Electron momentum transfer cross-section in cesium and related calculations of the local parameters of Cs + Ar MHD plasmas

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Published: 01/01/1979

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Link to publication

Citation for published version (APA):
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by

B. Stefanov
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IN CESIUM AND RELATED CALCULATIONS OF THE
LOCAL PARAMETERS OF Cs + Ar MHD PLASMAS

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TH-Report 79-E-96
ISBN 90-6144-096-3

Eindhoven
June 1979
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Abstract. There are many measurements of quite different physical quantities in cesium plasma which are related to the electron-atom momentum transfer cross-section $Q(v)$ in the range of energies $\varepsilon = \frac{mv^2}{2}$ from 0.05 to 2 eV. Nevertheless, no attempt has been made up to now to find a unique curve $Q(v)$ fitting all the reliable experimental data. In this paper the results of 9 experimental works are considered in which are measured such quantities as: a) width of the electron-cyclotron resonance, b) attenuation of microwaves, c) electrical conductivity in both equilibrium and nonequilibrium pure Cs or Cs + Ar plasmas, d) electron thermal conductivity, e) perpendicular electrical conductivity in a strong magnetic field, f) electron drift velocity. A convenient algorithm is proposed to variate $Q(v)$ until the best fit to all the data is obtained. As a result an almost unique curve $Q(v)$ is found so that the mean deviation between experimental and calculated values is 20%.

The recommended dependence $Q(v)$ could be used for different calculations in the range of electron temperatures (or equivalent mean energies) from $\sim 500$ to $2500$ K with an error less than 20%.

B. Stefanov

ELECTRON MOMENTUM TRANSFER CROSS-SECTION IN CESIUM AND RELATED CALCULATIONS OF THE LOCAL PARAMETERS OF Cs + Ar MHD PLASMAS.

This work was done in the Group Direct Energy Conversion, Department of Electrical Engineering, Eindhoven University of Technology, while the author was on leave from the Institute of Electronics, Bd. Lenin 72, Sofia 1113, Bulgaria.
I. INTRODUCTION

Calculations of transport properties using the Chapman-Enskog method in Cs + Ar plasmas have been published more than a decade ago [1 - 3]. Nevertheless, due to the uncertainty of the electron-cesium atom cross-section data simple formulae of the elementary kinetic theory have been used in most calculations of MHD generators (see for example [4,30]). It could happen only occasionally that such a practice gives results which are in good agreement with the strict (following Chapman-Enskog theory [5]) calculations. The purposes of this work are twofold. The first is to summarize well known formulae which have to be used to evaluate the local parameters of MHD plasmas. The second is to analyse all the available experimental measurements of different quantities which depend on the electron-cesium atom momentum transfer cross-section \( Q \) as a function of the electron velocity \( v \) and to recommend the best curve \( Q(v) \).

II. THEORETICAL BACKGROUND [2]

In a Faraday MHD generator several quantities are related to the velocity-dependent electron-atom momentum transfer cross-section \( Q(v) \) which is defined as

\[
Q(v) = 2\pi \int_0^\pi I(\phi) (1 - \cos \phi) \sin \phi d\phi,
\]

\( I(\phi) \) being the angle-dependent differential cross-section. Some of these quantities \( \sigma_Q \), \( \bar{v} \) appear in the electron energy equation

\[
\frac{2}{\sigma_Q} = 3 \pi n k \left( \frac{\bar{v}_{eAr}}{M_{Ar}} + \frac{\bar{v}_{eCs}}{M_{Cs}} + \frac{\bar{v}_{e}}{M_{Cs}} \right) (T_e - T_a) - R = 0,
\]

\( R \) being the radiation losses. The mean collision frequencies of electrons with Ar and Cs atoms \( \bar{v}_{eAr} \) and \( \bar{v}_{eCs} \) are given by the relation

\[
\bar{v}_{ea} = \frac{8N}{3} \left( \frac{2kT_e}{m} \right)^{1/2} \int_0^\infty z^2 e^{-z^2} Q(v) dz,
\]

where \( j \) is the current density assumed to be perpendicular to both the gas velocity and the magnetic field \( B \), \( m \) and \( M_{Ar}, M_{Cs} \) are the electron and atom (Ar and Cs) masses, \( n \) is the electron density, \( k \) the Boltzmann constant, \( T_e \) and \( T_a \) the electron and heavy particle temperatures and \( R \) the radiation losses.
where $N$ is the atom density and 

$$ z = (\frac{mv}{2kT})^\frac{1}{2} $$

is the dimensionless velocity.

The electron-ion mean collision frequency is

$$ \nu_{ei} = \frac{4 \sqrt{\pi}}{3m^2} n \ln A \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \left(\frac{kT}{m}\right)^{3/2}, $$

$\ln A$ being the Coulomb logarithm.

The electrical conductivity in a MHD plasma is a tensor with components $\sigma_H$, $\sigma_\perp$ and $\sigma_H$. The "quasiscalar" conductivity $\sigma_Q$, appearing in eq.(2), is expressed as

$$ \sigma_Q = \frac{\sigma_\perp^2 + \sigma_H^2}{\sigma_\perp}, $$

while the Hall parameter is

$$ \beta = \frac{\sigma_H}{\sigma_\perp}. $$

Explicit expressions for the components of $\sigma$ are known in the case of very low degree of ionization where the Coulomb interactions could be neglected (Lorentzian gas). For a Maxwellian distribution of the electrons:

$$ \sigma_{Q}^L = \frac{2n}{3\pi m} \int_0^\infty \frac{z^4}{v^2} e^{-z^2} dz, $$

$$ \sigma_{Q}^L = \frac{2n}{3\pi m} \int_0^\infty \frac{z^4}{v^2 + \omega^2} e^{-z^2} dz, $$

$$ \sigma_{Q}^H = \frac{2n}{3\pi m} \int_0^\infty \frac{z^4}{v^2 + \omega^2} e^{-z^2} dz, $$

where the velocity dependent collision frequency $\nu$ is given by

$$ \nu = \nu_{NQ}(v) $$

and

$$ \omega = eB/m $$

is the electron cyclotron frequency. For a mixture of Cs and Ar eq.(11) should be written as

$$ \nu = \sum_{eA} \nu_{eA} \left[ N_{Ar}\sigma_{eAr}(v) + N_{Cs}\sigma_{eCs}(v) \right]. $$
In the fully ionized limit (Spitzer gas) an explicit expression is
known only for $\sigma_H^S$:

$$\sigma_H^S = 1.975 \frac{ne^2}{m e_1}$$  \hspace{1cm} (13)$$
valid for singly ionized plasmas. The calculation of $\sigma_H^A$ and $\sigma_H^S$ is quite
complicated because it requires application of the Chapman-Enskog method -
see for example [6] where some numerical results can also be found. It
should be pointed out that the formulae (5) and (13) are derived under
the assumption $\ln \Lambda \ll 1$, i.e. the number of charged particles in a sphere
with a Debye radius is assumed large so that only collisions with deflection
on small angles are considered. A typical value of $\ln \Lambda$ in atmospheric
pressure arcs as well as in MHD generators is 5. In this case corrections
to eq. (5) and (13) must be introduced [7] and in eq. (5) the value of $\ln \Lambda$
is changed:

$$\ln \Lambda \rightarrow \ln \Lambda - 1.37$$  \hspace{1cm} (5a)$$
while in the expression for $\bar{v}_e^S$ in eq. (13)

$$\ln \Lambda \rightarrow \ln \Lambda - 0.52$$  \hspace{1cm} (13a)$$

Now the case of partially ionized plasmas will be considered where both
electron-atom and Coulomb interactions are important. The collision term
(the second in eq. (2)) is not changed because it contains a sum of
collision frequencies. The quasiscalar conductivity however could not be
expressed explicitly by means of relations like eq. (9) and (10). Instead,
elaborated computation is needed [1, 3].
Frost [8] has proposed a semiempirical rule (which has some theoretical
basis) to calculate $\sigma_H$ in partially ionized plasmas. The idea is to use
again eq. (8) introducing a supplementary term in the denominator of the
integral, namely $\bar{v} = v_{ea} + a v_c$, where $v_c$ takes into account the Coulomb
collisions (but does not coincide with $v_{ei}$) and the constant $a$ is chosen
so that in the limit $v_{ea} \rightarrow 0$ eq. (8) coincides with eq. (13). An extension
of the Frost rule for $\sigma_A$ and $\sigma_H$ was proposed in [3]. It was shown there
that the "exact" calculations and the results of the Frost rule agree within
less than 20 percent.
The formulae for $\sigma$ components using the Frost rule are listed below:

$$\sigma_F^S = \frac{8ne^2}{3m\pi^2} \int_0^{\infty} \frac{z^4}{\bar{v}_{ea}(v) + a v_c(v)} e^{-\frac{z^2}{\bar{v}}\frac{dz}{2}}$$  \hspace{1cm} (14)$$
where \( a = 0.476 \),

\[
\nu_c = \frac{8\pi n \ln A}{m^2/\nu^2} \left( \frac{e^2}{4m\varepsilon_0} \right)^2 \left( \frac{m}{2kT_e} \right)^{1/2}
\]  

and the functions \( h_1 \), \( h_\parallel \) are tabulated in [1, 3] for different values of \( \omega/\nu_{ei} \).

Short comment on the radiation losses. In many applications especially in non-equilibrium MHD-generators, eq. (2) is used to find the electron temperature elevation \( T_e - T_a \) due to the electric current. The radiation losses \( R \) must take into account both the resonance broadening and the Van der Waals' broadening (determined by Cs - Ar atom collisions). We have used the results of ref. [9-11] to obtain an expression for \( R \) in cases of cylindrical and slab geometry. The Van de Waals broadening was evaluated according to the experimental data summarized in [12]. A formula for the resonance broadening was taken from [13] and the calculations were found to be in good agreement with the experimental data [14]. Finally we obtained for \( T_e < 3000 \) K in SI units:

\[
R = 1.52 \times 10^{-14} \left( N_{Cs}/d \right)^{1/4} \left[ 1 + 0.77 \times 10^{-2} N_{Ar}/N_{Cs} \right] \exp \left( -16600/T_e \right)
\] (18)

Eq. (18) describes the mean radiation losses per unit volume of a long cylindrical column of plasma of diameter \( d \) with \( T_e = \text{const} \) inside and \( T_e = 0 \) outside the column and \( T_a = \text{const} \) everywhere inside and outside the column. When a slab with a thickness \( d \) is considered then again eq. (18) has to be used with the first factor equal to \( 0.71 \times 10^{-14} \) W.m\(^4\).

The estimates of \( R \) in [15] for \( N_{Cs}/N_{Ar} = 0.002 \) and 0.004 coincide within 20% with eq. (18). A comparison of some of the nonequilibrium experimental
data [28, 33] and the calculations of $\sigma$ using eq. (2) and (18) is shown on Fig.1 where $\ln(\sigma_{\text{exp}}/\sigma_{\text{calc}})$ is plotted against $T_e$. Because of the high electron densities the Coulomb collisions are predominant and the exact form of $Q(v)$ does not influence significantly the calculations. The error in the measurements of $\sigma$ does not exceed 40% and so the results shown on Fig.1 confirm that eq.(18) is accurate enough to be used to evaluate $R$ in eq.(2).

III. FORMULATION OF THE PROBLEM TO FIND $Q(v)$ AND A GENERAL OUTLINE OF THE METHOD TO SOLVE IT

It can be seen from eq.(3) or (8) that the problem of determining $Q(v)$ using measured values of some transport coefficient $k$ at different temperatures $T_e$ is equivalent to solving a Fredholm equation of the first kind:

$$k(T_e) = \int_0^\infty K(T_e,v) Q(v) dv$$  \hspace{1cm} (19)

(or instead of $Q$ we may need to take $Q^{-1}$ as in eq.(8)) where the kernel $K$ is specific for a given transport coefficient and depends on the electron distribution function (which is supposed to be Maxwellian in eqs.(3), (8 - 10) and (14 - 16)).

This technique for determination of low-energy electron atom cross-section was proposed by Frost and Phelps [16, 17] and was used to obtain $Q(v)$ for the noble and some molecular gases in the range 0.01 - 10 eV [18 - 20]. Nighan and Postma [21] used a trial-and-error method to solve eq.(19) analyzing drift velocity measurements in Cs but did not propose algorithm to optimize $Q(v)$.

We must clearly recognize that any procedure of solving eq.(19) is ill-posed [22]. Even if the exact analytical form of $k(T_e)$ is known small changes in $k(T_e)$ could lead to rapid changes in $Q(v)$ (instability of the solution). The situation is even worse when $k(T_e)$ contains an experimental error which may depend on $T_e$. In principle the solution of eq.(19) is not unique - an infinite set of functions $Q(v)$ could satisfy

* As the plasma volume in [28, 33] has been a finite cylinder the factor in eq.(18) has been chosen as $1.52 \times 10^{-14} /d_{\text{cyl}}^4 + 0.71 \times 19^{-14} /d_{\text{slab}}^4$. 
it within the limits of any prescribed accuracy. It is easily seen for
example that an addition of a quickly oscillating function to a solution
Q (v) will also be a solution.
To convert this ill-posed problem to a well-posed one in the sense of
Tikhonov according to [22] we need supplementary information (sometimes
rather subjective) to narrow the class of possible solutions. In our
particular case we will look for a curve Q (v) which belongs not to the
class of all functions but to the limited class of functions determined by
cubic splines [23] with few knots so that Q (v) is smooth enough and has
as few minima and maxima as possible. To avoid the uncertainty of the
problem arising from the experimental error in k (T_e) we have to take into
account as many experimental measurements (preferably of different transport
properties, i.e. with different kernels K) as possible but at the same time
we have to restrict ourselves to the most accurate of them.
So we will outline the method for determining Q (v) from measured values
of transport coefficients as follows. Sets of different k in some range
of T_e will be considered with known kernels K (T_e, v). Then for a given
representation of log Q (v) (using cubic splines with prescribed by us knots)
characterized by several constants C_j we will form the functional
\[ F = \sum_{i=1}^{\infty} R_i^2; R_i = \ln \{ \frac{k (T_e)}{\int_0^\infty K(T_e, v) Q(v) dv} \} = \ln \frac{k_{exp}}{k_{calc}} \]  
(20)
and look for the minimum of F (C_j) regarding C_j as independent variables.
The metric in eq.(20) is chosen so that relative values of k are considered.
At last when a curve Q (v) which minimizes F is found, its uniqueness and
sensitivity to the choice of a particular set of experimental points in
eq.(20) will be analyzed.

IV. EXPERIMENTAL MEASUREMENTS USED TO FIND Q (v)

In Table 1 a short description of all used experimental works is given.
No.1. Electron-cyclotron resonance measurements of Meyerand and Flavin [24].
The half-width \( v_h \) of the plasma absorption line has been determined in
Cs vapor with \( n/N < 10^{-6} \) so that the Coulomb collisions could be neglected.
The expression which relates $v_h$ to $Q(v)$ is
\[
2 \int_0^\infty \frac{z^2}{Q(v)} \mathrm{d}z = \int_0^\infty \frac{z^2}{Q(v)} \mathrm{d}z.
\] (21)

The authors have been using a procedure to find out
\[
\langle Q \rangle = \left[ 2 \int_0^\infty \frac{z^2}{Q(v)} \mathrm{d}z \right]^{-1}
\]
as function of $T_e$ taking into account the dependence $v(v)$. Therefore it is correct to use eq. (22) for $R_i$ in eq. (20):
\[
R_i = \ln \left( \frac{\langle Q \rangle_{\text{calc}}}{\langle Q \rangle_{\text{exp}}} \right).
\] (23)

No.2. Microwave interferometry measurements of Chen and Raether [25]
The high frequency complex conductivity in an afterglow of a Cs discharge has been measured and
\[
\langle Q \rangle = \int_0^\infty \frac{z^2}{Q(v)} \mathrm{d}z
\]
has been found. We accept here
\[
R_i = \ln \left( \frac{\langle Q \rangle_{\text{calc}}}{\langle Q \rangle_{\text{exp}}} \right).
\] (24)

No.3. Electrical conductivity measurements in pure Cs vapor [26, 31]. Here eq. (14) is used and
\[
R_i = \ln \left( \frac{\sigma_{\text{exp}}}{\sigma_{\text{calc}}} \right).
\] (26)

The data of Bohn et al. [26] only for $T_e > 1300$ K were considered because due to the electrode-plasma phenomena low-temperature measurements are not reliable (see for example [31]). For the same reason only one experimental point of Cox et al. [31] with the largest $N$ for $B = 0$ was considered.

No.4. Electrical conductivity measurements of Harris [27] in mixtures Ar + Cs. Again eq. (14) was used with $Q_{\text{Ar}}(v)$ taken from [20] and eq. (26) determined $R_i$. Three sets of experimental points were considered with $p_{\text{CS}} = 0.1, 1$ and 10 Torr ($p_{\text{Ar}} = 760$ Torr). It should be noted that at $p_{\text{CS}} = 0.1$ Torr $\sigma$ is affected by the Maxima in $Q(v)$ while at 1 and 10 Torr $\sigma$ is determined mostly by the minimum of $Q(v)$.

No.5. Electrical conductivity measurements of Bernard et al. [28] in an Ar + Cs plasma with $T_e \neq T_a$. The procedure was the same as in the previous
case 4 with $T_e$ calculated by means of eq. (2). Only data with $j = 1 \text{ A/cm}^2$ were taken into account but even they do not depend very much on $Q(v)$ because of the relatively high degree of ionization. The data with $j = 10 \text{ A/cm}^2$ correspond to a fully ionized plasma and were used in Fig. 1 to confirm the accuracy of using eq. (2) together with eq. (18).

No. 6. Electron thermal conductivity measurements of Stefanov [29] with $T_e = T_a$. The procedure of calculating $\lambda_e$ is described in [29]. The main contribution in $\lambda_e$ is from the integral

$$\lambda_e \propto \int_0^\infty \frac{z^3}{Q(v) + (n/N)Q_c(v)} e^{-z^2} dz,$$

but eq. (2) is used to interpret the experimental data so that integrals appearing in eq. (22) and (24) are also important. Only data with $p_{CS} > 4 \text{ Torr}$ were used to avoid as much as possible errors connected with a diffusion of charged particles and with plasma currents. The deviations were calculated as

$$R_i = \ln \left( \frac{\lambda_{e,\text{exp}}}{\lambda_{e,\text{calc}}} \right).$$

No. 7. Electrical conductivity measurements of Beynon and Brooker [30] in a mixture of Ar + Cs with $p_{CS} = 6 \text{ Torr}$ and $p_{Ar} = 760 \text{ Torr}$ are similar to No. 4. Only one point at 1300 K has been measured. The primary result on $\sigma$ is not given in the paper so that we calculated it back and found

$$\sigma = 6.31 \times 10^{-2} \text{ cm}^{-1}.\text{m}^{-1}.$$

No. 8. Electrical conductivity measurements of Cox et al. [31] in a strong magnetic field seem to be among the most reliable ones. We can see from eq. (15) that for $\omega \gg \nu$

$$\sigma \propto \int_0^\infty \frac{z^5}{Q(v)} e^{-z^2} dz,$$

i.e. the integral is the same as in eq. (24). We chose 12 experimental points in the linear parts of the logarithmic dependences $\sigma(N)$ (see Fig. 6 and 7 of [31]) for $N = 6.1 \times 10^{13}$ to $1.1 \times 10^{15} \text{ cm}^{-3}$. As $\sigma \propto Q$ we took

$$R_i = \ln \left( \frac{\sigma_{\text{calc}}}{\sigma_{\text{exp}}} \right).$$

No. 9. Drift velocity measurements of Chanin and Steen [32]. Here the procedure of Postma [43] was used in the calculations. First the electron distribution function had to be found for a given $Q(v)$ using eq. (8) of [43] together with the data of Zapesochnyi [44] for the excitation cross-section. Then

$$V_D \propto \int_0^\infty \frac{z^2 (\partial f/\partial z)}{Q(v)} dz$$

and
\[ R_i = \ln \left\{ \frac{V_{\text{Dexp}}}{V_{\text{Dcalc}}} \right\} \]  

(32)

The value of \( V_{\text{Dcalc}} \) is sensitive not only to the minimum of \( Q(v) \) but through \( f \) to all parts of \( Q(v) \).

In the calculations of No.3 to No.8 the electron densities were found from the Saha equation. The short analysis in [29] confirms the presence of a Saha equilibrium determined by \( T_e \).

Experimental works not taken into account. The measurements of Ingraham [34] of \( v_h \) were found to lie 2.5 to 3 times lower than the data [24 - 32]. When they were included in the minimization of the functional (20) a strong stratification of all \( R_i \) values was observed, the data of [34] opposing all the data of [24 - 32].

The microwave data of [35, 36] do not seem to be accurate enough. The slopes of the dependences (for example \( \nu(p) \)) which determine \( \langle Q \rangle^\nu \) are uncertain within a factor of 2 due to the scattering of the measured points. Nevertheless the reported values of \( \langle Q \rangle^\nu_{\exp} \) at 1600 K do not deviate substantially from \( \langle Q \rangle^\nu_{\text{calc}} \) based on [24 - 32]: \( \langle Q \rangle^\nu_{\exp}/\langle Q \rangle^\nu_{\text{calc}} = 0.93 \) and 0.61 for the two experimental tubes [36] while at 680 K [35] this ratio is 0.44.

The electrical conductivity measured in [37, 38] is much higher than [26]: 4 to 9 times in [37] and 2 to 3 times in [38] (lower figures for \( T = 1700 \) K and higher – for \( T = 1300 \) K). The discrepancy arises mainly from the high probing current density – of the order of \( 10^{-1} \) A/cm\(^2\) – which causes an elevation of \( T_e \) over \( T_a \) and increases \( \sigma \). This could be clearly seen from Fig.5 of [33] or Fig.2 of [26] – the plasma equilibrium is affected when \( j > 10^{-1} \) A/cm\(^2\) at 1700 K or \( j > 4 \times 10^{-4} \) A/cm\(^2\) at 1300 K for \( p = 4 \) Torr (for lower pressures this critical current is even smaller). It should be pointed out that in all the measurements of \( \sigma \) considered here in finding \( Q(v) \) [26 - 28, 30, 31] either the probing current has been well below the critical value or the dependence \( \sigma(j) \) has been measured. In [39] the pressure is unknown so that \( \sigma_{\exp} \) can not be compared with \( \sigma_{\text{calc}} \). The measurements of \( \sigma_i \) in [39] seem to be misinterpreted somehow and the proposed cross-section is one order of magnitude or more lower than that derived from [24 - 32].

The measurements of the drift velocities in cesium discharges [40, 41] have not been treated properly in [21, 42]. The electron-electron contribution to the Coulomb cross-section has been neglected and this is probably
the reason why \( Q(v) \) in [21] has a maximum in the region of 2 eV. In contrast with it \( Q(v) \) found in [43] from the data of [32] where the Coulomb interactions are negligible has no maximum in this region. Furthermore the solution of the Boltzmann equation in a partially ionized plasma may not be appropriate. Nevertheless as it is shown in [21, 42] part of the data of [40, 41] with lower degree of ionization are in good agreement with [32] so that to some extent the data of [32] represent also the measurements in [40, 41].

V. RESULTS AND DISCUSSION

The procedure was outlined in Section III. We were minimizing \( F \) in eq. (20) using different numbers of knots \( N \) ranging from zero (i.e. one cubic polynomial over the whole interval of integration 0.375 to 9.75 x 10^7 cm/s) to eight. The number of the coefficients in the B-spline representation [23] which are independent variables \( (C_j) \) is \( K = N + 4 \). However in the case of large \( K \) the value of \( F \) does not depend on \( C_1, C_{K-1} \) and \( C_K \) because they prescribe \( Q(v) \) near the ends of the integration interval where \( K(T_e, v) \) in eq. (19) is small enough. Therefore we fixed the values of \( Q(v) \) at \( v = 0.375 \) and near 9.75 x 10^7 cm/s.

The calculations were performed on the computer B7700 at the Eindhoven University of Technology. Standard NAG-library programs were used for the minimization of \( F \) and for the cubic spline representation of \( \log Q(v) \). Over 100 solutions were found for different choices of knots, number of variables, fixed end values of \( Q(v) \) and starting points (initial values of all \( C_j \)). Simple functions such as \( Q = \text{const} \) or monotonically decreasing \( Q(v) \) failed to fit the experimental data as it was also noted in [21, 43]. As the number of knots was increasing up to \( N = 6 \) or 7 the resulting minimum value of \( F = \Sigma R_i^2 \) was decreasing. No improvement was observed for \( N = 8 \) but \( Q(v) \) became unstable. In the most cases the solution \( Q(v) \) did not depend on the initial set of \( C_j \); in the two cases when two local minima of \( F \) were found one of them had substantially lower \( \Sigma R_i^2 \); and was believed to be an absolute minimum.

Some of the results are shown in Fig. 2. Curve A represents the best solution with \( \Sigma R_i^2 = 2.84 \) and is given also in Table 2. Curve B with different knots
represents another solution with the same \( \Sigma R_i^2 \) but has a more complicated form. A third solution with another choice of knots was obtained. It is almost the same as curve A and is therefore not shown in Fig.2. The deviations \( R_i \) for all the three solutions \( Q(v) \) almost coincide and are plotted against \( T_e \) in Fig.3. The numbers on the lines (or points) correspond to the numbers of the experiments considered in Section IV.

It can be seen that the main inconsistency of all the data comes from the fact that experiments No.1 and 3 are opposing No.4b, 4c and 7, all of them being related to the minimum of \( Q(v) \). The deviations were analyzed by means of the \( \chi^2 \) criterion and found to have a Gaussian distribution with a probability 0.50, this low value probably being caused by the small number (fifty) of the considered experimental points.

The dashed curve C in Fig.2 is the result of minimizing \( F \) with the data No.3 replaced by the data of [38] which are 2 to 3 times higher. A comparison could be made with \( Q(v) \) proposed by Nighan and Postma (their curve A in Fig.5 of Ref. [21]) and Postma (Fig.4 of Ref. [43]), the two curves being different only at \( v > 5 \times 10^7 \) cm/s and characterized by a minimum at \( v = 1.85 \times 10^7 \) cm/s and a broad maximum at \( v = 3 \times 10^7 \) cm/s. As it can be seen in Fig.4 some of the experiments are in good agreement with these curves. However, it should be noted that the procedure used in [21, 43] does not make it possible to locate the minimum and the maximum and the solution was not unique [46]. The position of the maximum was chosen to be in accordance with [45]. Moreover, \( \Sigma R_i^2 = 8 \) even for the better curve of Ref. [42].

The non-monotonous character of \( Q(v) \) is due to the fact that measured values of \( \langle Q \rangle^v \) are quite larger than \( \langle Q \rangle^e \) or \( \langle Q \rangle^\lambda \), i.e. to fit the experimental data both large and small values of \( Q(v) \) are needed in a comparatively narrow range of \( v \). This could be a curve with any number of minima and maxima as mentioned in Section III. When too many knots were introduced or some of them were too close together then one more maximum and minimum appeared with no improvement of \( \Sigma R_i^2 \). When moving the knots closer the appearance of a new peak at the bottom of the deep minimum of \( Q(v) \) was observed, then it grew and pushed the two maxima away and the right peak was lowered until it disappeared, being replaced finally by the new maximum.
Analysis of curve A. The first check was to vary \( Q(v) \) and to observe how the quantities \( R_i \) were changed. Parts of \( Q(v) \) along intervals with lengths \( \Delta v = 0.5 \) to \( 1 \times 10^7 \) cm/s were multiplied by factor of 2 or 0.5. The computations showed that \( R_i \) are almost insensitive to \( Q(v) \) at \( v < 1.5 \times 10^7 \) cm/s and \( v > 8 \times 10^7 \) cm/s. Below \( v = 2 \times 10^7 \) cm/s, \( Q(v) \) is determined mainly by experiments No.1 and 2, the left maximum - by No.2, 6 and 8, the minimum - by No.1, 3, 4, 6 and 7, the right maximum - by No.6, 8 and 9 and the falling part at the right - by No.6 and 9. It can be seen that \( Q(v) \) is more sensitive to the experiment No.6.

The second check was to withdraw different experimental data and then to minimize again \( F \) in eq. (20) using the knots of curve A. Withdrawing No.3, 4, 5, 6, 8 and 9 did not change curve A substantially. In Fig.5 the curves D, E, F are solutions where experimental data No.1, 2 and 7 correspondingly have not been taken into account. We paid special attention to curve F because there the most deviating data (No.7) have been withdrawn. For it \( ER_2^2 = 1.87 \) (instead of 2.84) and the mean quadratic deviation of all the remaining data is 0.174. Nevertheless \( \langle Q \rangle_0 \) was changed by less than 12 percent and this value could be used to evaluate the accuracy of the integrated values of \( Q(v) \) for the recommended curve A. Another test for accuracy is curve C in Fig.2 for which \( \langle Q \rangle_0 \) was changed by less than 25 percent.

Although the withdrawal of experiment No.9 did not change curve A when using different sets of knots a family of curves was obtained with quite different positions of the two maxima and the minimum. Therefore experiment No.9 is crucial for the determination of their location but only used together with No.1 - 8.

The last check consisted in comparing for a particular experiment \( R_i \) calculated using curve A with \( R_i \) calculated using the curve \( Q(v) \) obtained when this particular experiment was withdrawn from the procedure. The largest change was when experiment No.2 was withdrawn - then the maximum value of \( R_i \) for No.2 was increased from 0.17 to 0.67. This is because experiment No.2 alone provides information about \( \langle Q \rangle_0 \) in the range of \( T_e \) near 500 K. The withdrawal of experiment No.7 increased its \( R_i \) from 0.40 to 0.55.

For No.9 the change in \( R_i \) was up to 0.20 but the maximum deviation was not changed. For all the other experiments the changes of \( R_i \) were less than 0.11.
VI. CONCLUSION

The recommended curve A is probably unique in the sense discussed in Section III, i.e. if it is supposed to be smooth enough and to have not more than two maxima and one minimum. The possible variations of its form are given by the other curves in Fig.2 and 5. The first maximum is situated between $v = 2$ and $2.5 \times 10^7$ cm/s, the minimum - between 2.8 and $3.3 \times 10^7$ cm/s and the second maximum - between 3.7 and $4.4 \times 10^7$ cm/s. In the future a direct beam-type measurement of $Q(v)$ for at least one value of $v$ with a spread $\Delta v$ not exceeding $0.2 \times 10^7$ cm/s (equivalent to $\Delta \varepsilon = 0.04$ eV at electron energy $\varepsilon = 0.4$ eV) is highly desirable. Another alternative is to have available experimental measurements like No. 1 - 9 with substantially higher accuracy.

The data of Table 2 representing curve A can be used in all kinds of calculations of transport properties in the range 500 - 2500 K with an error probably not exceeding 20 percent. The concept of a mean cross-section could be wrong by one order of magnitude - for example the ratio $\langle Q \rangle^{\lambda} : \langle Q \rangle^{\alpha} : \langle Q \rangle^{V}$: at 2000 K is 1 : 3 : 10.

VII. ACKNOWLEDGEMENTS

The author is particularly grateful to Prof.dr.J.Kistemaker and to Prof.dr.L.H.Th.Rietjens for the opportunity to perform this work in the Eindhoven University of Technology (THE) and for the discussion of the results. He highly appreciates the constant help and encouragement of Dr.A.Veefkind and the other colleagues from the group Direct Energy Conversion at THE.
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As $f_e$ is not Maxwellian the values of $T_e$ are calculated from the mean logarithmic slope of $f_e$ (obtained using curve A of Fig.2) in the range 0.1-1 ev.

Table 1. Characteristics of the experimental works used to find $Q(v)$. 

<table>
<thead>
<tr>
<th>No</th>
<th>References</th>
<th>Number of experimental points considered</th>
<th>Overall weight of the points</th>
<th>$f_e$ is Maxwellian</th>
<th>Coulomb interactions</th>
<th>Eq. (2) used to find $T_e$</th>
<th>$T_e$ range (K)</th>
<th>$N_{eq}/N_{eq}$</th>
<th>Equation used to integrate $Q(v)$</th>
<th>Parts of $Q(v)$ related to the measured quantity</th>
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<td>(22)</td>
<td>min</td>
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<td>no</td>
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<td>0</td>
<td>(14)</td>
<td>min</td>
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<tr>
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<td>1600-2000</td>
<td>$10^2$-$10^4$</td>
<td>(14)</td>
<td>min max</td>
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<td>yes</td>
<td>2100-2400</td>
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<td>(14) &amp; (3)</td>
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<td>(31)</td>
<td>all (strong dependence)</td>
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</table>

$^a$
Table 2. Recommended values of the electron-cesium atom momentum transfer cross-section (curve A in Fig.2).
Fig. 1. The logarithm of the ratio measured/calculated electrical conductivity. The electron temperature is calculated from the energy equation. Curve 1: current density $j = 1 \text{ A/cm}^2$, curve 2: $j = 10 \text{ A/cm}^2$, both for Ar + Cs plasma with $P_{\text{Ar}} = 760$ Torr and $P_{\text{Cs}}$ decreasing from 4.71 to 0.27 Torr [28]. Curve 3: $P_{\text{Cs}} = 8$ Torr, curve 4: $P_{\text{Cs}} = 1$ Torr, both for Cs plasma with heavy particles temperature increasing from 1400 to 1800 K [33].
Fig. 2. Electron-cesium atom momentum transfer cross-section obtained from the experimental values of different transport coefficients. Internal knots (values of the electron velocity in $10^7$ cm/s for the points of smooth transition from one to another cubic polynomial) as follows: curve A (best solution): 2, 2.4, 2.8, 3.2, 3.6, 4.5, 6; another curve practically coinciding with curve A: 1.5, 2, 2.5, 3, 3.75, 4.5, 6; B: 2, 2.5, 3, 3.5, 4, 4.75, 6.25; C: 1.8, 2.6, 3, 3.4, 3.8, 4.5, 6 (curve C is obtained with the electrical conductivity data [38] instead of [26, 31], the former being 2 to 3 times higher than the latter).
Fig. 3. Relative deviations $R_i = \ln \left( \frac{K_{\text{exp}}}{K_{\text{calc}}} \right)$ or $\ln \left( \frac{\langle Q \rangle_{\text{calc}}}{\langle Q \rangle_{\text{exp}}} \right)$ of 9 different experiments listed in Table 1. Curve A from Fig. 2 is used in the calculations. Three curves representing experiment No. 4 correspond to different cesium pressures: a: 0.1 Torr, b: 1 Torr, c: 10 Torr.
Fig. 4. Relative deviations of 9 different experiments listed in Table 1 from the calculated values. \( Q(v) \) of Nighan and Postma [21] (their curve A) is used. For \( Q(v) \) proposed by Postma [43] only the deviations of experiments No. 6 and 9 are substantially changed.
Fig. 5. Change of curve A from Fig. 2 when some of the experimental data are withdrawn from the procedure of minimization of the deviations: D: without experiment No. 1; E: without No. 2; F: without No. 7.
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