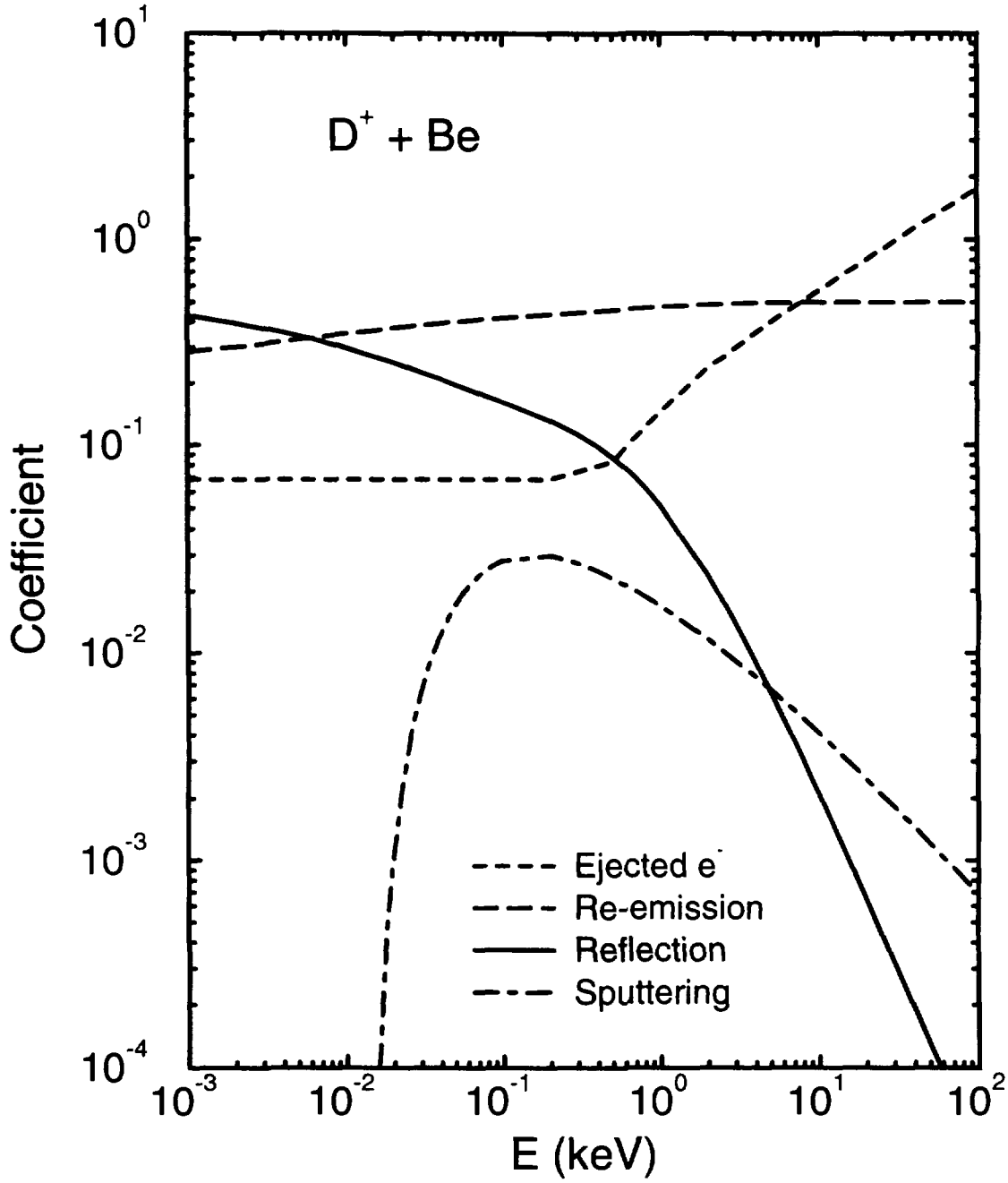

Fig. AII.1 Estimated coefficients for Reflection, Re-emission, Sputtering and Electron Ejection for D^+ on Be

Table AII.2 D^+ on Carbon - Emergent Particles and Electrons

Energy (keV)	λ_D	λ_{D_2}	λ_{Au}	λ_e
0 100E-02	0 416E+00	0.292E+00	-	0 390E-01
0 200E-02	0 385E+00	0 308E+00	-	0 390E-01
0 500E-02	0.335E+00	0 332E+00	-	0 390E-01
0 100E-01	0.294E+00	0 353E+00	-	0.390E-01
0.200E-01	0 252E+00	0.374E+00	-	0 390E-01
0.500E-01	0 201E+00	0.400E+00	0 259E-02	0 390E-01
0 100E+00	0.168E+00	0 416E+00	0.143E-01	0 390E-01
0 200E+00	0.142E+00	0 429E+00	0.236E-01	0.390E-01
0.500E+00	0.107E-00	0 446E+00	0 235E-01	0 421E-01
0.100E+01	0 753E-01	0 463E+00	0 187E-01	0 182E-00
0.200E+01	0 417E-01	0.480E+00	0.136E-01	0 444E+00
0 500E+01	0.130E-01	0 493E+00	0 812E-02	0 923E+00
0 100E+02	0.446E-02	0 498E+00	0 520E-02	0 142E+01
0 200E+02	0 141E-02	0 499E+00	0.320E-02	0 208E+01
0.500E+02	0 291E-03	0 500E+00	0.161E-02	0 336E+01
0.100E+03	0.858E-04	0.500E+00	0 928E-03	0 478E+01

Reflection

$$\lambda_D = \frac{a_1 \ln(a_2 E + 2.72)}{1 + a_3 E^{a_4} + a_5 E^{a_6}}$$

Re-emission

$$\lambda_{D_2} = \frac{(1-\lambda_D)}{2}$$

Sputtering

$$\lambda_C = \frac{Y_o(\epsilon_L E)^{1/2} \ln(\epsilon_L E + 2.72)}{1+2.06(\epsilon_L E)^{1/2}+1.57\ \epsilon_L E+8.32\ (\epsilon_L E)^{3/2}} \left[1-\left(\frac{E_{th1}}{E}\right)^{2/3}\right]\left[1-\frac{E_{th1}}{E}\right]^2$$

Electron Emission

$$\lambda_e = \gamma_p + C\sqrt{E}\left(1-\frac{E_{th2}}{E}\right)^2$$

Fitting Coefficients:

$a_1 = 0\,5173$ $a_2 = 5\,710$ $a_3 = 8\,445$ $a_4 = 0\,5119$ $a_5 = 5\,199$ $a_6 = 1\,933$

$Y_o = 0.325$ $\epsilon_L = 2.24$ $E_{th1} = 29.5 \times 10^{-3}$

$\gamma_p = 3\,9 \times 10^{-2}$ $C = 0\,478$ $E_{th2} = 0\,452$

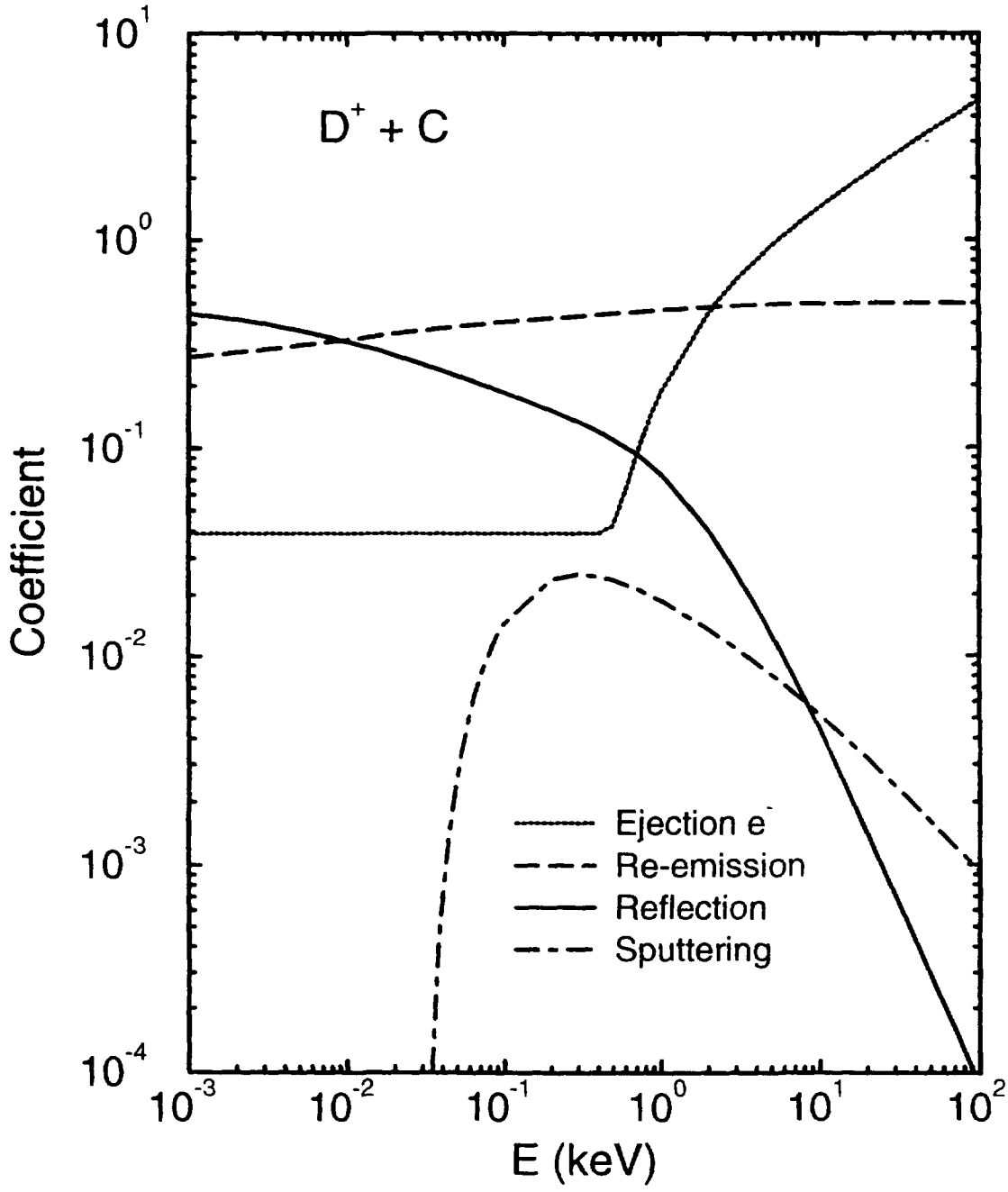

Fig. AII.2 Estimated coefficients for Reflection, Re-emission, Sputtering and Electron Ejection for D^{+} on C

Table AII.3 D^+ on Tungsten - Emergent Particles and Electron

Energy (keV)	λ_D	λ_{D_2}	λ_W	λ_e
0 100E-02	0 834E+00	0 831E-01	-	0 639E-01
0.200E-02	0 824E+00	0 880E+01	-	0 639E-01
0 500E-02	0 803E+00	0 983E+01	-	0 639E-01
0 100E-01	0 780E+00	0 110E+00	-	0 639E-01
0 200E-01	0 747E+00	0 127E+00	-	0 639E-01
0 500E-01	0 688E+00	0 156E+00	-	0 639E-01
0.100E+00	0 633E+00	0 183E+00	-	0 639E-01
0 200E+00	0 575E+00	0 213E+00	-	0 639E-01
0 500E+00	0 501E+00	0 249E+00	0 109E-02	0 639E-01
0 100E+01	0.451E+00	0 274E+00	0 358E-02	0 880E-01
0 200E+01	0.399E+00	0 300E+00	0 572E-02	0 172E+00
0 500E+01	0 315E+00	0 343E+00	0 622E-02	0 337E+00
0 100E+02	0 235E+00	0 383E+00	0 519E-02	0 506E+00
0 200E+02	0 149E+00	0 425E+00	0 387E-02	0 730E+00
0 500E+02	0 587E-01	0 471E+00	0 240E-02	0 116E+01
0 100E+03	0 227E-01	0 489E+00	0 159E-02	0 163E+01

Reflection

$$\lambda_D = \frac{a_1 \ln(a_2 E + 2.72)}{1 + a_3 E^{a_4} + a_5 E^{a_6}}$$

Re-emission

$$\lambda_{D_2} = \frac{(1-\lambda_D)}{2}$$

Sputtering

$$\lambda_W = \frac{Y_o(\epsilon_L E)^{1/2} \ln(\epsilon_L E+2.72)}{1+2.06(\epsilon_L E)^{1/2}+1.57\ \epsilon_L E+8.32\ (\epsilon_L E)^{3/2}} \left[1-\left(\frac{E_{th1}}{E}\right)^{2/3}\right]\left[1-\frac{E_{th1}}{E}\right]^2$$

Electron Emission

$$\lambda_e = \gamma_p + C\sqrt{E}\left(1-\frac{E_{th2}}{E}\right)^2$$

Fitting Coefficients:

$a_1 = 0\ 852$ $a_2 = 2\ 157$ $a_3 = 1\ 97$ $a_4 = 0\ 6425$ $a_5 = 2\ 289 \times 10^{-2}$ $a_6 = 1\ 927$

$Y_o = 0.058$ $\epsilon_L = 0.1$ $E_{th1} = 0.218$

$\gamma_p = 6\ 39 \times 10^{-2}$ $C = 0\ 1584$ $E_{th2} = 0\ 610$

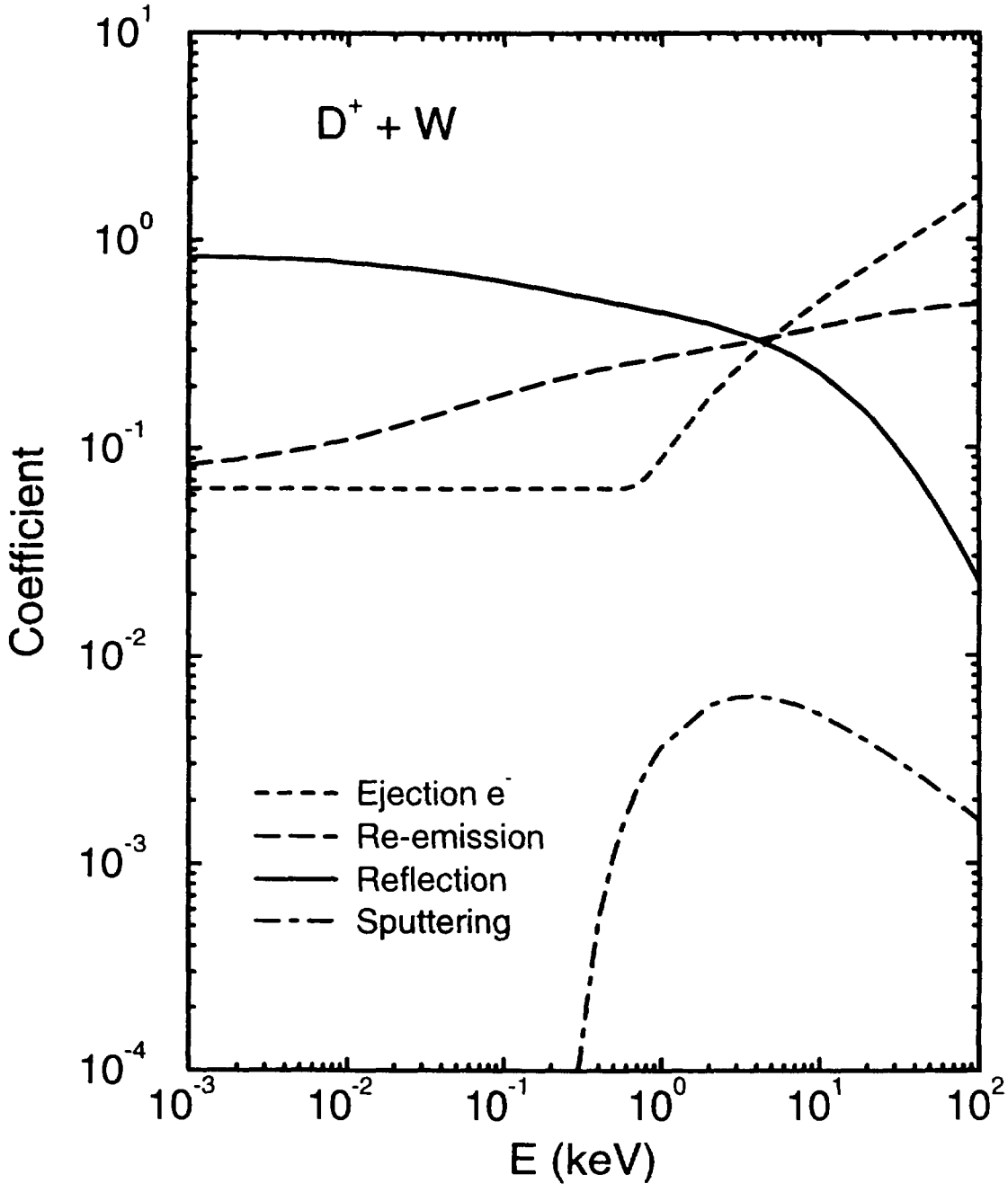

Fig. AII.3 Estimated coefficients for Reflection, Re-emission, Sputtering and Electron Ejection for D^{+} on W

Table AII.4 D^+ on Gold - Emergent Particles and Electron

Energy (keV)	λ_D	λ_{D_2}	λ_{Be}	λ_e
0 100E-02	0 808E+00	0 958E-01	-	0 190E-01
0 200E-02	0.799E+00	0 100E+00	-	0 190E-01
0.500E-02	0.780E+00	0 110E+00	-	0 190E-01
0 100E-01	0 758E+00	0 121E+00	-	0.190E-01
0 200E-01	0.728E+00	0.136E+00	-	0 190E-01
0 500E-01	0 672E+00	0 164E+00	-	0 190E-01
0 100E+00	0 620E+00	0 190E+00	0 469E-09	0.190E-01
0 200E+00	0 563E+00	0 218E+00	0 317E-02	0 190E-01
0.500E+00	0 492E+00	0 254E+00	0.190E-01	0 190E-01
0 100E+01	0 443E+00	0 279E+00	0 328E-01	0 521E-01
0 200E+01	0 393E+00	0.303E+00	0 415E-01	0 180E+00
0.500E+01	0 313E+00	0.343E+00	0 401E-01	0.432E+00
0.100E+02	0.237E+00	0 381E+00	0 323E-01	0 691E+00
0.200E+02	0 154E+00	0.423E+00	0 236E-01	0 103E+01
0.500E+02	0.630E-01	0.468E+00	0 145E-01	0.169E+01
0 100E+03	0.249E-01	0 488E+00	0 959E-02	0 241E+01

Reflection

$$\lambda_D = \frac{a_1 \ln(a_2 E + 2.72)}{1 + a_3 E^{a_4} + a_5 E^{a_6}}$$

Re-emission

$$\lambda_{D_2} = \frac{(1-\lambda_D)}{2}$$

Sputtering

$$\lambda_{Au} = \frac{Y_o(\epsilon_L E)^{1/2} \ln(\epsilon_L E+2.72)}{1+2.06(\epsilon_L E)^{1/2}+1.57\ \epsilon_L E+8.32\ (\epsilon_L E)^{3/2}} \left[1-\left(\frac{E_{th1}}{E}\right)^{2/3}\right]\left[1-\frac{E_{th1}}{E}\right]^2$$

Electron Emission

$$\lambda_e = \gamma_p + C\sqrt{E}\ \left(1-\frac{E_{th2}}{E}\right)^2$$

Fitting Coefficients:

$a_1 = 0\ 825$ $a_2 = 1.981$ $a_3 = 1.865$ $a_4 = 0.6425$ $a_5 = 1\ 942 \times 10^{-2}$ $a_6 = 1\ 927$

$Y_o = 0.329$ $\epsilon_L = 0.0926$ $E_{th1} = 99.7 \times 10^{-3}$

$\gamma_p = 1\ 9 \times 10^{-2}$ $C = 0\ 242$ $E_{th2} = 0\ 630$

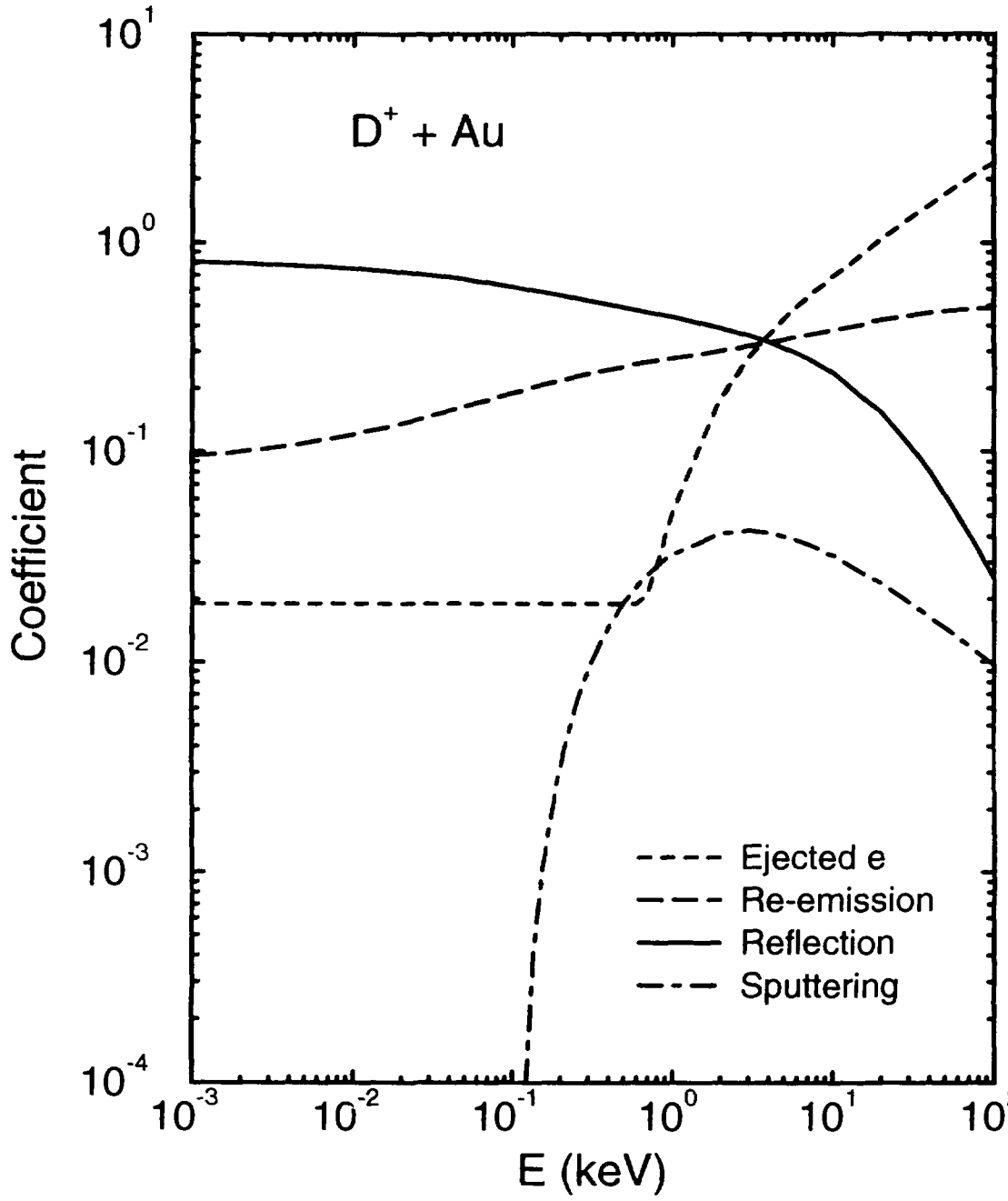

Fig. AII.4 Estimated coefficients for Reflection, Re-emission, Sputtering and Electron Ejection for D^+ on Au