International Atomic Energy Agency

INDC(NDS)-253/N2

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

IAEA CONSULTANTS' MEETING ON

"HE-BEAM DATA BASE FOR ALPHA PARTICLE DIAGNOSTICS OF FUSION PLASMAS"

Vienna, June 3-5, 1991

SUMMARY REPORT

Prepared by R.K. Janev

January 1992

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

INDC(NDS)-253/N2

IAEA CONSULTANTS' MEETING ON

"HE-BEAM DATA BASE FOR ALPHA PARTICLE DIAGNOSTICS OF FUSION PLASMAS"

Vienna, June 3-5, 1991

<u>SUMMARY REPORT</u>

Prepared by R.K. Janev

January 1992

Abstract

The present Report contains the Summary of the IAEA Consultants' Meeting on "He-Beam Data Base for Alpha Particle Diagnostics of Fusion Plasmas" which was organized by the Atomic and Molecular Data Unit and held on June 3-5, 1991 at the IAEA Headquarters in Vienna, Austria. The Meeting Proceedings are briefly described and the reports of the Working Groups on the electron- and ion-impact processes are reproduced. A survey on the atomic data needs and required cross section accuracies for helium beam stopping calculations and alpha particle diagnostics of JET- and ITER-like plasmas is included. The conclusions and recommendations of the Meeting regarding the status of present data base (availability and quality) and the needs for its improvement are also given in this Summary Report.

Reproduced by the IAEA in Austria
January 1992

92-00160

Table of Contents

1. INTRODUCTION

Following a recommendation of the Subcommittee on Atomic and Molecular (A+M) Data for Fusion of the International Fusion Research Council, given at its 6th Meeting (October, 1990), the IAEA Atomic and Molecular Data Unit convened on June 3-5, 1991, a Consultants' Meeting on "He-Beam Data Base for Alpha Particle Diagnostics of Fusion Plasmas" at the IAEA Headquarters in Vienna.

The Meeting objectives were:

1) to review the available atomic data base required in the He-beam alpha particle diagnostics of fusion plasmas, and
2) to establish a selfconsistent set of recommended data for He-beam attenuation in plasmas and alpha particle diagnostics.

The Meeting was attended by 17 participants (see Appendix 1), representing both the fusion and atomic physics communities. Well before the Meeting, the participants were asked to perform either a compilation and preliminary assessment of the available data or to generate a substantial amount of new, accurate theoretical data for the processes with defficient or inadequate data base. The participants from fusion community were asked to provide surveys of the atomic data needs for He-beam penetration and diagnostics of fusion alphas, including indication of required data accuracies. The participants have thoroughly performed these tasks which resulted in a very efficient work of the meeting. The presentations at the meeting, after their appropriate formatting and completion, will be published in "Atomic and Plasma-Material Interaction Data for Fusion" vol. 3 (1992), and the recommended cross section data will be included in the databases of the IAEA (ALADDIN) and major fusion laboratories (JET, PPPL, Kurchatov Institute, etc).

2. MEETING PROCEEDINGS

After adopting the Meeting Agenda (see Appendix 2), the work of the meeting proceeded in the following sessions:

1) Atomic data needs for He-beam penetration into fusion plasmas and alpha particle diagnostics;
2) Electron collisions with helium;
3) Heavy-particle collisions with helium;
4) Specification of the required He-beam data base;
5) Data evaluation and selection of the best data sets;
6) Meeting conclusions and recommendation.

Below we give a brief description of the presentations and discussions in the sessions.

In an introductory talk given in the first session, M. Petrov described the physical and experimental basis for fusion alpha particle diagnostics including both the charge exchange recombination scheme (based on the single electron state-selective capture reaction $He^{o}(D^{o}) + He^{2+} \rightarrow He^{+}\ (D^{+}) + He^{+*}$ and the emmission ($n=4 \rightarrow n=3$) of the He^{+*} excited product) and the neutral particle analysis scheme (based on the double-electron capture reaction $He^{o} + He^{2+} \rightarrow He^{2+} + He^{o}$). While for the first diagnostic scheme, the typical beam energies (as anticipated for use in JET) are on the order of 50 keV/amu, the use of the second technique requires He^{o} with energies on the order of 80-160 keV/amu (e.g. for JET) and up to 880 keV/amu (for ITER). The critical role of the knowledge of accurate atomic cross sections for optimization of the diagnostic schemes was emphasized in this talk. H.P. Summers presented an exhaustive review of the atomic data requirements for the JET He-beam based charge-exchange diagnostics of slowed-down fusion alpha particles. The collision energy range of interest extends from 20 keV/amu to 100 keV/amu (corresponding beam energies are up to 30 keV/amu for ^{4}He and 53 keV/amu for ^{3}He). Summers discussed in detail the required cross section accuracies for the collision processes involved in the He-beam attenuation and in the kinetic scheme of charge-exchange recombination diagnostic method. The role of beam metastable fractions in the beam attenuation kinetics and signal analysis has also been elucidated in Dr. Summer's presentation. In the presentation of A.A. Korotkov the question of sensitivity of He-beam stopping cross section on the accuracy of the cross sections for specific collision processes (and classes of processes) has been addressed. An extensive set of beam stopping cross section calculation was performed by varying the individual collision cross sections within the range of a factor of two or so, and the effective beam energy (E_b/Z) between 100 and 1000 keV/amu (Z is the impurity ion charge). A detailed table of required cross section accuracies for individual (and/or classes of) processes has been provided for the effective beam energy E_b/Z in the ranges 100-200 keV/amu and 0.5-1 MeV/amu, plasma densities in the range 10^{13}-10^{15} cm^{-3}, and plasma temperatures of 10-20 keV. A similar and independent sensitivity analysis of the beam attenuation results on the individual collision cross sections has also been presented by R.E. Olson for beam energies in the range 0.5-1 MeV/amu, plasma density of 10^{14} cm^{-3} and plasma temperature of 10 keV. Apart from the information regarding the accuracy requirements for different collision cross sections, this study provided several important findings regarding the smaller enhancement of the He-beam stopping cross section due to multistep processes with respect to that for H beams (caused by the faster dipole-allowed radiative decay of the first excited state in He), that the possible $He(2^1S)$ fraction in the He beam (produced by stripping of fast He^-) will not degrade its penetration, but any admixture of $He(2^3S)$ would have a significant effect. T. Kato presented the results of a collisional-radiative model (which included all the individual singlet and triplet states up to n=7, degenerate singlet and triplet states for n=8-10, and hydrogenic levels for n=11-20) regarding the effective ionization of a He beam (energy 50 keV - 1 MeV) penetrating into a plasma of electron density in the range 10^{10}-10^{18} cm^{-3}) and temperature 1-10 keV. The defficiencies in the available atomic data base for He-beam penetration calculations have been also extensively discussed in this report.

In the second session of the Meeting devoted to electron-impact processes of He, A. Kingston presented an extensive critical review of the theoretical data base for electron-impact excitation of ground state He atoms. Special attention in the presentation was given to the low energy region and the results of recent multi-state R-matrix calculations. The review included also the high energy region with an analysis of the results of high-energy approximations for this process. An exhaustive survey of the experimental data for electron-impact excitation of ground state helium atoms was presented by F.J. de Heer. The accuracy of the available data was carefully analyzed and renormalization procedures were suggested (and applied) for many experimental data sets to reduce their uncertainties. A set of criteria has been formulated in this presentation for selection of the best available data and construction of a recommended data base for electron-impact excitation of He. T. Kato presented a systematic compilation of virtually all the available (theoretical and experimental) data for excitation of He atoms (including metastable states). The data were presented in graphical form and served as useful basis for the evaluation work of the Working Group on electron-impact processes.

In the Meeting session on heavy-particle collisions, the theoretical data base for excitation of helium by proton and impurity ion impact was thoroughly reviewed by W. Fritsch. The accuracy level which can be provided by various theoretical methods for cross section calculations in different energy regions was discussed in detail. An extensive set of new excitation cross section data for collisions of He with multiply charged ions, generated by the atomic orbital coupled-channel method, has been also presented in Dr. Fritsch's talk. A comprehensive compendium of experimental cross section data for excitation of a variety of singlet transitions in He by protons and multiply charged ions has been presented by K.-H. Schartner. A significant portion of these data has been reported for the first time. It has been demonstrated that the excitation cross sections for a given term series scale as n^{-3} (n being the principal quantum number of excited one-electron state) and, except for H^+ and He^{2+}, they follow a (charge state) q-scaling (to within 20%) in the scaled energy (E/q) range between 10 keV/amu and 100 keV/amu. A comprehensive review of the theoretical and experimental data on inelastic processes taking place in collisions of H^+ and He^{2+} with He^o, He^* (2^1S) and He^+ has been presented by R.E. Olson. The presentation was supplemented by a large amount of new classical-trajectory Monte Carlo inelastic cross section calculations for the above systems in the energy range from 100 keV/amu to 2 MeV/amu. The considered processes included: ionization (of He^o, He^*, He^+ and He^{+*}), excitation (of He^o and He^+), excitation transfer between He^* and He^{+*} (in particular for the metastable $He(2^1S)$ state), single and double electron capture from He^o and He^* and single capture from He^+. The scaling of the cross sections for single and double electron removal was also discussed. A similarly extensive review of the charge exchange and ionization collisions of multiply charged ions with helium atoms has been presented in this session by H.B. Gilbody. The review included a critical analysis of the accuracy of the available data for these processes, a selection of data recommendable for use in fusion applications and discussion of the validity of existing cross section scaling relationships. J. Reading provided an in-depth analysis of the potential of various high-energy (first-and second-order) theoretical methods for generation of accurate cross sections for the inelastic processes in He^{2+} - He collisions. A special attention in this analysis was given to the choice of the basis, the treatment of continuum states and the inclusion of correlation effects. The adequacy of particular second-order methods (continuum distorted wave (CDW) approximation, 2nd Born, one-and-a half centre expansion (OHCE)) for description of specific processes (charge exchange, excitation, ionization) in the He^{2+} - He (and, in general, in A^{q+} - He) system was discussed and some illustrative results were shown. A comprehensive set of new data have been reported at the meeting by R. Gayet for the electron capture, excitation and ionization processes in high energy collisions of He with H^{+}, He^{2+} and other multiply charged ions of fusion interest. Systematic state-selective electron capture cross sections for He - A^{Z+} collisions (A=H, He, Li, Be, B, C, N, O; Z being the nuclear charge of A) in the impact energy range from 70 keV/amu to 15 MeV/amu were reported. These cross sections have been calculated by using the CDW-2 computer program and a Hartree-Fock-Slater description of initial state orbitals. Results on the excitation of He(1s2ℓ) and He(1s3ℓ) states in collisions with medium- to high-energy fully stripped ions, obtained by using the Schwinger variational principle, were also presented. Cross sections for transfer ionization (capture + ionization) and double ionization, obtained in the independent particle model but with correct treatment of individual transitions were reported for a number of fully stripped ions colliding with He at 1.4 MeV/amu.

R. Hoekstra presented an evaluated data base for the total and state-selective electron capture cross sections in H^{+}, He^{2+} + He low- to intermediate-energy collisions, prepared for use in JET He-beam diagnostics. The evaluated set of data is based on the best available experimental and theoretical cross section information and satisfies certain self-consistency criteria. An analysis of the accuracy of a number of cross section collections for excitation and ionization of helium by protons and multicharged ions was reported by V. Abramov. This analysis showed that there exist inconsistencies in the collisional data bases for He presently used in fusion applications, which are particularly significant in the case of excitation.

In session 4 of the Meeting, the participants discussed the general situation of the atomic data base for the He-beam alpha particle diagnostics of fusion plasmas (availability, quality, defficiencies) and on the basis of the reports from the preliminary studies regarding the sensitivity of the beam stopping cross sections on the cross sections of individual processes (and classes of processes), they identified the most important processes which should be included in the calcualtions of beam attenuation kinetics and in the optimization of diagnostic techniques. For a detailed analysis of the required data accuracies and for evaluation of the available data (including those reported at the Meeting), the participants during the fifth session of the Meeting split into three Working Groups (WGs):

1) WG for Required Data and Accuracies;
2) WG for Electron-Impact Processes;
3) WG for Ion-Impact Processes.

The results of the work performed by these Working Groups are summarized in their reports which are given in the next section.

At the last plenary session of the Meeting, the participants discussed and adopted the Reports of the Working Groups and formulated the conclusions and recommendations of the Meeting. These are reproduced in Section 4 of the present Report.

3. WORKING GROUP REPORTS

3.1. Survey of atomic data base needs and accuracies for helium beam stopping and alpha particle diagnostics for ITER

H.P. Summers and M. von Hellermann*

1. Introduction.

This report is concerned with establishing a recommended collection of atomic collision data for the modelling , experimental investigation and exploitation of helium beams. The initial and principal motivation stems from proposals for diagnostic beams for ITER, targeted at alpha particle measurement via double charge transfer/neutralised alpha analysis and spectroscopic analysis of recombination radiation. For the former, a 50keV/u helium beam is suggested and for the latter, a 100keV/u hydrogen beam. In the essentially abstracted exercise of atomic data judgement, it is necessary to avoid an over-restricted view of the requirements, particularly in collision energies. Evolution and modification of ideas is rapid in this field and will occur because of progress or lack of progress in beam development, because of information arising from existing fusion machines, and because of the linking of other beam/plasma validation experiments to the alpha particle detection task. In this respect, we note three points. Firstly beam emission spectroscopy (BES) and if possible charge exchange spectroscopy (CXS) should ideally be conducted in parallel with neutral particle analysis using the same (helium) beam. This maximises the mutual diagnostic support although strictly beam penetration and charge exchange state selectivity factors favour CXS with hydrogen beams. Secondly, evolution of related particle distribution functions such as slowing and thermalised alpha particles, the He^+ beam plume and the total helium inventory will be examined simultaneously with beam stopping and alpha particle source functions by modellers. Finally, models and the usefulness of the atomic data base will be assessed experimentally for some considerable period of time only on the present generation of machines. In this context, the JET experiment is particularly important since it is operating ^3He and ^4He beams at up to 55 keV/u and is commisioning neutral particle analysis, BES and CXS viewing these beams. The beams are the heating beams and therefore may allow assessment of minimum requirements for ITER diagnostic beams. In summary the helium data base should span possible ITER diagnostic beams and existing JET heating beams, enable alpha particle detection by neutral particle analysis and CXS, and support concommittant BES and CXS beam validation studies.

2. Beam energies, species and plasma conditions.

Detection of neutralised alpha particles using neutral helium beams depends on (i) penetration of the neutral helium beam to the point of collision with an alpha particle, (ii) neutralising of the alpha particle by double charge transfer, (iii) escape of the He^0 from the plasma for measurement. Since alpha particles are born by deuterium/tritium fusion at 880keV/u, this energy sets the upper limit for He^0 ion/atom stopping cross-sections. The lower limit is set by the beam He^0 particles in collision with thermal plasma ions. A beam energy $\sim$30keV/u (JET ^4He beams) and plasma ion

* Contributor to the final version of the survey.

temperatures up to 30keV (15keV/u for D^+) would set ~1keV/u as the lower limit for ion/atom collision cross-sections. For ITER helium beams , which should certainly have particle energies ≥50keV/u, a lower energy limit for cross-sections ~10-20 keV/u is adequate. It should be noted that at 50keV/u, helium beams would only penetrate one quarter of the ITER minor plasma radius and not be capable of detecting central alpha particle sources.
Electron collisions contribute to beam stopping. Electron temperatures > 1keV corresponding to the low density plasma periphery, up to 25keV at the plasma core are relevant. However noting the sideline interest of HeI plasma edge emission for helium recycling and the helium inventory, and the present state of e/He^0 data, it is appropriate now to recommend cross-sections complete in energy from threshold to infinity.

Only fully ionised low and moderate mass ions, in collision with He^0 need to be considered. Of principal importance are the D^+, T^+ fuel and the He^{+2} ash or added minority. Other relevant impurities are due to choices of plasma facing first wall materials and then deposition and gettering strategies. This gives in order of importance C^{+6} (walls, X-point target plates, limiters, carbonisation), Be^{+4} (JET X-point target plates, limiters and evaporation) and B^{+5} (boronisation). The gettering procedures have reduced the importance of oxygen, but nontheless O^{+8} must be included. Other species are of less concern. Titanium, iron and nickel are possible structural materials, neon and argon useful added trace gases for diagnostics, and silicon a possible impurity. A representative set through the second and third period which would act as a basis for interpolation is Ne^{+10}, Si^{+14},Ar^{+18}, Fe^{+26}.

It is appropriate to make a broad statement of minimum accuracy requirements in cross-section data although more specific assessments are made in later contributions. Typically detector calibration, window transmission variation, spectral feature isolation and uncertainties in temperature and density profiles limit experimental accuracy to >40%, so this is the acceptable accuracy for modelling prediction of the final observed quantities. Therefore in beam driven diagnostics, 30% error in beam attenuation and 30% error in local particle production coefficients (eg. He^0 by neutralising) or photon effective emission coefficients (eg. by single charge transfer in CXS) calculation is acceptable. Beam attenuation up to a factor 10 is typically encompassed in an experiment, therefore net stopping cross-sections at <10% accuracy are required. Individual acceptable cross-section tolerances are then in inverse proportion to their contribution. Impurity cross-sections scale at worst as Z^2 and so their acceptable tolerances are in inverse proportion to Z^2 times the fractional impurity abundance. Helium fractional abundance at up to 20% may be expected in fusion plasmas, but experimental test plasmas of pure helium are possible. Carbon and light impurities at <5% are anticipated. The contribution of each impurity to Zeff is a helpful measure of its importance.

3. The required cross-section data

In presenting the following, it has been convenient to allow some repetition of cross-sections so that the different areas can appear complete. A coding (*1) - (*6) has been used to rank importance. A minimum accuracy is suggested with an indication of its variation with energy. For beam stopping, the accuracy is based on the proportion of each individual cross-section's contribution and its being the sole source of error. This is of course subject to revision in the light of improvement of our cross-section knowledge and progress in modelling. The lower limit for accuracy is set at 100%. Impurity cross-section accuracies are assessed as though the impurity alone is contributing. Zeff based adjustment of these as described in section 2 is appropriate. For electron collisions, for the reasons mentioned in section 2, 20% accuracy is suggested at all energies.

3.1. Alpha particle neutralisation

This is the essential reaction between beam He^0 and the alpha particle produced by deuterium/tritium fusion which allows the neutral particle diagnostics to probe the alpha particle sources.

He^{+2} neutralisation

(*1) $He^0(1^1S) + He^{+2} \rightarrow He^{+2} + He^0$,	20%

3.2. Beam and fusion He^0 stopping at low density

Most helium is in its ground state so that the dominant stopping is by electron loss directly from the ground state. If the plasma density is very low so that excited helium populations are negligible, this is the only pathway.

Ground state single electron loss with primary species and impurities

(*1) $He^0(1^1S) + D^+ \rightarrow He^+ + D^+ + e$,	87% @ 20keV/u, 13% @ > 100keV/u
(*1) $He^0(1^1S) + D^+ \rightarrow He^+ + D^0$,	11% @ 20keV/u, 42% @ > 100keV/u
(*1) $He^0(1^1S) + He^{+2} \rightarrow He^+ + He^{+2} + e$,	100% @ 20keV/u, 18% @ > 100keV/u
(*1) $He^0(1^1S) + He^{+2} \rightarrow He^{+1} + He^{+1}$,	16% @ 20keV/u, 20% @ > 100keV/u
(*2) $He^0(1^1S) + X^{+z} \rightarrow He^+ + X^{+z} + e$,	100% @ 20keV/u, 47% @ > 100keV/u
(*2) $He^0(1^1S) + X^{+z} \rightarrow He^{+1} + X^{+z-1}$,	12% @ 20keV/u, 19% @ > 100keV/u

[With the data at this stage, an approximate stopping can be obtained. However improvement at lower beam energies requires the following:]

Ground state double electron loss with primary species and impurities

(*2) $He^0(1^1S) + D^+ \rightarrow He^{+2} + D^+ + e + e$,	100%
(*2) $He^0(1^1) + D^+ \rightarrow He^{+2} + D^0 + e$,	100%
(*2) $He^0(1^1S) + He^{+2} \rightarrow He^{+2} + He^{+2} + e + e$,	100%
(*2) $He^0(1^1S) + He^{+2} \rightarrow He^{+1} + He^{+1} + e$,	100%
(*2) $He^0(1^1S) + He^{+2} \rightarrow He^{+2} + He^0$,	33% @ 20keV/u, 100% @ > 100keV/u
(*3) $He^0(1^1S) + X^{+z} \rightarrow He^{+2} + X^{+z} + e + e$,	83% @ 20keV/u, 44% @ > 100keV/u
(*3) $He^0(1^1S) + X^{+z} \rightarrow He^{+1} + X^{+z-1} + e$,	83% @ 20keV/u, 44% @ > 100keV/u
(*3) $He^0(1^1S) + X^{+z} \rightarrow He^{+2} + X^{+z-2}$,	100%

Ground state ionisation by electron impact

(*2) $He^0(1^1S) + e \rightarrow He^+ + e + e$,	20%

3.3. Beam and fusion He^0 stopping at moderate and high density

At plasma densities appropriate to ITER, impact excitation of helium from its ground state to excited states is sufficiently large for the latter populations to be non-negligible. Then electron loss from the excited states can occur before return to the ground. This enhances the stopping. The metastable state (1s2s ^1S and 1s2s ^3S) populations are the most important in this respect, so cross-sections involved in their formation and destruction are the first priority. Thereafter other excited state populations up to an effective cut-off principal quantum shell, at which Lorentz electric field or collisional merging to the continuum occurs, matter.

Ground state excitation to the n= 2 shell by primary species and impurities

(*2) $He^0(1^1S) + D^+ \rightarrow He^0(2^1S, 2^1P) + D^+$, 100%
(*2) $He^0(1^1S) + He^{+2} \rightarrow He^0(2^1S, 2^1P) + He^{+2}$, 100%
(*3) $He^0(1^1S) + X^{+z} \rightarrow He^0(2^1S, 2^1P) + X^{+z}$, 100%

Ground state excitation to the n= 2 shell by electrons

(*3) $He^0(1^1S) + e \rightarrow He^0(2^1S, 2^1P, 2^3S, 2^3P) + e$, 20%
[It is to be noted that ion impact excitations are spin system preserving, while electron collisions allow exchange]

n= 2 state single electron loss with primary species, impurities and electrons

(*2) $He^0(2^{2S+1}L) + D^+ \rightarrow He^+ + D^+ + e$, 100%
(*2) $He^0(2^{2S+1}L) + D^+ \rightarrow He^+ + D^0$, 100%
(*2) $He^0(2^{2S+1}L) + He^{+2} \rightarrow He^+ + He^{+2} + e$, 100%
(includes inner electron ionisation)
(*2) $He^0(2^{2S+1}S) + He^{+2} \rightarrow He^{+1} + He^{+1}$, 100%
(*3) $He^0(2^{2S+1}L) + X^{+z} \rightarrow He^+ + X^{+z} + e$, 100%
(includes inner electron ionisation)
(*3) $He^0(2^{2S+1}S) + X^{+z} \rightarrow He^{+1} + X^{+z-1}$, 100%
(*3) $He^0(2^1S, 2^1P, 2^3S, 2^3P) + e \rightarrow He^+ + e + e$, 20%

Redistributive collisions within the n= 2 shell by primary species, impurities and electrons

(*2) $He^0(2^{2S+1}L) + D^+ \rightarrow He^0(2^{2S+1}L') + D^+$, 100%
(*2) $He^0(2^{2S+1}L) + He^{+2} \rightarrow He^0(2^{2S+1}L') + He^{+2}$, 100%
(*3) $He^0(2^{2S+1}L) + X^{+z} \rightarrow He^0(2^{2S+1}L') + X^{+z}$, 100%
(*3) $He^0(2^{2S+1}L) + e \rightarrow He^0(2^{2S'+1}L') + e$, 20%
[With the data at this stage, the 2^1S state populations and enhanced stopping via the singlet side can be obtained approximately. The 2^3S state population is incorrect and requires the following:]

Ground state excitation to the 2<n≤4 shells by primary species and impurities

(*3) $He^0(1^1S) + D^+ \rightarrow He^0(n^1L) + D^+$, 100%
(*3) $He^0(1^1S) + He^{+2} \rightarrow He^0(n^1L) + He^{+2}$, 100%
(*4) $He^0(1^1S) + X^{+z} \rightarrow He^0(n^1L) + X^{+z}$, 100%
[It is to be noted that excitation to 4^1F opens access to the triplet side through state mixing with 4^3F]

Ground state excitation to the 2<n≤4 shell by electrons

(*3) $He^0(1^1S) + e \rightarrow He^0(n^1L, n^3L) + e$, 20%

$2<n\leq 4$ state single electron loss with primary species, impurities and electrons

(*3) $He^0(n^{2S+1}L) + D^+ \rightarrow He^+ + D^+ + e$,	100%
(*3) $He^0(n^{2S+1}L) + D^+ \rightarrow He^+ + D^0$,	100%
(*3) $He^0(n^{2S+1}L) + He^{+2} \rightarrow He^+ + He^{+2} + e$,	100% (includes inner electron ionisation)
(*3) $He^0(n^{2S+1}S) + He^{+2} \rightarrow He^{+1} + He^{+1}$,	100%
(*4) $He^0(n^{2S+1}L) + X^{+z} \rightarrow He^+ + X^{+z} + e$,	100% (includes inner electron ionisation)
(*4) $He^0(n^{2S+1}L) + X^{+z} \rightarrow He^{+1} + X^{+z-1}$,	100%
(*4) $He^0(n^{2S+1}L) + e \rightarrow He^+ + e + e$,	20%

Redistributive collisions between $2\leq n,n'\leq 4$ shells by primary species, impurities and electrons

(*3) $He^0(n^{2S+1}L) + D^+ \rightarrow He^0(n'^{2S+1}L') + D^+$,	100%
(*3) $He^0(n^{2S+1}L) + He^{+2} \rightarrow He^0(n'^{2S+1}L') + He^{+2}$,	100%
(*4) $He^0(n^{2S+1}L) + X^{+z} \rightarrow He^0(n'^{2S+1}L') + X^{+z}$,	100%
(*4) $He^0(n^{2S+1}L) + e \rightarrow He^0(n'^{2S+1}L') + e$,	20%

Residual cross-sections up to $n=10$ by primary species, impurities and electrons

(*5) $He^0(n) + D^+ \rightarrow He^0(n') + D^+$,	100%
(*5) $He^0(n) + He^{+2} \rightarrow He^0(n') + He^{+2}$,	100%
(*6) $He^0(n) + X^{+z} \rightarrow He^0(n') + X^{+z}$,	100%
(*5) $He^0(n) + e \rightarrow He^0(n') + e$,	20%

[Spin system merging and l-subshell mixing is large beyond $n=4$ and merging with the continuum by field ionisation occurs by $n=10$ typically.]

3.4. Beam emission spectroscopy

Spectral emission from the beams is an important opportunity for experimental verification of beam attenuation and of the correctness of the enhancements attributed to the finite plasma density. Exploitation of the scope of beam emission spectroscopy dictates that emission from helium excited states up to the $n=4$ shell should be modelled carefully. For example the transitions $4\,^1L - 2\,^1P$ are of particular interest since the forbidden components and linear Stark shifts are diagnostic. The overall atomic data requirements are the same as for beam stopping at moderate and high density. However the priority and accuracy for processes populating and depopulating upper states of observable spectrum lines are altered. These are repeated here.

Ground state excitation to the $2<n\leq 4$ shells by primary species and impurities

(*2) $He^0(1^1S) + D^+ \rightarrow He^0(n^1L) + D^+$,	30%
(*2) $He^0(1^1S) + He^{+2} \rightarrow He^0(n^1L) + He^{+2}$,	30%
(*2) $He^0(1^1S) + X^{+z} \rightarrow He^0(n^1L) + X^{+z}$,	30%

Ground state excitation to the $2<n\leq 4$ shell by electrons

(*2) $He^0(1^1S) + e \rightarrow He^0(n^1L, n^3L) + e$, 20%

[Initial estimates suggest that 4^1L - 2^1P on the singlet side and 3^3P - 2^3S on the triplet side should be studied experimentally.]

2<n≤4 state single electron loss with primary species, impurities and electrons

(*2) $He^0(n^{2S+1}L) + D^+ \rightarrow He^+ + D^+ + e$,	36% @ 20keV/u, 36% @ > 100keV/u
(*2) $He^0(n^{2S+1}L) + D^+ \rightarrow He^+ + D^0$,	100%
(*2) $He^0(n^{2S+1}L) + He^{+2} \rightarrow He^+ + He^{+2} + e$,	36% @ 20keV/u, 39% @ > 100keV/u (includes inner electron ionisation)
(*2) $He^0(n^{2S+1}L) + He^{+2} \rightarrow He^{+1} + He^+$,	49% @ 20keV/u, 100% @ > 100keV/u
(*3) $He^0(n^{2S+1}L) + X^{+z} \rightarrow He^+ + X^{+z} + e$,	42% @ 20keV/u, 32% @ > 100keV/u (includes inner electron ionisation)
(*3) $He^0(n^{2S+1}L) + X^{+z} \rightarrow He^+ + X^{+z-1}$,	100%
(*3) $He^0(n^{2S+1}L) + e \rightarrow He^+ + e + e$,	20%

Redistributive collisions between 2≤n,n'≤4 shells by primary species, impurities and electrons

(*2) $He^0(n^{2S+1}L) + D^+ \rightarrow He^0(n'^{2S+1}L') + D^+$,	30%
(*2) $He^0(n^{2S+1}L) + He^{+2} \rightarrow He^0(n'^{2S+1}L') + He^{+2}$,	30%
(*3) $He^0(n^{2S+1}L) + X^{+z} \rightarrow He^0(n'^{2S+1}L') + X^{+z}$,	30%
(*3) $He^0(n^{2S+1}L) + e \rightarrow He^0(n'^{2S'+1}L') + e$,	20%

3.5. Charge exchange spectroscopy

State selective single electron charge transfer from neutral helium beam atoms in their ground state to alpha particles forming excited states of He^{+1} is the initial concern. Subsequent HeII emission, such as n=4-3 at 4685A, is the CXS signal to be contrasted with the neutral particle analyser signals. There is a futher aspect however , in that, neutral helium beams may be useable in CXS for all light impurity densities. Consistency with impurity densities used for modelling beam stopping may then be sought.

State selective charge transfer from ground state to primary species

(*2) $He^0(1^1S) + He^{+2} \rightarrow He^+ + He^+(nl\,^2L)$, 30%

(*2) $He^0(1^1S) + D^+ \rightarrow He^+ + D(nl\,^2L)$, 30%

[The first is the key reaction for CXS. The second is relevant for formation of the D^0 halo associated with the helium beams. For He, 1≤n≤6, and for D, 1≤n≤4, are relevant ranges.]

State selective transfer ionisation from ground state to primary species

(*4) $He^0(1^1S) + He^{+2} \rightarrow He^{+2} + He^+(nl\,^2L) + e$, 100%

(*4) $He^0(1^1S) + D^+ \rightarrow He^{+2} + D(nl\,^2L) + e$, 100%

[These reactions tend to populate low n shells. They provide a correction of CXS using short wavelength transitions.]

State selective charge transfer from metastables to primary species

(*4) $He^0(2^1S, 2^3S) + He^{+2} \rightarrow He^+ + He^{+1}(nl\ ^2L)$,   100%
(*4) $He^0(2^1S, 2^3S) + D^+ \rightarrow He^+ + D(nl\ ^2L)$,   100%
[These reactions are most relevant at low beam energies and to CXS with visible lines since the dominant receiving n-shell is usually close to the line emitting n-shell. Expectations of beam metastable populations suggest this is only a modest correction. For He, $1 \leq n \leq 6$, and for D, $1 \leq n \leq 4$, are relevant ranges.]

State selective charge transfer from ground state to impurities

(*3) $He^0(1^1S) + X^{+z} \rightarrow He^+ + X^{+z-1}(nl\ ^2L)$,   30%
[This allows a full CXS diagnostic for impurities using helium beams. The relevant range is $1 \leq n \leq 2z^{0.75}$.]

4. Conclusions

We have sought to lay out the set of atomic collision cross-section data required to model and support alpha particle diagnostics for ITER using neutral helium beams. However, we have gone further in that we have also addressed the data required in practise to support and validate such a diagnostic fully. It is anticipated that the data will form the high quality input to comprehensive excited population, effective ionisation coefficient and effective emissivity coefficient codes in the collisional-radiative sense. There remain some anxieties. As has been mentioned, fast neutral helium atoms in tokamak plasmas will experience a strong vxB electric field establishing a Stark state structure. Whether this can alter the balance of atomic reactions significantly is largely unexplored. Also assumptions of isotropic averages of collision cross-sections cannot really be sustained. We therefore anticipate some elaboration or at least clarification of these points.

3.2. Recommended data base for electron impact excitation and ionization of helium atoms

F.J. de Heer, T. Kato, A.E. Kingstom and R.K. Janev

1. Introduction and Basic Data Sources

In the context of He-beam attenuation in plasmas and fusion alpha particle diagnostics, the cross section data base for the following electron-impact processes of He is required (we indicate the initial and final state of He):

A. Excitation

a) $1s^2 \rightarrow 1sn\ell|^1L$, $n \leqq 4$

$\rightarrow 1sn\ell|^3L$, $n \leqq 4$

b) $1sn\ell|^{2S+1}L \rightarrow 1sn'\ell'|^{2S'+1}L'$, $n,n' \leqq 4$

c) $1s^2 \rightarrow 1sn$, $5 \leqq n \leqq 7$,

d) $1sn \leqq 1sn'$, $5 \leqq n, n' \leqq 7$, $(n \neq n')$.

B. Ionization

a) $1s^2 \rightarrow He^+ + e$

b) $1sn\ell \rightarrow He^+ + e$

c) $1sn\ell \rightarrow n'\ell' + e$

d) $1sn\ell \rightarrow (n\ell, n'\ell')^{**} \rightarrow$ autoionization

$\rightarrow$ radiation

e) $1s^2 \rightarrow He^{2+} + 2e$

f) $1s^2 \rightarrow (n\ell) + e$

Because of the large variety of processes this Working Group could not establish a final recommendation for all relevant cross sections. It appears that sufficient knowledge is available for application in calculations of He beam stopping cross sections in a fusion plasma. Although for several cases more accurate cross section data can be evaluated, several existing reviews are sufficiently well provided with relevant data. They are mentioned below:

Reviews useful for He beam stopping and diagnostics in fusion plasmas.

1) R.K. Janev, W.D. Langer, K. Evans Jr. and D.E. Post Jr., "Elementary processes in hydrogen-helium plasmas. Cross Sections and Reaction Rate Coefficients", 1987, Springer Verlag., in particular pages 70-114 and 244-249.

2) T. Fujimoto, IPPJ-AM-8, 1978, "Semi-empirical cross sections and rate coefficients for excitation and ionization by electron collision and photoionization of helium", Institute of Plasma Physics, Nagoya University. Note that the first review often makes use of this report, occasionally with some corrections.

3) V.A. Abramov, L.A. Vainshtein, G.I. Krotova and A.Yu. Pigarov, INDC(CCP)-286/GA, IAEA Nuclear Data Section, 1988, "Recommended atomic data for hydrogen and helium plasmas". This article contains some bibliography on experimental and theoretical data, and theoretical results calculated numerically by the "Atom" program developed at the Lebedev Physical Institute of the USSR Academy of Sciences (FIAN, see L.A. Vainshtein and V.P. Shevel'ko: The Structure and Characteristics of Ions in a Hot Plasma", Nauka, Moscow (1986), in Russian). The results of this paper (Coulomb-Born approximation, 3-100 eV) should be critally compared with those in references 1) and 2) above and recent R-matrix close coupling calculations of Kingston et al., (see below).

4) H.P. Summers, F.J. de Heer and R. Hoekstra, "JET data base for helium beam stopping and related spectral emission in the energy region 20-100 keV/amu". The cross sections and reaction rates are partly based on the schemes used in references 1) and 2), supplemented with excitation results of R-matrix close-coupling calculations of the Belfast group (Kingston et al., see further on) near excitation threshold up to the ionization threshold, results of the first Born approximation at high energies (Bell et al. see further on) ($\gtrsim E_d$ = 1000 eV) and experimental data in between. This work is still in progress. Experimental excitation data were provided at this meeting in the reports of T. Kato and F.J. de Heer and R-matrix and Born data by A.E. Kingston. The experimental data for He(1^1S) excitation are to a large extent taken from Refs. 5) and 6) below.

5) D.W.O. Heddle and Jean W. Gallagher, Rev. of Modern Physics 61, 221, 1989. (Contains data on measurements of electron impact optical excitation functions).

6) F.J. de Heer and R.H.J. Jansen, J. Phys. B: Atom. Molec. Phys. 10, 3741, 1977. (Total cross sections for electron scattering by He).

7) B.H. Bransden and M.R.C. McDowell, Physics Reports 46, 249, 1978. Electron scattering by atoms at intermediate energies.

8) Y. Itikawa, Physics Reports, 143, 69, 1986. "Distorted wave methods in electron-impact excitation of atoms and ions".

9) L. Vriens and W. Smeets, Phys. Rev. A 22, 940, 1980, "Empirical cross section and rate formulas for electron impact ionization, excitation, and total depopulation of excited atoms".

10) K.L. Bell et al. UKAEA Report Culham CLM-R216, "Recommended cross sections and rates for electron ionisation of light atoms and ions".

11) F.J. de Heer and M. Inokuti, in: "Electron Impact Ionization", 1985, Eds. T.D. Märk and G.H. Dunn, Springer Verlag.

12) K.L. Bell, D.J. Kennedy and A.E. Kingston, J. Phys. B: Atom. Mol. Phys. 2, 26, 1969. "Accurate first Born-approximation cross sections for the excitation of helium by fast electrons" (theory and analytical expressions, at very high energies, $\gtrsim$ 10 keV; relativistic corrections may give changes ~ 5%).

13) A.E. Kingston et al. (to be published): R-matrix close coupling calculations (29-state) for different transitions with both initial ground and excited states.

2. Recommended Data for Excitation Processes

2.1. Singlet excitation from the He ground state

a) $e + He(1^1S) \rightarrow e + He(n^1S)$

	Energy Range	Method	Reference	Accuracy
2^1S	$\leqq$ 24.58 eV	R-matrix 29-state	Kingston[13]	< 10%
	24.58 $\leqq$ E $\leqq$ 50 eV	exp	Trajmar, Hall	< 10-30%
	200 $\leqq$ E $\leqq$ 700 eV	exp	Dillon	< 10%
	E > 1000 eV	Born	Bell[12]	< 5%
	24.58 $\leqq$ E $\leqq$ 1000 eV	exp empirical	de Heer[6]	< 10-20%

contd.

	Energy Range	Method	Reference	Accuracy
n^1S (n=3,4,5,6)	≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10-30%
	< 50 eV	exp	Zapesochnyi (normalized)	< 10-30%
	50-2000 eV	exp benchmark	van Zyl	< 10%
	E > 1000 eV	Born	Bell[12)]	< 5%
	all energies	review exp	Heddle[5)]	

I.P. Zapesochnyi and P.V. Feltsan, Ukr. Fiz. Zh. (Russ. Ed.) 10, 1197, 1965

Van Zyl et al., Phys. Rev. A 22, 1916, 1980

S. Trajmar, Phys. Rev. A 8, 191, 1973

R.I. Hall et al., J. Physique 34, 827, 1973

M.A. Dillon and E.N. Lassettre, J. Chem. Phys. 62, 2373, 1975

b) e + He (1^1S) → e + He(n^1P)

	Energy Range	Method	Reference	Accuracy
n^1P, (n=2,3)	E ≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10%
	25 - 2000 eV	exp	Westerveld	< 10%
	> 500 eV	Born	Bell[12)]	< 5%
	all energies	review	Heddle[5)]	
	all energies	exp empirical analytical	Shemansky	
n^1P, n=4	40 - 3000 eV	exp series III	de Jongh	< 10%
	all energies	exp empirical analytical	Shemansky	
	> 500 eV	Born	Bell[12)]	< 5%
	30 - 2000 eV	exp	Donaldson	< 10%

contd.

F.G. Donaldson, M.A. Hender and J.W. McConkey, J. Phys. B: Atom. Mol. Phys. 5, 1192, 1972

W.B. Westerveld, H.G.M. Heideman and J. van Eck, J. Phys. B: Atomic Molec. Phys. 12, 115, 1979 and references therein

D.E. Shemansky et al., Astrophysical Journal, 296, 774, 1985

J.P. de Jongh, Ph.D. Thesis, University of Utrecht 1971, Utrecht, The Netherlands

c) $e + He\ (1^1S) \rightarrow e + He(n^1D)$

	Energy Range	Method	Reference	Accuracy
n^1D, (n=3-6)				
Cuscade from ^1F levels neglected in experiment	≦ 24.58 eV	R-matrix 29-state	Kingston[13])	< 30%
	< 50 eV	exp	Zapesochnyi (normalized)	< 30%
	> 2000 eV	Born	Bell[12])	< 10%
	all energies	review exp	Heddle[5])	
n=3	80 - 2000 eV	exp	Moustafa Moussa	(scaled down with a factor of 1.15)
	50 - 80 eV	use scaling with n=4: $\sigma(4^1D)/1.9$		30%
	300 eV	exp	Showalter	30%
n=4	25 - 50 eV	exp	van Raan (1971)	20%
	300 - 2000 eV	exp	van Raan (1974)	20%
	50 - 1000 eV	exp	Moustafa Moussa	20-30%
	50 - 800 eV	exp no cascade correction	Showalter	20-30%
n=5	50 - 2000 eV	exp	Moustafa Moussa	30%
	25 - 1000 eV	exp	van Raan (1971, 1974)	30%
	300 eV	exp	Showalter	30%

contd.

	Energy Range	Method	Reference	Accuracy
n=6	100 - 1000 eV	exp	van Raan	30%
	50 - 2000 eV	exp	Moustafa	inaccurate
		scale with n=5: $\sigma(5^1D)$ 1.72		30%

A.F.J. van Raan et al., Physica 53, 45, 1971 (van Raan I)
A.F.J. van Raan et al., J. Phys. B 7, 950, 1974 (van Raan II)
H.R. Moustafa Moussa, F.J. de Heer and J. Schutten, Physica 40, 517, 1969
J.G. Showalter and R.B. Kay, Phys. Rev. A. 11, 1899, 1975

2.2. Triplet excitation from the He ground state

a) $e + He(1^1S) \rightarrow e + He(n^3S)$

		Energy Range	Method	Reference	Accuracy
2^3S,		$\leqq$ 24.58 eV	R-matrix	Kingston	< 10%
		$\leqq$ 100 eV	exp averaged; exp used:	de Heer[6]) Hall* Trajmar* Brongersma* Crooks*	< 30%
			not available then:	Johnston Joyez	
	unsolved problem	> 100 eV	Scale with exp n=4: $\sigma(4^3S)/0.14$	de Heer[6])+	uncertain
		> 60 eV	theory	Scott	deviates from de Heer+ and E_{el}^{-3} behaviour.
		45 - 200 eV	exp	Yagashita	uncertain; deviates from E_{el}^{-3} behaviour

A. Yagashita, in: W.C. Fon et al., J. Phys. B: At. Mol. Phys. 11, 186, 1979
A.R. Johnston and P.D. Burrow, J. Phys. B: T. Mol. Phys. 16, 613, 1983
C. Joyez et al., Abstracts IX ICPEAC 1975, University of Washington Press, Seattle, p. 827

contd.

T. Scott and M.R.C. McDowell, J. Phys. B: At. Mol. Phys. 8, 1851, 1975

* References available in Reference 6) and see under: singlet exciation (Section 2.1).

+ Change σ for 90 eV into σ=0.0063 a_o^2 (scaled with van Raan I)
100 eV into σ=0.0047 a_o^2.

See also T. Kato, At. Nucl. Data Tables 42, 212, 1989.

	Energy Range	Method	Reference	Accuracy
3^3S,	≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10%
	≦ 30 eV	empirical scaling $\sigma(3^3S)=2.27x\sigma(4^3S)$ at high energy (see Mathur)		< 30% at high energies E_{el}^{-3}

K.C. Mathur and M.R.H. Rudge, J. Phys. B: At. Mol. Phys. 7, 1033, 1974
For some other scattered experimental and theoretical data see A. Chutian and L.D. Thomas, Phys. Rev. A., 11, 1583, 1975
B.H. Bransden and M.R.C. McDowell: Ref. 7) and I.P. Bogdanova et al., Optics and Spectroscopy 61, 156, 1986.

	Energy Range	Method	Reference	Accuracy
4^3S,	≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10%
	≦ 50 eV	exp	Zapesochnyi normalized	< 10-30%
	25 - 100 eV	exp	van Raan I 1971	< 20%
	100 - 200 eV	exp normalized (multiplied by 1.15)	van Raan 1974	E_{el}^{-3} behaviour
	all energies	review exp	Heddle[5)]	

A.F.J. van Raan, P.G. Moll and J. van Eck, J. Phys. B: At. Mol. Phys., 7, 950, 1974

b) $e + He(1^1S) \rightarrow e + He(n^3P)$

	Energy Range	Method	Reference	Accuracy
2^3P	≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10%
	30 - 100 eV	exp	Jobe, cascade corrected by de Heer[6)]	< 30%
unsolved discrepancy	> 100 eV	extrapo- lation		$\sigma \sim E_{el}^{-3}$
	100 - 200 eV	theory	Fon	
3^3P	≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10%
	≦ 50 eV	exp normalized	Zapesochnyi	< 30%
	≦ 100 eV	exp	van Raan (1971)	< 30%
	100 - 1500 eV	exp normalized factor 1.58	van Raan (1974)	$\sigma \sim E_{el}^{-3}$
	all energies	review exp	Heddle	

A.F.J. van Raan , et al., Physica 53, 45, 1971

A.F.J. van Raan at al., J. Phys. B. 7, 950, 1974

W.C. Fon, K.A. Berrington and A.E. Kingston, J. Phys. B: At. Mol. Phys. 13, 2309, 1980

J.D. Jobe and R.M. St. John, Phys. Rev. 64, 117, 1967

Only collected but not analysed data of I.P. Bogdanova et al. Opt. and Spectroscopy 61, 156, 1986 (exp)

A. Chutjian and L.D. Thomas, Phys. Rev. 11, 1583, 1975 (exp, theory)

c) $e + He(1^1S) \rightarrow e + He(n^3D)$

	Energy Range	Method	Reference	Accuracy
2^3D	≦ 24.58 eV	R-matrix 29-state	Kingston[13)]	< 10%
	all energies	exp review	Heddle[5)]	no reli- able data
	all energies	theory (gives all theoretical and exp data)	Tully	uncertain

J.A. Tully, J. Phys. B: At. Mol. Phys. 13, 4845, 1980
I.P. Bogdanova et al., Opt. and Spectr. 61, 156, 1986 (exp) not analysed.

2.3. Electron collision induced transitions between excited helium states

Work on these processes is mainly theoretical and has to be continued. So far we have to take the recommendations cited in references 1), 2), 9) of the Introduction, and to check how the R-matrix calculations of the Belfast group (see J. Phys. B: At. Mol. Phys. 1975-1990) fit in these data. Also, the calculations by the ATOM code (see Ref. 3 of Section 1) have to be considered more carefully. Generally, cross sections in refs. 1), 2) and 9) may have accuracy better than 30%.

3. Ionisation Processes

3.1. Ionisation of He(1^1S)

$$e + He\ (1^1S) \rightarrow e + He^{+} + e$$

$$e + He\ (1^1S) \rightarrow e + He^{2+} + 2e$$

The most accurate data available at present between threshold and 10.000 eV are those of Shah et al. (J. Phys. B: At. Mol. Opt. Phys. 21, 2751, 1988, having an overall accuracy of about 5% and consistent with previous experimental and theoretical work (see Refs. 6), 10) and 11) of the Introduction).

3.2. Ionisation of excited states of He

A.J. Dixon, M.F.A. Harrison and A.C.H. Smith, J. Phys. B: At. Mol. Phys. 9, 2617, 1976 did careful measurements for electrons on metastable He mainly in the 2^3S state, (see also D.R. Long and R. Geballe, Phys. Rev. A 1, 260, 1970)

We recommend the data derived from the formulas given in Refs. 1), 2) and 9) given in the Introduction, which provide accuracies below 30%. See also theoretical Born calculations by J.S. Briggs and Y.K. Kim, Phys. Rev. A 3, 1342, 1971, for ionisation of He (2^1S) and He (2^3S).

3.3. DATABASE FOR COLLISION PROCESSES INVOLVING HELIUM ATOMS AND IONS

W Fritsch, R Gayet, H B Gilbody, R E Olson and K Schartner

1 COLLISIONS OF PROTONS AND IMPURITY IONS WITH GROUND STATE HELIUM ATOMS

The energies of primary interest range from ~ 10 to 1000 keV u^{-1}.

(a) Charge changing and ionizing collisions

The relevant processes are:–

One–electron capture

$$X^{q+} + He \rightarrow X^{(q-1)+} + He^{+} \tag{1}$$

including capture into specified excited states.

Two–electron capture

$$X^{q+} + He \rightarrow X^{(q-2)+} + He^{2+} \tag{2}$$

including capture into specified excited states.

Transfer ionization

$$X^{q+} + He \rightarrow X^{(q-1)+} + He^{2+} + e \tag{3}$$

which includes contributions from autoionization following two–electron capture into excited states.

Single ionization

$$X^{q+} + He \rightarrow X^{q+} + He^{+} + e \tag{4}$$

Double ionization

$$X^{q+} + He \rightarrow X^{q+} + He^{2+} + 2e \qquad (5)$$

For H^+, He^{2+} and Li^{3+} experimental data on total cross sections for processes (1), (3), (4) and (5) have been measured[1] to an accuracy within ± 10% over the energy range 50–2380 keV u^{-1}. These are shown in Tables 1 and 2. Similar data with an accuracy within ± 13% are available[2] for H^+ and He^{2+} for energies down to 10 keV u^{-1}.

The available data for the total two–electron capture process (2) for He^{2+} impact (see ref 3) are subject to large uncertainties ranging from ± 20% for energies up to about 400 keV u^{-1} to about a factor of two at higher energies[40]. More accurate measurements are desirable.

For ions of atomic number $Z > 3$ data are much less extensive and reliable. However scaling relations for $q \geq 4$ can provide reasonable estimates (within ± 50%) of some cross sections. For example a simple scaling relation[4] based on classical parameters given by Bohr provides total cross sections for one electron capture (1) including transfer ionization (3). Similarly a simple scaling relation based on classical trajectory Monte–Carlo (CTMC) calculations[5] provides total cross sections for one–electron removal (capture plus ionization).

Experimental data for the ratio R of the cross sections for double to single ionization increases with Z for fully stripped ions. For example, at 1.4 MeV u^{-1} it is found[6] that R increases as Z^2 for Z up to 8. For higher values of Z the departure from Z^2 scaling is believed to reflect the breakdown of the Born approximation.

Cross sections for double capture have been measured[1] to an accuracy within ± 10% for Li^{3+} impact but are not extensive for $Z > 3$. However experimental data (c.f. ref 7) indicate that while true double capture is dominant for $q \leq 4$, for primary ions with $q > 4$ the autoionizing double capture process

$$\begin{array}{l} A^{q+} + He \rightarrow A^{(q-2)+**} + He^{2+} \\ \qquad\qquad\quad \downarrow \\ \qquad\qquad\quad A^{(q-1)+*} + He^{2+} + e \end{array}$$

becomes progressively more important. Further experimental studies of these processes are required.

For $Z > 3$ data on the transfer ionization process (3) are not extensive although it is known that the ratio of cross sections for (3) to (1) increases as q increases. A simple scaling relation[8] fits the available experimental data for transfer ionization surprisingly well over the range $0.05 - 10\ E^{\frac{1}{2}}/q$ keV u^{-1}

There is a need for more experimental and theoretical studies of state–selective one and two–electron capture processes. In the case of one–electron capture by protons data for 2p and 2s capture are consistent (c.f. ref 9) while for nl states for $n > 2$ there are serious discrepancies. For proton impact energies above 70 keV u^{-1} calculations based on the continuum distorted wave (CDW) approximation[10] are expected to be increasingly reliable for all nl states. Similar calculations for He^{2+} impact are also expected to be reliable for both 2p and 2s capture above 70 keV u^{-1}. For ions of higher Z these calculations are expected to be reliable only at higher energies[11].

A boundary corrected Born approximation has been used[12] to calculate cross sections for state–selective electron capture by He^{2+} and Li^{3+} ions in helium within the ranges 50–2500 keV u^{-1} and 50–1000 keV amu^{-1} respectively. The accuracy is expected to be within $\pm$ 30%/.

(b) Excitation of helium

Direct excitation processes of the type

$$X^{q+} + He \rightarrow X^{q+} + He^*$$

are of considerable importance. Excitation in H^+ $-He(1^1S)$ collisions was studied extensively during the 1960's and Thomas[13] has carried out a critical review of these measurements. More recent measurements[14,15], extend to higher energies and indicate the need for normalizing earlier experimental data to theoretical predictions based on the Born approximation at high velocities. Improved and mutually consistent evaluations[16,17] of the available data have been presented at this meeting.

The first experimental data on excitation by heavy multiply charged ions was provided by Reymann et al[18] and additional data has been reported at this meeting[19]. New close–coupling calculations on H^+ and He^{2+} impact excitation of $He(1^1S)$ have been presented[17] together with theoretical studies of high energy collisions[11].

The available data on excitation are summarized as follows:–

(i) Excitation of $He(1^1S)$ by proton impact

The experimental data base for H^+–$He(1^1S)$ collisions within the range 5–1000 keV u^{-1} is fairly complete for the full set of n^1L final states (n = 2–5, L = S,P,D). After re–normalising[16] to the high energy experimental results of Hippler and Schartner[15] and Hasselkamp et al[14], which are in close agreement with high energy Born predictions, the available data from the different experimental groups are in good general accord and provide consistent sets of curves showing the dependence of cross section on energy. This is illustrated by the data in Fig 1 which are believed to be accurate to within about 10% at higher energies and about 20% at the low energies. These curves generally exhibit an n^{-3}

scaling so that reasonable predictions for higher n states can be made.

At energies below 30 keV u^{-1}, cross sections for excitation of the 2^1S and 2^1P states are still not well established. Theoretical predictions based on close coupling calculations[20] appear to decrease much too rapidly as the energy decreases. However more recent calculations[17] provide cross sections for excitation of these states which are in better accord with the energy dependence exhibited by the other n^1L data and in agreement with low energy values from another recent close coupling study[21]. These data are therefore recommended. Alternatively one may scale the re–normalised 3^1S and 3^1P data to provide reasonable estimates for 2^1S and 2^1P excitation. However it is desirable to carry out further studies both theoretically and experimentally of cross sections for excitation of these states below 30 keV u^{-1}.

(ii) Excitation of $He(1^1S)$ by multiply charged ions

Measured cross sections (which agree to within 15%) are available[18,19] for populating n^1P (n=3,4), n^1S and n^1D (n = 3–5) states of He by impact of partially stripped O^{6+} – Bi^{45+} 1.4 meV u^{-1} ions, by Si^{3+} – Si^{10+} and Cu^{5+} – Cu^{12+} ions within the range 63–1000 keV u^{-1} and by He^{2+} and H^+ ions within the range 35–1000 keV u^{-1}. These cross sections are subject to an estimated 30% uncertainty in absolute magnitude. A scaling behaviour corresponding to $\sigma/q = f(E/Mq)$ is observed (Fig 2) where M is the number of nucleons in the projectile. The near universal function f can be determined empirically to within 30% in the range 15–200 keV u^{-1} q^{-1} from the mean values of data for $q \geq 2$. The data for proton impact deviates from the scaled He^{2+} data by up to a factor of two.

A similar scaling behaviour for n^1L states n = 2–3 is observed in theoretical studies[17] for both H^+ and He^{2+} impact at energies within the range 15–40 keV u^{-1} but fails at lower impact energies.

Theoretical studies based on a Schwinger variational approach[11] of excitation of He by heavy ions show cross sections at equivelocity approaching a saturation value as q increases. This behaviour has also been observed experimentally.

Most of the available experimental and theoretical data are concentrated around the (scaled) cross section maxima of the n^1S and n^1D series and on the low–energy side of the n^1P series. More studies are required for the bare nuclei He^{2+}, Be^{4+}, C^{6+}, Si^{14+} and Fe^{26+} for a better justification of the scaling behaviour and for improvement in the data base especially below 100 keV u^{-1} q^{-1}.

As in the case of proton impact, cross sections for excitation of 2^1L and higher n states may be estimated by n^{-3} scaling, a procedure which is consistent with the limited data base available.

He^+ projectiles may be treated as just another singly charged ion at energies above 30 keV u^{-1} for excitation of n^1P and n^1D states and at energies above 125 keV u^{-1} for n^1S states (see 22,23 and references therein). At lower energies, symmetry effects in the quasi–molecule make the He^+–He system a special case like the H^+–H system. The data base for this system is complete except for excitation of the 2^1L states at low energies where further investigation is required.

Triplet excitation in He^+–He collisions becomes important below 100 keV u^{-1} and should therefore be included in the data base. However, for proton or highly charged projectiles, triplet states are populated only via the singlet triplet mixing of F states. The 4^1F states of He are populated only with very small probability and can therefore be ignored.

2 CHARGE TRANSFER AND IONIZATION IN COLLISIONS BETWEEN HELIUM IONS AND OTHER IONS

Experimental data on collisions between positive ions are still very limited but measurements based on the fast intersecting beam technique, while difficult, do provide absolute cross sections.

Measured cross sections for the processes

$$\begin{aligned} H^+ + He^+ &\rightarrow H + He^{2+} \\ &\rightarrow H^+ + He^{2+} + e \end{aligned}$$

available within the range 10–500 keV u^{-1} are now well established with an accuracy within ± 15% (see ref 26 and references therein).

Cross sections for the processes

$$\begin{aligned} He^+ + He^+ &\rightarrow He + He^{2+} \\ &\rightarrow He^+ + He^{2+} + e \end{aligned}$$

are also available[27] within the energy range 10–130 keV u^{-1}.

Cross sections for the charge transfer process

$$^4He^+ + {}^3He^{2+} \rightarrow {}^4He^{2+} + {}^3He^+$$

have been measured in the range 0.001–30 keV u^{-1} (see ref 28 and references therein) but are of very limited accuracy due to incomplete collection of the product ions. Agreement with theoretical predictions is also poor. **Very recently[41] measurements have been extended to the range 1.3–67 keV u^{-1} in an experiment with greatly improved product detection. The results are in good agreement with theory and are recommended.**

There is a need for data on collisions of multiply charged ions with both He^+ and He^{2+} ions. Some theoretical estimates of total cross sections for electron removal from He^+ in collisions with fully stripped ions have been calculated[29] using the CTMC method in the range 100–2000 keV u^{-1} for Z = 1–26. These values are probably accurate to within ± 50%.

The CDW approximation has also been used[30] to calculate both total and state–selective electron capture cross sections for collisions of $He^{+}(1s)$ ions with fully stripped ions for Z = 1–8 within the range 160–15,000 keV u^{-1}. The calculations are believed to be accurate to within ± 30%[31].

Olson[29] has also used the CTMC method to calculate cross sections for the direct excitation process

$$H^{+} + He^{+} \rightarrow H^{+} + He^{+}(n)$$

within the range 100–1000 keV u^{-1} for n = 2–4. The estimated accuracy is ± 30%.

3 COLLISIONS INVOLVING EXCITED HELIUM ATOMS

(a) Formation and destruction of fast helium metastable atoms

Data on the formation and collisional destruction of fast metastable helium atoms are important in the context of neutral beam production and penetration. Some cross sections measured using a beam attenuation technique first developed by Gilbody and collaborators (see review[32] and references therein) are available for the processes of electron loss

$$He\,(2^3S + 2^1S) + X \rightarrow He^{+} + X(\Sigma) + e$$

where Σ denotes all final bound and continuum states, and electron capture.

$$He^{+} + X \rightarrow He(2^3S + 2^1S) + X^{+}$$

for He, Ne, Ar, Kr, Xe and H_2 targets. These measurements at energies ranging from 1–300 keV u^{-1} are subject to uncertainties due to a number of simplifying assumptions made in the analysis. Estimates are also made of the fractional yields of metastable atoms formed by electron capture in targets ranging from 'thin' (single collision conditions) to 'thick' where the various charge state components of the beam attain equilibrium populations. At energies above about 13 keV u^{-1}, measured cross sections and metastable populations are believed to be fairly reliable and generally accurate to well within a factor of two.

At energies below 50 keV u^{-1}, the experimental measurements of Gilbody et al[33] indicate that fast helium atom beams prepared by electron capture neutralization of He^+ in thick helium contain very small fractions (< 1%) of metastable atoms. Although strictly a lower limit to the true metastable fractions, these measured fractions are believed to be not greatly in error. In apparent contradiction to these observations, Pedersen et al[34] measured a metastable fraction of 14% in helium atom beams prepared using a thick helium neutralizer at 75 keV u^{-1}. However, this high metastable fraction is difficult to reconcile with any reasonable estimates of the relevant cross sections for de–excitation of metastable helium and for excitation of ground state helium which should be considered in a full analysis.

There are no measurements of helium metastable formation for He^{2+} ions in helium, although Dunn et al[35] have studied the growth and equilibration of helium metastables in the passage of 50 keV u^{-1} He^{2+} through H_2 targets.

(b) Electron capture and ionization in collisions of ions with excited helium atoms

The processes

$$A^{q+} + He^*(n,l) \rightarrow A^{(q-1)+} + He^+$$
$$\rightarrow A^{q+} + He^+ + e$$

are of considerable interest but there are no experimental measurements and calculations have so far been limited to those based on the CTMC approach. This approach assumes hydrogen–like targets[37,38]. These results have been put into parameterised form by Janev[39] and can be used to provide rough estimates of cross sections for both electron capture and total one–electron removal (electron capture plus ionization) within the scaled energy $\tilde{E}$ range 0.01 – 1000 keV u^{-1} where $\tilde{E} = \tilde{E}/q\,(I_H/I_n)$.

Here I_n is the ionization potential of $He^*(n,l) \rightarrow He^+(1s)$ and I_H is that of the ground state of hydrogen. The validity of this scaling relation should improve with increasing n and should be used with caution for low n.

Olson[29] has used the CTMC approach to calculate cross sections for both single and double electron removal from He^* (1s, n = 2) targets within the range 100–2000 keV u^{-1}. Fully stripped ions Z = 1–26 are considered.

(c) <u>Excitation of excited He atoms</u>

At present there is little information available on the excitation of excited helium atoms by ion impact. At this meeting the results of close–coupling calculations have been presented[17] for the formation of 3^1L states in H^+–He (2^1S) and He^{2+}–He(2^1S) collisions for energies within the range 6–80 keV u^{-1} q^{-1}. These results agree to within 30% with high energy Born approximation predictions. The cross sections also exhibit q scaling within a factor of two at energies E $\gtrsim$ 15 keV u^{-1} q^{-1} indicating that scaling can be used to predict cross sections for higher charge states. In the energy range considered, the calculations show that the 3^1D final state is by far the dominant state in the n = 3 manifold. The 3^1P final state is only weakly populated and about a factor of five weaker than the 3^1P population predicted on the basis of the dipole allowed close coupling (DACC) approximation[24]. This result indicates that predictions based on the DACC approximation are subject to large uncertainties.

More studies are required of these systems. A particularly promising approach[25] may be through the use of one–centre close coupling schemes if a large number of high l pseudo states can be demonstrated to extend the method to low energies.

REFERENCES

1 M B Shah and H B Gilbody, J Phys B: At Mol Phys 18 (1985) 899.

2 M B Shah, P McCallion and H B Gilbody, J Phys B: At Mol Opt Phys 22 (1989) 3983.

3 C F Barnett, H T Hunter, M I Kirkpatrick, I Alvarez, C Cisneros and R A Phaneuf, 'Collisions of H, H_2, He and Li atoms and ions with atoms and molecules'. Oak Ridge National Laboratory Report, ORNL 6086/VI 1990.

4 H Knudsen, H K Haugen and P Hvelplund, Phys Rev A 23 (1981) 597.

5 R E Olson, Phys Rev A 18 (1978) 2464.

6 J H McGuire, A Muller, B Schuch, W Groh and E Salzborn, Phys Rev A 35 (1987) 2479.

7 F W Meyer, C C Havener, R A Phaneuf, J K Swenson, S M Shafroth and N Stolterfoht, Nuc Inst and Methods B 24/25 (1987) 106.

8 J A Tanis, M W Clark, R Price, S M Ferguson and R E Olson, Nuc Inst and Methods B 23 (1987) 167.

9 L Meng, C O Reinhold and R E Olson, Phys Rev A 42 (1990), 3637.

10 Dz Belkic, R Gayet and A Salin, Computer Phys Comm 32 (1984) 385.

11 R Gayet and J Hanssen, 1991, contribution to this meeting.

12 Dz Belkic, Physica Scripta, 40 (1989) 610.

13 E W Thomas 'Excitation in heavy particle collisions', Wiley, New York, 1972.

14 D Hasselkamp, R Hippler, A Scharmann and K H Schartner, Z Phys 248 (1971) 254.

15 R Hippler and K H Schartner, J Phys B: At Mol Phys 7 (1974) 618.

16 F J de Heer, 1991, contribution to this meeting.

17 W Fritsch, 1991, contribution to this meeting.

18 K Reymann, K H Schartner, B Somner and E Träbert, Phys Rev A 38 (1988) 2990.

19 M Anton, D Detleffsen and K H Schartner, 1991, contribution to this meeting.

20 M Kimura and C D Lin, Phys Rev A 34 (1986) 176.

21 H A Slim, E L Heck, B H Bransden and D R Flower, 1991, private communication.

22 R Hippler, K H Schartner and H F Beyer, J Phys B 11 (1978) L337.

23 D Hasselkamp, R Hippler, A Scharmann and K H Schartner, Z Phys 257 (1972) 43.

24 R K Janev, W D Langer, K Evans and D E Post, 'Elementary processes in hydrogen–helium plasmas', Springer, Berlin 1987, pp 152 ff.

25 J Reading, 1991, contribution to this meeting.

26 M F Watts, K F Dunn and H B Gilbody, J Phys B: At Mol Phys 19 (1986) L355.

27 F Melchert, K Rink, K Rinn, E Salzborn and N Grün, J Phys B: At Mol Phys 20 (1987) L223.

28 B Peart and K Dolder, J Phys B: At Mol Phys 12 (1979) 4155.

29 R E Olson, 1991, contribution to this meeting.

30 Dz Belkic, 1991, contribution to this meeting.

31 Dz Belkic, R Gayet and A Salin, Phys Rep 56 (1979) 279.

32 H B Gilbody, Inst Phys Conf Ser No 38 (1978) 156.

33 H B Gilbody, K F Dunn, R Browning and C J Latimer, J Phys B: At Mol Phys 4 (1971) 800.

34 E H Pedersen, J Heinemeier, L Larsen and J V Mikkelsen, J Phys B: At Mol Phys 13 (1980) 1167.

35 K F Dunn, B J Gilmore, F R Simpson and H B Gilbody, J Phys B 11 (1978) 1797.

36 R W McCullough, F R Simpson and H B Gilbody, J Phys B: At Mol Phys 6 (1973) L323.

37 R E Olson, J Phys B: At Mol Phys 13 (1980) 483.

38 D K Schultz, L Meng, C O Reinhold and R E Olson, Physica Scripta – in course of publication.

39 R K Janev, 1991, contribution to this meeting. (Phys. Lett. A 160 (1991) 67).

40 R Schuch, E Justiano, H Vogt, G Deco and N Gruen, J Phys B: At Mol Opt Phys 24 (1991) L133.

41 F Mellhert, S Krudener, R Schulze, S Pfaff, S Petri and E Salzborn, Abstracts Proc. 17th Int. Conf. on Phys. of Electronic and Atomic Collisions, 1991, Brisbane, p.571.

FIGURE CAPTIONS

Figure 1 Summary of the data base for excitation to n^1P He states in H^+–He collisions. The data by Hippler and Schartner[15] (diamonds) agree with the Born results (broken lines) by Bell et al. Data by Thomas and Bent (Δ for n = 3–5) and by van den Bos et al. (o) have been re–normalised. For the 2^1P state, the data by Kvale et al. (□) and by Park and Schowengerdt (Δ) are consistent with the theoretical MO results[20] (______) but the energy and n–dependence of the recent close–coupling calculations[17] (_._.) appears to be more reasonable. For a complete bibliography, see Thomas[13] and ref 17.

Figure 2 Scaled $1^1S - 3^1P$ excitation cross sections in A^{q+}–He collisions. Heavy–ion impact data are by Reymann et al[18], proton impact data (...) by van den Bos (normalized) and by Hippler and Schartner, cf ref 18 and references therein.

file HpHeexPr June 18, 1991 11:35:20 AM

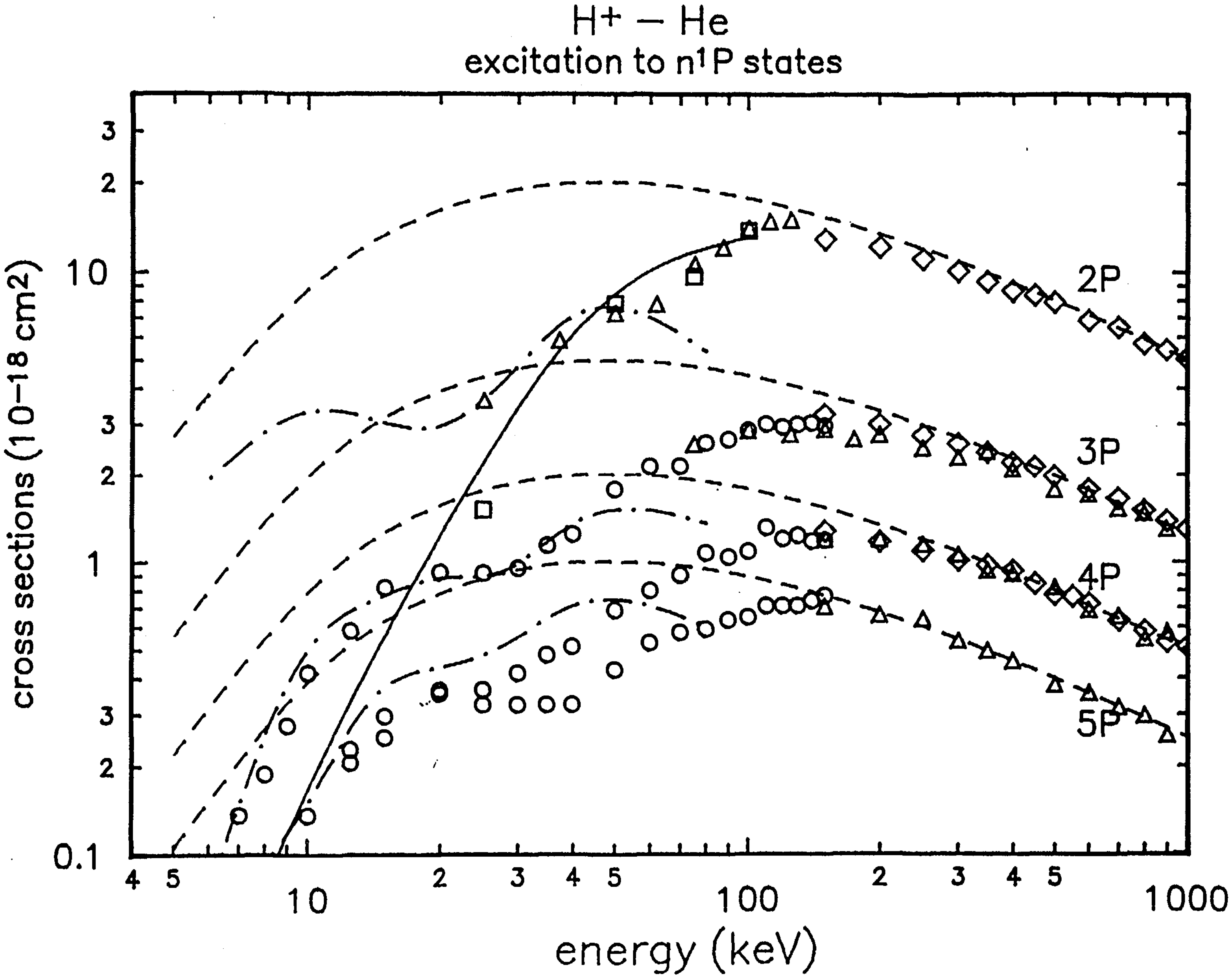

Fig. 1

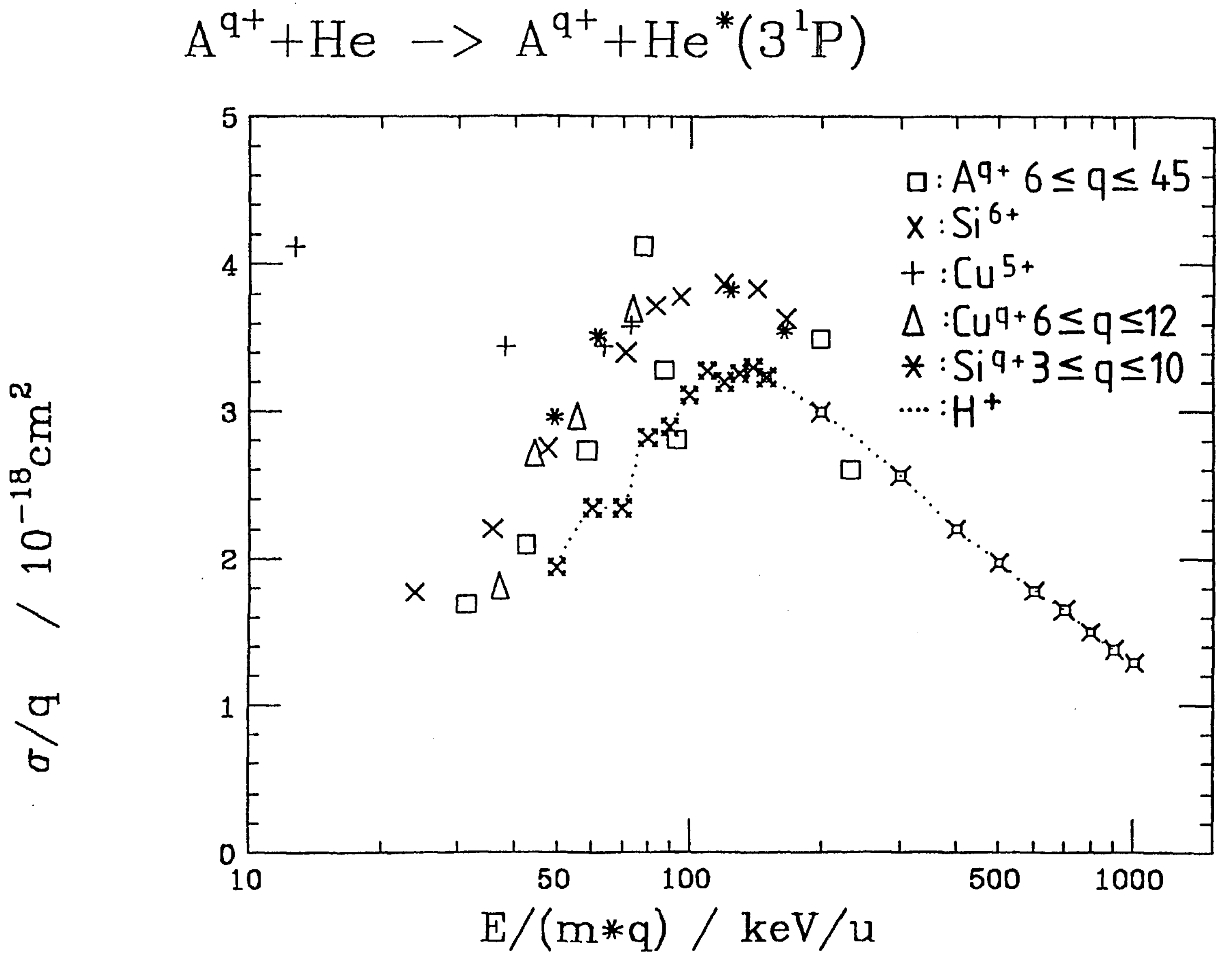
A^{q+}+He -> A^{q+}+He*(3^1P)
□ : A^{q+} 6 ≤ q ≤ 45
x : Si^{6+}
+ : Cu^{5+}
Δ : Cu^{q+} 6 ≤ q ≤ 12
✳ : Si^{q+} 3 ≤ q ≤ 10
···· : H^+
σ/q / 10^{-18}cm^2
E/(m*q) / keV/u
0
1
2
3
4
5
10
50
100
500
1000

Fig. 2

TABLE 1 Cross sections $_{z0}\sigma_{z1}$ and $_{z0}\sigma_{z2}$ for single and double ionization of He by H^+, He^{2+} and Li^{3+} impact. corresponding to processes (4) and (5) respectively (from Shah and Gilbody[1]). In addition to the uncertainties shown, $_{z0}\sigma_{z1}$ and $_{z1}\sigma_{z2}$ are subject to estimated uncertainties in absolute magnitude of ± 7% and ± 9% respectively.

H^+ + He

Energy keV u^{-1}	$_{10}\sigma_{11}$ (10^{-17} cm²)	$_{10}\sigma_{12}$ (10^{-20} cm²)
64	7.50 ± 0.23	
80	8.32 ± 0.13	105.7 ± 10.1
100	9.43 ± 0.18	96.1 ± 10.3
115	-	-
130	8.09 ± 0.12	79.3 ± 6.8
145	-	-
160	7.57 ± 0.09	70.6 ± 3.3
180	-	-
200	6.93 ± 0.17	56.0 ± 1.7
260	5.87 ± 0.11	41.4 ± 2.6
320	5.16 ± 0.09	31.5 ± 2.2
400	4.41 ± 0.09	23.6 ± 1.2
500	3.70 ± 0.15	17.2 ± 0.8
640	3.14 ± 0.07	12.7 ± 1.0
800	2.67 ± 0.03	9.60 ± 0.51
1000	2.26 ± 0.08	7.45 ± 0.27
1280	1.86 ± 0.03	5.71 ± 0.47
1600	1.59 ± 0.02	4.54 ± 0.37
2000	1.295 ± 0.011	3.65 ± 0.35
2380	1.125 ± 0.013	3.00 ± 0.21

He^{2+} + He

Energy keV u^{-1}	$_{20}\sigma_{21}$ (10^{-17} cm²)	$_{20}\sigma_{22}$ (10^{-19} cm²)
50	7.20 ± 0.31	21.4 ± 2.9
65	11.68 ± 0.20	25.3 ± 2.1
80	15.25 ± 0.26	36.6 ± 4.1
100	18.50 ± 0.21	54.0 ± 3.4
125	20.3 ± 0.4	65.4 ± 3.3
160	20.9 ± 0.3	68.3 ± 2.3
200	20.2 ± 0.3	65.3 ± 2.1
280	18.81 ± 0.35	54.9 ± 1.4
320	16.75 ± 0.14	41.2 ± 1.4
400	15.14 ± 0.21	31.1 ± 1.1
500	13.08 ± 0.26	21.9 ± 0.7
640	11.10 ± 0.20	14.8 ± 0.5
800	9.74 ± 0.14	10.53 ± 0.47
1000	8.26 ± 0.10	7.07 ± 0.50
1280	6.93 ± 0.41	4.78 ± 0.35
1585	5.77 ± 0.10	3.24 ± 0.18

Li^{3+} + He

Energy keV u^{-1}	$_{30}\sigma_{31}$ (10^{-17} cm²)	$_{30}\sigma_{32}$ (10^{-19} cm²)
50	5.77 ± 0.60	23.1 ± 7.5
57	8.85 ± 0.41	31.7 ± 3.9
70	15.6 ± 0.8	39.6 ± 4.5
80	20.3 ± 0.7	55.4 ± 3.1
100	27.2 ± 1.2	90.0 ± 6.0
125	32.5 ± 1.2	136.0 ± 7.0
160	35.2 ± 1.1	177.0 ± 7.0
200	35.9 ± 8.0	192.0 ± 8.0
250	34.3 ± 1.3	179,9 ± 9.0
313	31.4 ± 1.3	153.0 ± 8.0
390	29.7 ± 0.6	126.0 ± 4.0

TABLE 2 Cross sections $_{z0}\sigma_{(z-1)1}$ and $_{z0}\sigma_{(z-1)2}$ for one electron capture and transfer ionization in collisions of H+, He2+ and Li3+ with He corresponding to processes (1) and (3) (from Shah and Gilbody[1]). In addition to the uncertainties shown, $_{z0}\sigma_{(z-1)1}$ and $_{z0}\sigma_{(z-1)2}$ are subject to estimated uncertainties in absolute magnitude of ± 6%.

H^+ + He

Energy keV u^{-1}	$_{10}\sigma_{01}$ (10^{-17} cm^2)	$_{10}\sigma_{02}$ (10^{-18} cm^2)
80	4.65 ± 0.23	1.31 ± 0.08
100	2.72 ± 0.10	0.80 ± 0.08
130	1.40 ± 0.20	0.407 ± 0.015
160	0.752 ± 0.011	0.226 ± 0.006
200	0.365 ± 0.004	0.102 ± 0.008
260	0.141 ± 0.003	0.0397 ± 0.0038
320	0.0624 ± 0.0009	0.0178 ± 0.0045
400	0.0222 ± 0.0010	0.0071 ± 0.0006
500	0.0081 ± 0.0002	0.0028 ± 0.0011
640	0.00274 ± 0.00025	
800	0.00093 ± 0.00012	

He^{2+} + He

Energy keV u^{-1}	$_{20}\sigma_{11}$ (10^{-17} cm^2)	$_{20}\sigma_{12}$ (10^{-17} cm^2)
50	22.20 ± 0.30	3.60 ± 0.06
65	19.30 ± 0.19	3.45 ± 0.08
80	15.10 ± 0.30	2.89 ± 0.06
100	11.50 ± 0.14	2.36 ± 0.02
125	7.76 ± 0.08	1.66 ± 0.02
160	4.56 ± 0.03	0.978 ± 0.018
200	2.60 ± 0.02	0.518 ± 0.005
250	1.44 ± 0.01	0.263 ± 0.004
320	0.659 ± 0.010	0.105 ± 0.003
400	0.309 ± 0.007	0.0427 ± 0.0026
500	0.136 ± 0.001	0.0161 ± 0.0004
600	0.0703 ± 0.0015	0.00698 ± 0.00097

Li^{3+} + He

Energy keV u^{-1}	$_{30}\sigma_{21}$ (10^{-17} cm^2)	$_{30}\sigma_{22}$ (10^{-17} cm^2)
50	53.9 ± 0.9	6.16 ± 0.13
57	45.1 ± 0.4	6.19 ± 0.07
70	37.8 ± 0.4	6.76 ± 0.05
80	31.4 ± 0.3	6.64 ± 0.10
100	22.0 ± 0.2	6.00 ± 0.11
125	14.1 ± 0.2	4.83 ± 0.07
160	8.07 ± 0.07	3.31 ± 0.04
200	4.79 ± 0.04	2.15 ± 0.04
250	2.74 ± 0.07	1.24 ± 0.03
313	1.477 ± 0.020	0.630 ± 0.011
390	0.774 ± 0.024	0.301 ± 0.011

4. MEETING CONCLUSIONS AND RECOMMENDATIONS

The discussions at the last plenary session of the Meeting, following the adoption of Working Group Reports, can be summarized by the following conclusions:

1) The atomic data base required for calculation of the He-beam attenuation in a fusion plasma and optimization of alpha particle diagnostics schemes based on charge-exchange recombination spectroscopy and neutral particle analysis is, generally speaking, in a good shape, in terms of both availability and data accuracy. The data base is, however, still incomplete, particularly for the processes involving excited initial states. The required cross section accuracies for various processes are somewhat different for the two types of diagnostics and are high (on the order of 10%) only for a limited number of processes. For most of the atomic reactions which are essential for determination of the He-beam attenuation the existing data have the required accuracy. Improvements in the quality of the data and completion of the data base is required for optimization of the diagnostic schemes.

2) The major defficiencies in the data base for electron-impact processes are in the cross sections for low-energy excitation transitions between excited states and ionization from excited states. Particularly important is the information for the spin changing transitions which are at present inadequately documented. New extensive R-matrix calculations for these processes are required at low energies, and in the intermediate-to-high energy region advanced methods should be used to generate the cross section data.

3) The required data base for collision processes of He atoms with protons and plasma impurity ions is inadequate in the low and intermediate energy regions (10-200 keV/amu) and fairly complete in the high energy region (0.5-1.5 MeV/amu). The main uncertainties at low energies are in the excitation by impurities, and in the processes involving excited initial states. The basic processes involved in the two alpha particle diagnostic schemes have adequate accuracy.

For completion of the required data base for He-beam alpha particle diagnostics and preparation of a recommended set of data to be used by the fusion researchers, the Meeting recommends:

1) Continuation of the effort initiated by the Agency's Atomic and Molecular (A+M) Data Unit on generation, collection and evaluation of new data for the collisions involving He atoms. Most of the Meeting participants agreed to take part in this process.

2) Preparation of the recommended set of data by the IAEA A+M Data Unit in a form suitable for use by fusion researches (analytic fits) and their dissemination to interested users in fusion laboratories.

3) Publication in "Atomic and Plasma-Material Interaction Data for Fusion" vol. 3 (1992) (a regular supplement to "Nuclear Fusion") of those contributions to the Meeting for which the authors are willing to prepare an appropriate manuscript.

5. POST-MEETING ACTIVITIES

As a first step towards implementation of Meeting conclusions, the IAEA has invited Dr. T. Kato from the National Institute for Fusion Science, Nagoya, to visit the Agency during November 1991 and assist the Atomic and Molecular Data Unit with formatting the recommended electron-impact excitation data and their storage in the Agency's ALADDIN data base. The recommended data for these processes are the same as those prepared by Dr. F.J. de Heer for use in the JET He-beam diagnostics. The recommended data will be fitted to appropriate analytic expressions which preserve the correct threshold and asymptotic behaviour of the cross sections. The data formatting activity will be continued for all of the recommended data.

Appendix 1

IAEA Consultants' Meeting on
"He-Beam Data Base for Alpha Particle Diagnostics of Fusion Plasmas"

3 - 5 June 1991, IAEA Headquarters, Vienna, Austria

LIST OF PARTICIPANTS

Dr. V.A. Abramov	Institut Atomnoi Energii I.V. Kurchatova, Ploshchad I.V. Kurchatova, Moscow D-182, 1231182, U.S.S.R.
Dr. F.J. de Heer	FOM Instituut voor Atoom- en Molecuulfysica, Kruislaan 407, NL-1098 SJ Amsterdam-Watergraafsmeer, NETHERLANDS
Dr. W. Fritsch	Bereich Kern- und Strahlenphysik, Hahn-Meitner-Institut für Kernforschung Berlin, Glienicker Strasse 100, Postfach 3900128, D-W-1000 Berlin 39, GERMANY
Dr. Robert Gayet	Université de Bordeaux I, Laboratoire des Collisions Atomiques, 40, Rue Lamartine, F-33400 Talance, FRANCE
Prof. H.B. Gilbody	Dept. of Pure and Applied Physics, Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland, UNITED KINGDOM
Dr. R. Hoekstra	Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, NETHERLANDS
Dr. T. Kato	Data and Planning Center, National Institute for Fusion Science, Nagoya 464, JAPAN
Prof. A. Kingston	Dept. of Applied Mathematics and Theoretical Physics, Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland, UNITED KINGDOM
Dr. A. Korotkov	A.F. Ioffe Physico-Technical Institute, Academy of Sciences of the USSR, ul. Politechnicheskaya, 26, 194021 Leningrad K-21, U.S.S.R.
Prof. R.E. Olson	University of Missouri-Rolla, Physics Department, 102 Physics Building, 65401-0249 Rolla, Missouri, U.S.A.
Dr. M.P. Petrov	A.F. Ioffe Physico-Technical Institute, Academy of Sciences of the USSR, ul. Politechnicheskaya, 26, 194021 Leningrad K-21, U.S.S.R
Prof. J. Reading	Taxas A&M University, Department of Physics, College Station, Texas 77843-4242, U.S.A.
Prof. K. Schartner	I. Physikalisches Institut der Universität Giessen, Heinrich Buff-Ring 16, D-W-6300 Giessen, GERMANY
Dr. H.P. Summers	UKAEA - JET Joint Undertaking, Culham Laboratory, Abingdon Oxfordshire OX14 3EA, UNITED KINGDOM

Appendix 2

IAEA Consultants' Meeting on "He-Beam Data Base for Alpha Particle Diagnostics of Fusion Plasmas"

3 - 5 June 1991, IAEA Headquarters, Vienna, Austria

MEETING AGENDA

MONDAY, June 3

09:30 - 09:40	- Opening - Adoption of Agenda	(Room: C07-VI)

Session 1: Atomic data needs for He-beam penetration into fusion plasmas and alpha particle diagnostics

Chairman: A. Kingston

09:40 - 10:20	M. Petrov:	Charge exchange diagnostics of fast confined alpha particles in fusion reactors
10:20 - 11:00	H. Summers:	Helium beam stopping and related spectral emission in the energy region 20-100 keV/amu
11:00 - 11:10	Coffee break	
11:10 - 11:40	A. Korotkov:	Sensitivity of the He-beam enhanced stopping cross section on collision processes in fusion plasmas
11:40 - 12:10	R. Olson:	Atomic collision problems in He neutral beam penetration of an ITER plasma
12:10 - 12:30	T. Kato:	Effective ionization rate coefficient of He-beam in tokamak plasmas
12:30 - 14:00	Lunch	

Session 2: Electron collisions with helium

Chairman: H. Summers

14:00 - 14:45	A. Kingston:	Status of electron impact excitation data base for He
14:45 - 15:25	F.J. de Heer:	Experimental cross sections for excitation of He (1 ^1S) by electrons
15:25 - 15:55	T. Kato:	Electron impact excitation data for He
15:55 - 16:10	Coffee break	

Session 3: Heavy particle collisions with helium

Chairman: J. Reading

16:10 - 16:50	W. Fritsch:	Electron excitation in A^{q+}-He collisions
16:50 - 17:30	K.H. Schartner:	Ion impact excitation of He: experimental total cross sections
17:30 - 18:10	R. Olson:	Heavy particle charge-changing collisions involving the He atom and its ions

TUESDAY, June 4

Session 3: (Cont'd)

Chairman: W. Fritsch

09:00 - 09:45	H.B. Gilbody:	Status of experimental database for charge exchange and ionization in collisions of heavy particles with He
09:45 - 10:30	J. Reading:	Alpha particle collisions with helium
10:30 - 10:45	Coffee break	
10:45 - 11:25	R. Gayet:	Cross sections for capture, excitation and ionization in helium by fast bare ions
11:25 - 12:05	R. Hoekstra:	Charge transfer cross sections for the JET database
12:05 - 12:40	V.A. Abramov:	Analysis of the database for excitation and ionization of He by protons and multicharged ions
12:40 - 14:30	Lunch	

Session 4: General discussion on the required He-beam database

Chairman: R. Janev

14:30 - 15:00

- Identification of required atomic database for He-beam attenuation modelling and alpha particle diagnostics;
- Identification of required cross section accuracies for different collision processes

15:00 - 15:15 Coffee break

Session 5: Data evaluation and selection of best data sets

15:15 - 18:00 Work in parallel sessions:

A) Working Group for Required Data and Accuracies (Room: C07-VI)
B) Working Group for Electron-Impact Processes (Room: C07-55)
C) Working Group for Ion-Impact Processes (Room: C07-VI)

WEDNESDAY, June 5

Session 5:	Data evaluation and selection of best data sets Preparation of Working Group Reports
09:00 - 12:00	Work in parallel sessions:
	A) Working Group for Required Data and Accuracies (Room: C07-VI) A) Working Group for Electron-Impact Processes (Room: C07-55) B) Working Group for Ion-Impact Processes (Room: C07-VI)
12:00 - 14:00	Lunch
Session 6:	Meeting Conclusions and Recommendations
Chairman:	R.K. Janev
14:00 - 15:00	Discussion of Working Group Reports
15:00 - 15:15	Coffee break
15:15 - 16:00	Adoption of Meeting conclusions and recommendation
16:00 -	Adjourn of the Meeting