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R. Hoekstra, H.P. Summers, F.J. de Heer
and JET Team

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R. Hoekstra[1,2], H.P. Summers[3], F.J. de Heer[2] and JET Team*

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*Kemfysisch Versneller Instituut, Zemikelaan, Groningen, The Netherlands*
[2]*FOM Institute for Atomic and Molecular Physics, Amsterdam, The Netherlands*
[3]*JET Joint Undertaking, Abingdon, Oxon, OX14 3EA*
** See Annex*

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ABSTRACT.

In the energy range of $3x10^2 – 5x10^5$ eV/amu data for total and state selective electron capture in collisions of protons on helium have been evaluated critically. From this investigation we have constructed a set of recommended data which are part of the atomic database at JET and which, therefore, are used for modelling of He beam stopping and related diagnostics. The assessment of the cross sections is motivated and the corresponding uncertainties are inferred.

Introduction

Recently, at the Joint European Torus (JET) the neutral beam injector assemblies have been upgraded such that He beams can be injected, as well as the D beams used previously. In the plasma these neutral beams are stopped by ionizing and/or charge changing collisions. Photon emission spectroscopy of light in the visible spectral range, emitted by plasma particles following electron capture from the He beam and by collisionally excited He beam atoms, is being assessed as a tool to measure plasma quantities as e.g. the ion temperature and the impurity densities. This type of diagnostics has been used successfully in combination with the neutral deuterium heating beams (Boileau et al [1] and von Hellermann et al [2]). To be able to develop the potentialities of this method fully it is needed to know accurately the absolute cross sections for the basic charge transfer, excitation and ionization processes. These cross sections have to be known in the energy range of approximately 1 - 100 keV/amu. This range is defined by the energy of the He beams, at present up to 53 keV/amu and 30 keV/amu for ^{3}He and ^{4}He beams, respectively, and the energy distribution of the plasma ions. For future machines such as ITER the energy range of interest extends towards higher energies since, to match the velocity of the fusion produced α-particles, diagnostic beams with energies of a few hundreds of keV/amu are foreseen (e.g. these proceedings and Janev [3]).

In this paper we review and recommend total and state selective cross sections for electron capture by protons, the most abundant plasma species. Schematically the charge transfer processes are given by:

$$H^+ + He \rightarrow H(nl) + He^+ \qquad (1)$$

Throughout the paper the emphasis will be on experimental data for processes (1); this is possible because the processes have been studied extensively over the whole energy range of plasma fusion interest, $\sim 10^3$ - 10^6 eV/amu, refs. 4 - 43. Notwithstanding the fact that rather recently recommended cross sections have been presented by Barnett and coworkers [44], further on referred to as the Redbook, we have investigated the status of the available data again. The investigation was motivated by the large differences between theory and experiment at energies below 10^4 eV/amu, the advent of new elaborate experimental and theoretical data in the energy range of

10^4 - 10^5 eV/amu and some inconsistencies in the ratio of the recommended *3l* and *2l* cross sections given in the Redbook.

In the following sections we will discuss the cross sections for total electron capture and the ones for state selective charge transfer into states with $n \leq 3$ and present the corresponding recommended cross sections in graphical and tabular form.

Assessment of recommended cross sections

Total cross sections for electron capture

The experimental data for total charge transfer in collisions of protons on helium are presented in figure 1. Due to the good agreement between the different data sets and the large amount of data we have indicated all results by the same symbol. Unfortunately a lot of these data were only presented in graphical form by the authors. Whenever possible we have used for these data the numerical values given in the data compilation of Wu et al [45], which includes results up to March 1986, and otherwise we have extracted them directly from the figures. It is seen that at energies above ~5×10^3 eV/amu both recommended curves closely follow the experiments whereas at lower impact energies they strongly deviate from the experimental data. At these lower energies we have decided not to follow the trend in the experimental data (mainly from Hasted and Stedeford [4] and from Hasted as quoted by Allison [5]) but the one in the theoretical results of Kimura [46] and Kimura and Lin [47]. There are two arguments to justify this choice.
i) Although charge transfer mainly populates the H(*1s*) ground state it is still a highly endothermic process. Therefore it may be expected that the cross sections decrease strongly with decreasing impact energy which is not the case for the experimental results, cf. figure 1. Furthermore it is noted that the population of excited H states has to proceed via couplings with the molecular orbital corresponding, at infinity, to the H(*1s*) ground state. Since, as can be seen in the next paragraph (figure 3), the theoretical results of Kimura and Lin [47] for capture into such a state, H(*2p*), are in good agreement with the most sophisticated experimental results it is likely that theory is also rather reliable for capture into H(*1s*).

ii) Experimentally the conditions were such that the residual gas pressure was about 1% of the pressure of the He target [4]. Since for protons the cross sections for electron capture from gases such as H_2, N_2, Ar and O_2 [4,5,6] are in the order of a few times 10^{-16} cm^2, the interaction with the residual gas yields an extra apparent cross section of a few times 10^{-18} cm^2. Therefore electron capture from the background gas can well explain the magnitude of the experimental cross sections at the lower impact energies.

Values of our recommended cross sections are presented in table 1. At energies between 4×10^3 and 3×10^5 eV/amu the uncertainties are expected to be smaller than 20%. Whereas at higher energies the uncertainty increases only slightly up to ~30% at 8×10^5 eV/amu, the uncertainty at lower impact energies may be considerably larger, we estimate a factor of 2 at 10^3 eV/amu and an even larger factor at still lower impact energies.

Cross sections for electron capture into H(2l) states

The data for electron capture into H(*2s*) and H(*2p*) are shown in figures 2 and 3, respectively. Excluding for electron capture into H(*2p*) the results of Hippler et al [29] and Van Zyl et al [33], we see from figure 3 that at impact energies below 10^4 eV/amu the other data exhibit the same trend as the total charge transfer cross sections (cf. figure 1), i.e. compared to theory a less steep decrease with decreasing energy. Again this may be due to charge changing collisions with the background gas. However in this case there is a second process that may significantly contribute to the observed H(*2p*) cross sections, namely excitation of the neutrals in the hydrogen beam (a small fraction of the proton beam may be neutralized during transport to the collision center). The cross section for H(*2p*) excitation in H-He collisions is relatively large ~5×10^{-17} cm^2 (Birely and McNeal [50]), more than two orders of magnitude larger than the one for charge transfer into H(*2p*) in proton helium collisions. Since Hippler et al [29] and Van Zyl et al [33] corrected for these effects, we recommend to follow their results below 10^4 eV/amu. The AO-MO results of Kimura and Lin [47] are in good agreement with these experimental data. Our recommended cross sections below 3×10^3 eV/amu are an extrapolation of the AO-MO results and are based on the E^2 dependence derived by Rapp and Francis [51] for endothermic electron capture processes. As can be seen from figure 3 the scaling describes well the results results between 1 and 3×10^3 eV/amu. At high energies, energies above 2×10^5 eV/amu the energy dependence of our recommended curve is defined by the theoretical results of Belkič [48].

The procedure for the assessment of the cross sections for capture into H(*2s*) has been the same as for capture into H(*2p*): Below 3×10^3 eV/amu we extrapolated the curve by means of the E^2 dependence and at high energies we used the results of Belkič [48] as guide line. Note from figure 2 that especially around the cross section maximum the status of the experimental results is not optimal.

For the recommended H(*2s*) and H(*2p*) electron capture cross sections shown in figures 2 and 3 and presented in table 1 we expect that in the energy range of approximately 2×10^3 to 2×10^5 eV/amu the uncertainties are about 30 and 20% for H(*2s*) and H(*2p*), respectively. At lower and higher energies the data are less certain.

Cross sections for electron capture into H(3l) states

The data for electron capture into H(*3s*), H(*3p*) and H(*3d*) are shown in figures 4, 5 and 6, respectively. Besides the results dating from the seventies [14,31,34-39] there are recent results stemming from experimental work directed towards the determination of the full density matrices for charge transfer into H(*3l*) states [40,41]. These latter measurements define mainly the shape and magnitude of our recommended cross sections around the cross section maxima. In this energy range, $\sim 10^4$ - 10^5 eV/amu the uncertainties in the *3s* and *3p* cross sections are expected not to exceed 30% but the ones in the *3d* cross sections may be as large as 50%. However, in this respect it has to be noted that the cross section for electron capture into H(*3d*) is approximately one order of magnitude smaller than the ones for H(*3s*) and H(*3p*).

At impact energies lower than 10^4 eV/amu we have again used the E^2 scaling of Rapp and Francis [51] to extrapolate our recommended curve. This curve deviates strongly from the one given in the Redbook [44] which follows the trend in the experimental data of Ford and Thomas [36] and Conrads et al

[35]. Support of our extrapolated curves is presented by the Balmer-α measurements of Van Zyl et al [42]. In table 2 we show the comparison of their Balmer-α cross sections and the ones constructed of our *3l* cross sections. The Balmer-α cross section is related to *3l* cross sections via the respective branching ratios of these *3l* states, i.e. the Balmer-α cross section is equal to $\sigma(3s) + 0.12\ \sigma(3p) + \sigma(3d)$. From table 2 it is obvious that there is good agreement between the experimental data [42] and the ones determined from our recommended cross sections.

To interpret as accurate as possible photon emission spectra it is important to know cascade contributions from high-*n* levels to the line under observation. The high-*n* electron capture cross sections are generally estimated from scalings of the type $n^{-\gamma}$ (see e.g. Spence and Summers [53]). In high energy approximations based on the available density of states in the ion, γ becomes equal to 3. However, at lower impact energies it has been noted that the high-*n* cross sections are relatively smaller (see e.g. von Hellermann et al [2] and Hoekstra et al [54] for the case of electron capture in He^{2+} - H collisions). To get an impression of this scaling power γ for H^+ - He collisions figure 7 shows γ determined from the $n = 2$ and $n = 3$ recommended cross sections of the Redbook [44] and of the present work. It is seen that going up from the energy of 10^3 eV/amu the present γ decreases from ~6 to 2.6 at 3.5×10^4 eV/amu and reaches the expected value of about 3 at ~10^5 eV/amu. At high energies the difference with the Redbook arises mainly from the fact that their *3s* cross sections are larger, cf. figure 4.

Conclusions

The database for electron capture in collisions of protons on helium has been investigated. For impact energies of 3×10^2 - 5×10^5 eV/amu we have determined a set of recommended cross sections for total electron capture and state selective electron capture into H(*2l*) and H(*3l*) states. At energies above ~10^5 eV/amu and especially below 10^4 eV/amu the present assessment differs from the one given in the Redbook compilation [44]. At the low energy side we feel fairly confident about our recommendation due to the good agreement with Balmer-α measurements of Van Zyl et al [42] and at the high energy side the cross sections are support by the fact that the scaling power γ ($n^{-\gamma}$ scaling) reaches neatly the expected high energy value of 3.

Acknowledgement

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Table 1 Recommended cross sections (in units of 10^{-18} cm^2) for electron capture in H^+ - He collisions.

E(keV/amu)	σ(tot)	σ(2s)	σ(2p)	σ(3s)	σ(3p)	σ(3d)
0.3	0.01	0.001	0.0056			
0.5	0.045	0.0029	0.0155			
0.7	0.11	0.0054	0.031			
1	0.31	0.011	0.062	0.00165	0.0027	0.0016
2	2.28	0.044	0.24	0.0066	0.011	0.0065
3	7.6	0.095	0.475	0.015	0.024	0.015
5	35	0.24	1.02	0.041	0.068	0.041
7	70	0.49	1.6	0.081	0.132	0.081
10	114	0.88	2.25	0.16	0.27	0.16
20	178	2.7	3.6	0.57	0.75	0.23
30	170	4.6	3.45	1.42	1.1	0.2
50	107	6.8	2.0	2.1	0.65	0.11
70	62	5.5	1.1	1.7	0.34	0.045
100	27	3.0	0.55	0.85	0.16	0.015
200	3.3	0.39	0.075	0.11	0.021	0.0012
300	0.82	0.08	0.015	0.024	0.004	0.0002
500	0.087	0.01	0.0012	0.003		

Table 2. Balmer-α emission cross sections in units of 10^{-21} cm^2.

E (keV/amu)	our scaling	Van Zyl et al [42]
1.25	5.5	6 ± 3
2	14.2	16 ± 6

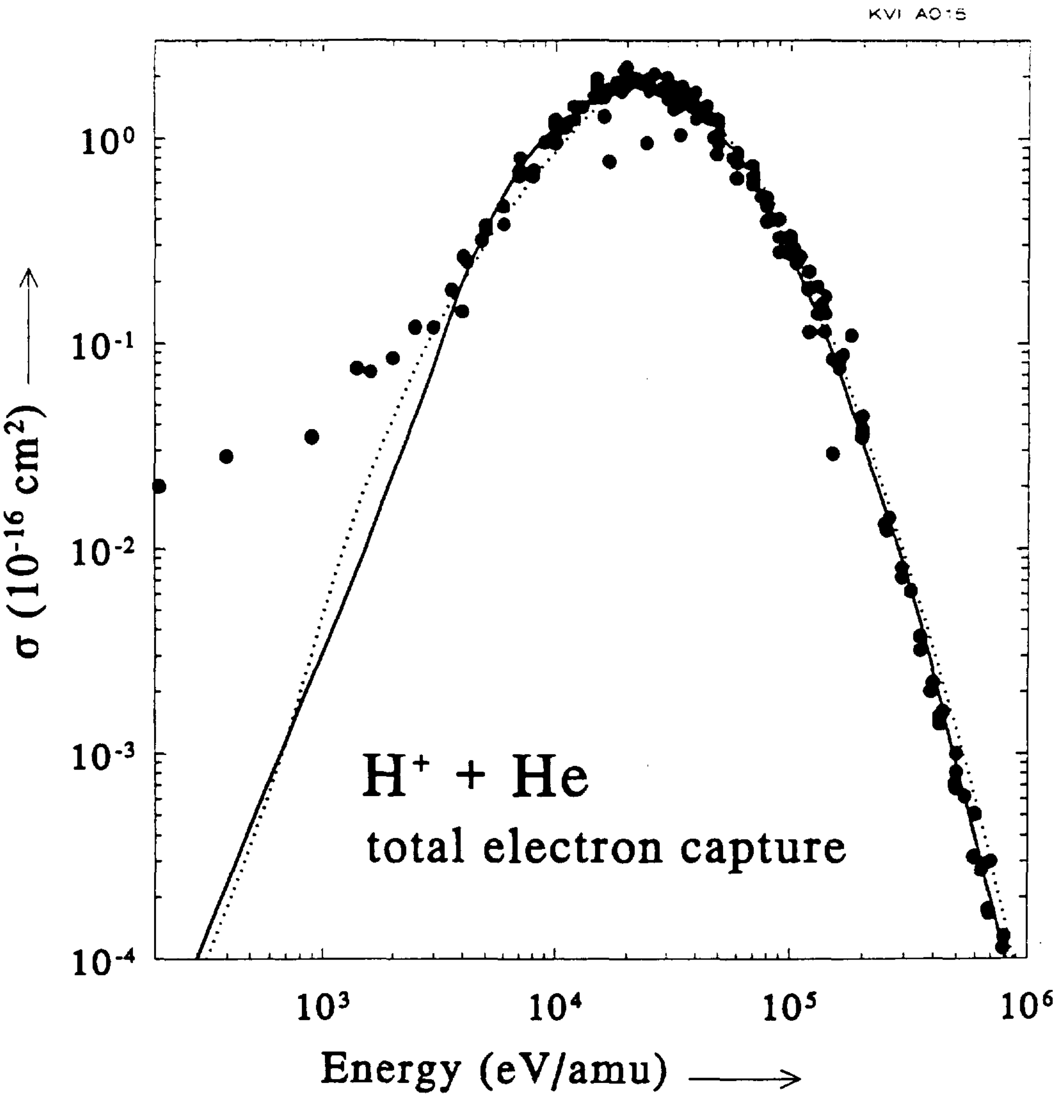


Figure 1. Total one electron capture cross sections in H^+ - He collisions. Experiment: refs. [4] - [19]. Recommended data: ..... Redbook [44], —— this work.

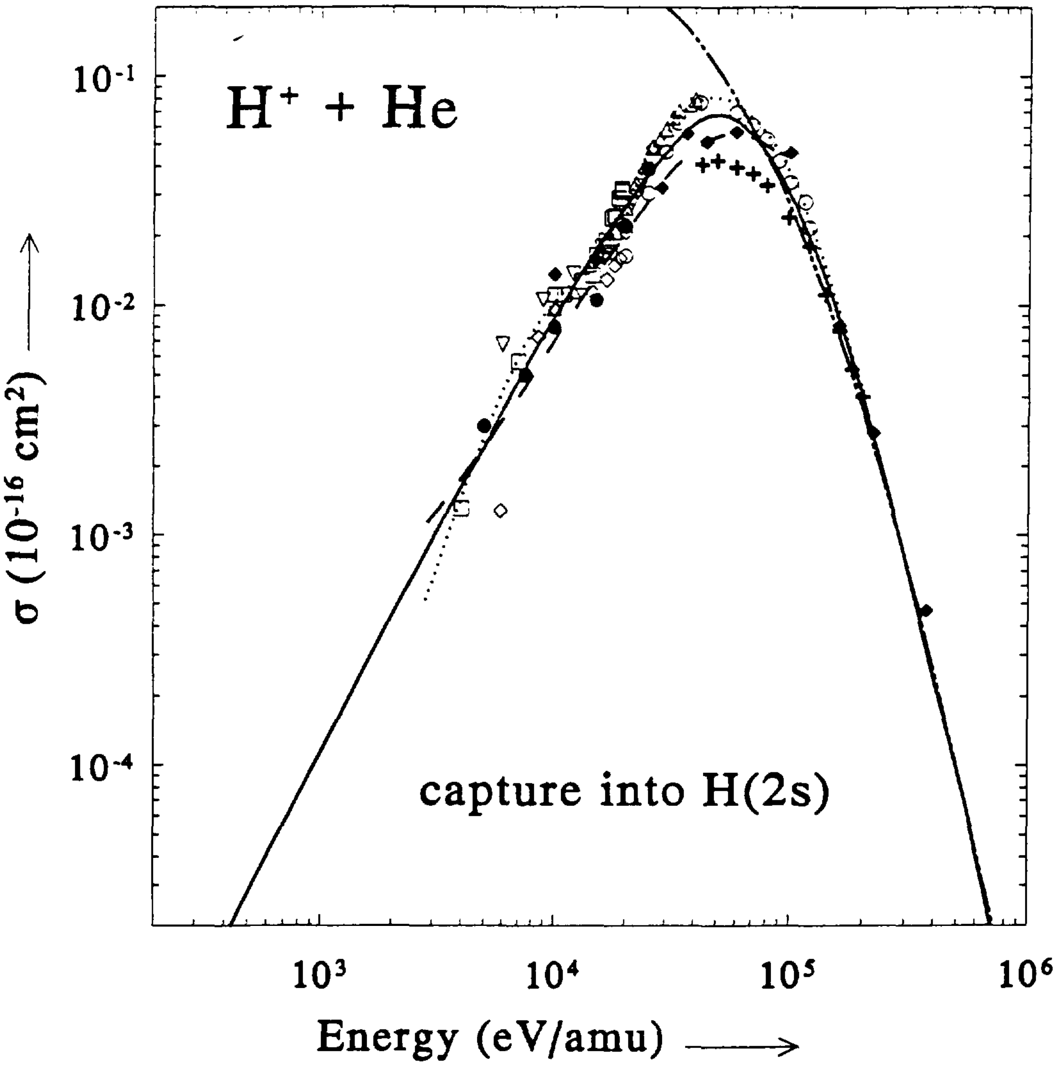


Figure 2. Cross sections for electron capture into H(2*s*) in collisions of H^+ on He. Experiment: ∇ Jaecks et al [22], Δ Andreev et al [24], + Ryding et al [21], ◊ Fitzwilson and Thomas [23], o Hughes et al [26], ▫ Crandall and Jaecks [20], ◆ Rodbro and Andersen [27] and ● Hippler et al [25]. Theory: – – – Kimura and Lin [47], –..–..– Belkič [48]. Recommended data: ..... Redbook [44], —— this work.

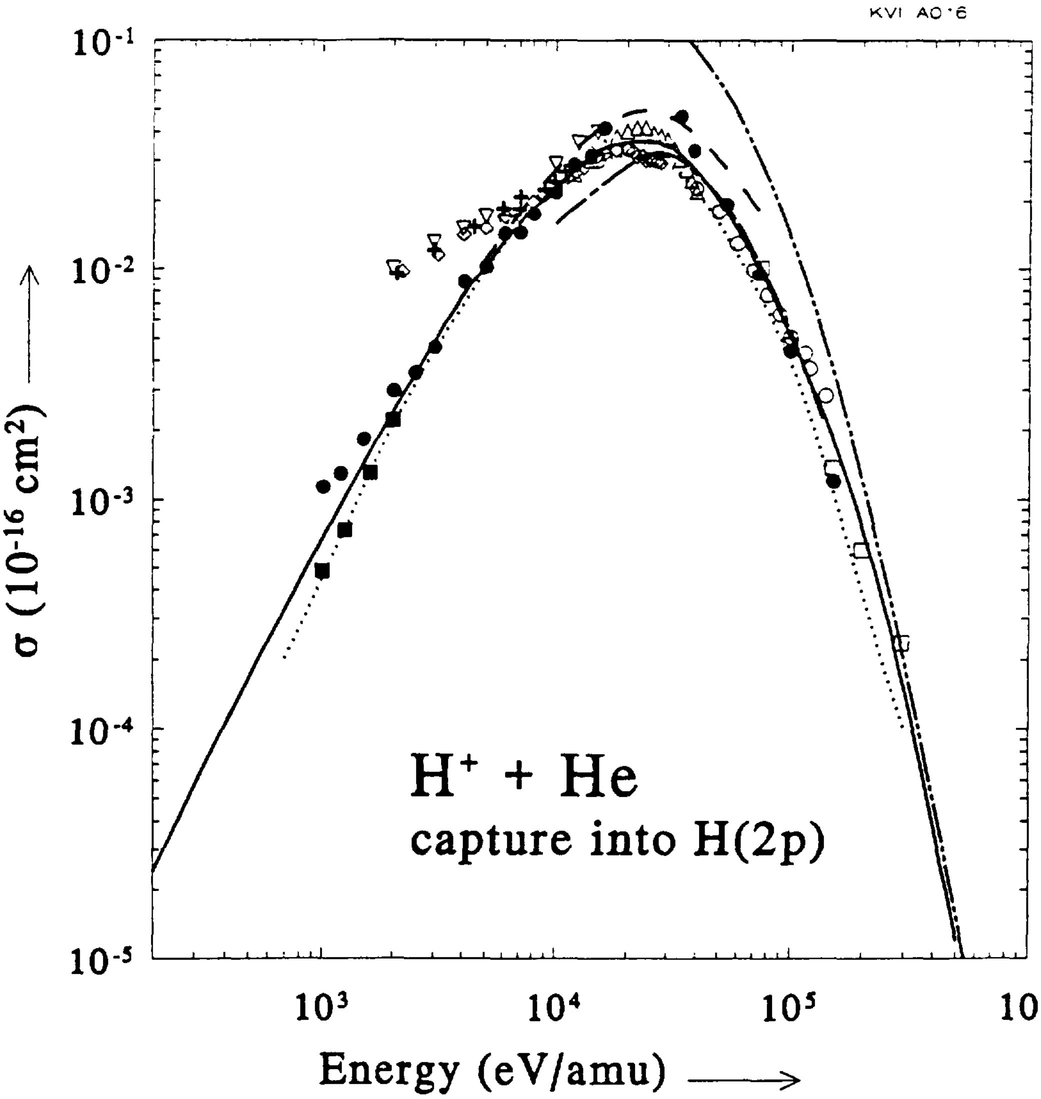


Figure 3. Cross sections for electron capture into H(*2p*) in collisions of H^+ on He. Experiment: ∇ Risley et al [31], Δ Andreev et al [24], + Gaily et al [32], ◊ Pretzer et al [30], o Hughes et al [26], ▫ Hippler et al [28], ▪ VanZyl et al [33] and • Hippler et al [29]. Theory: – – – Kimura and Lin [47], –..–..– Belkič [48] and —— – —— Slim et al [49]. Recommended data: ..... Redbook [44], —— this work.

KVI A018

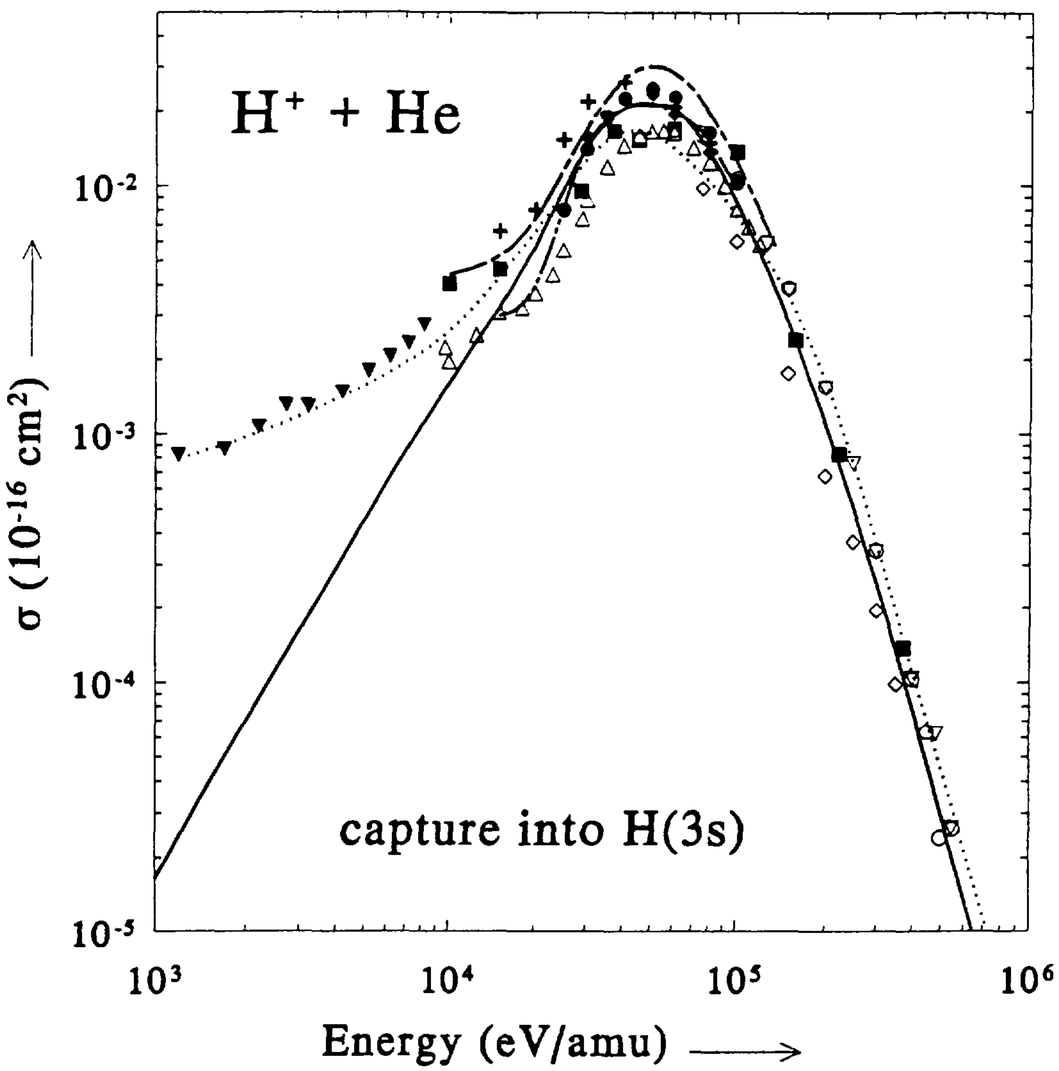


Figure 4. Cross sections for electron capture into H(*3s*) in collisions of H^+ on He. Experiment: ∇ Dawson and Loyd [37], ▼ Ford and Thomas [36], Δ Hughes et al [34], + Lenormand [39], ◊ Edwards and Thomas [38], o Conrads et al [35], ▪ Rodbro and Andersen [27], ♦ Brower and Pipkin [41] and o Ashburn et al [40]. Theory: -..-..- Shingal and Lin [52] and — - — Slim et al [49]. Recommended data: ..... Redbook [44], —— this work.

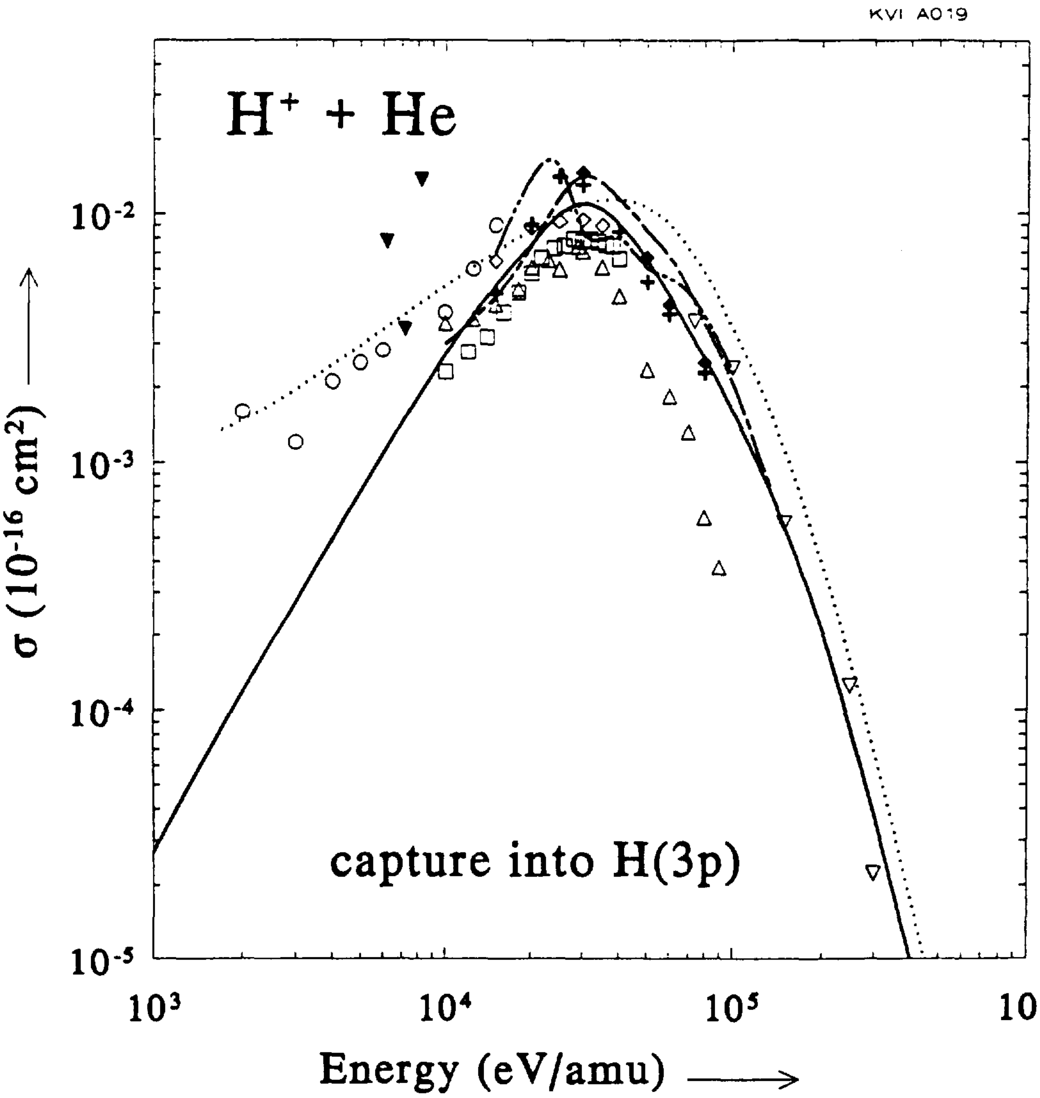


Figure 5. Cross sections for electron capture into H(*3p*) in collisions of H^+ on He. As figure 4 except o Risley et al [31] and ◊ de Heer et al [14].

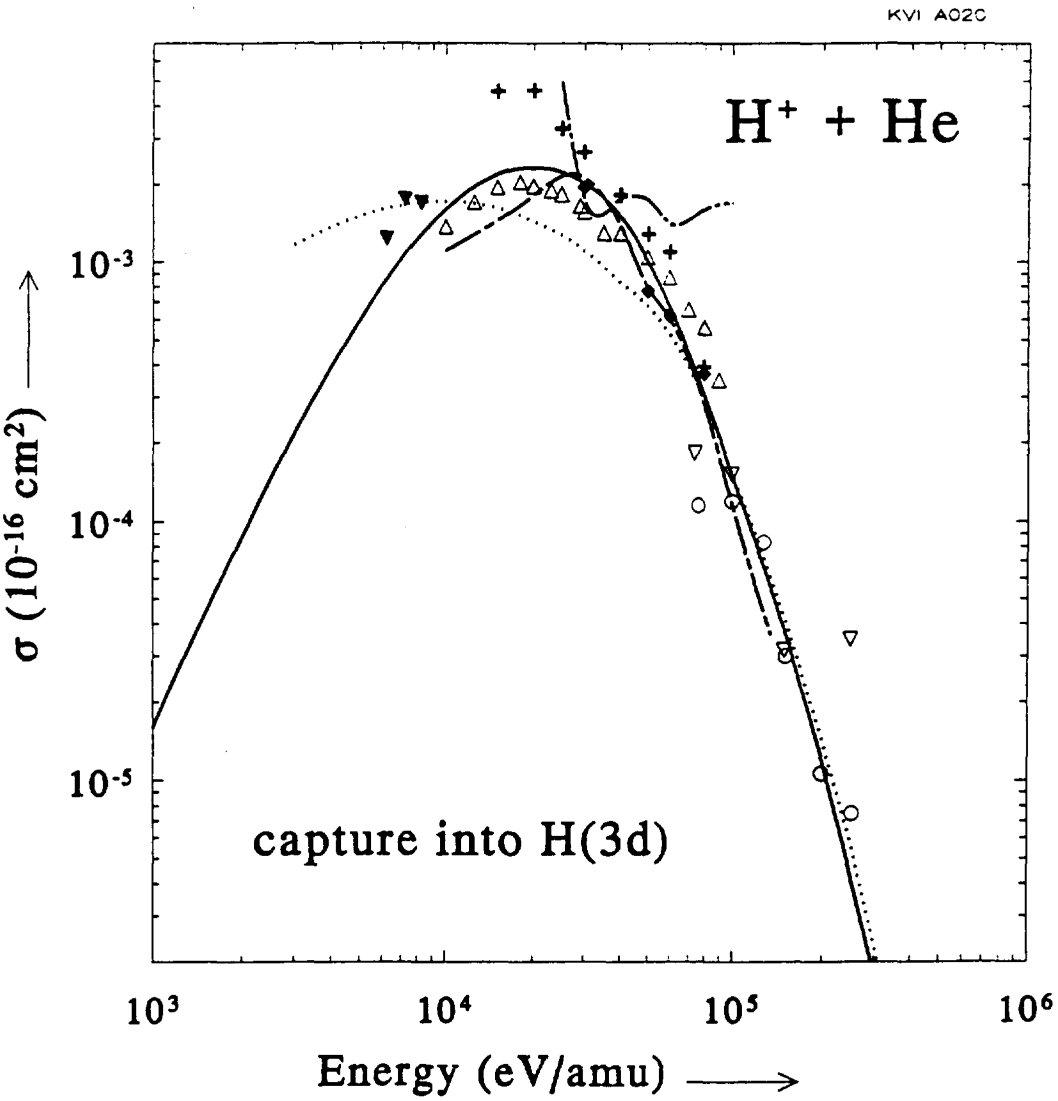


Figure 6. Cross sections for electron capture into H(*3d*) in collisions of H^+ on He. As figure 4.

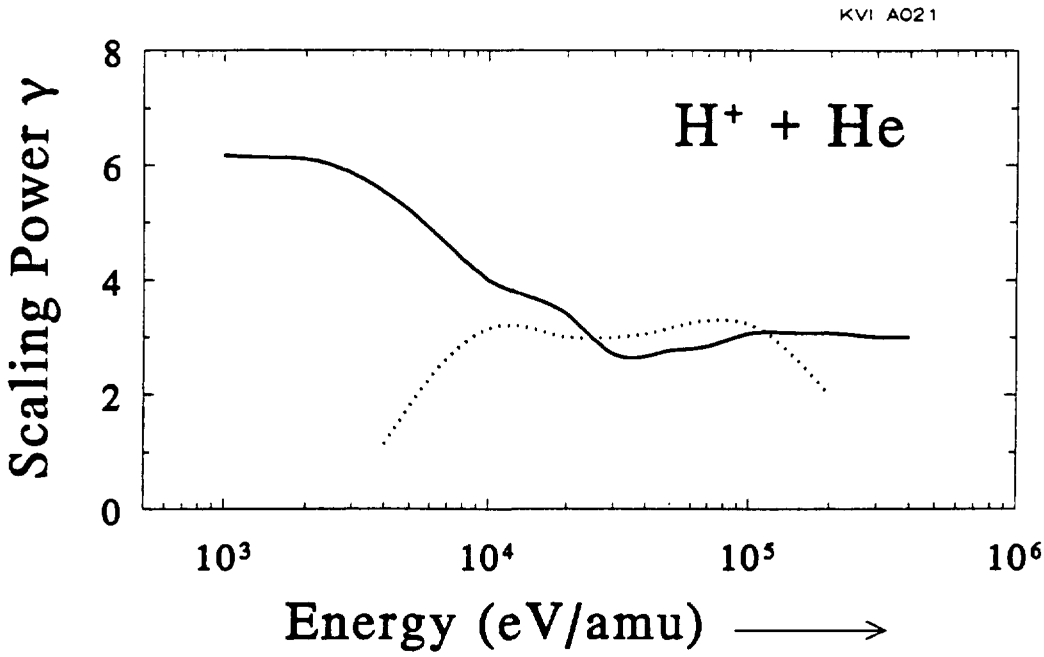
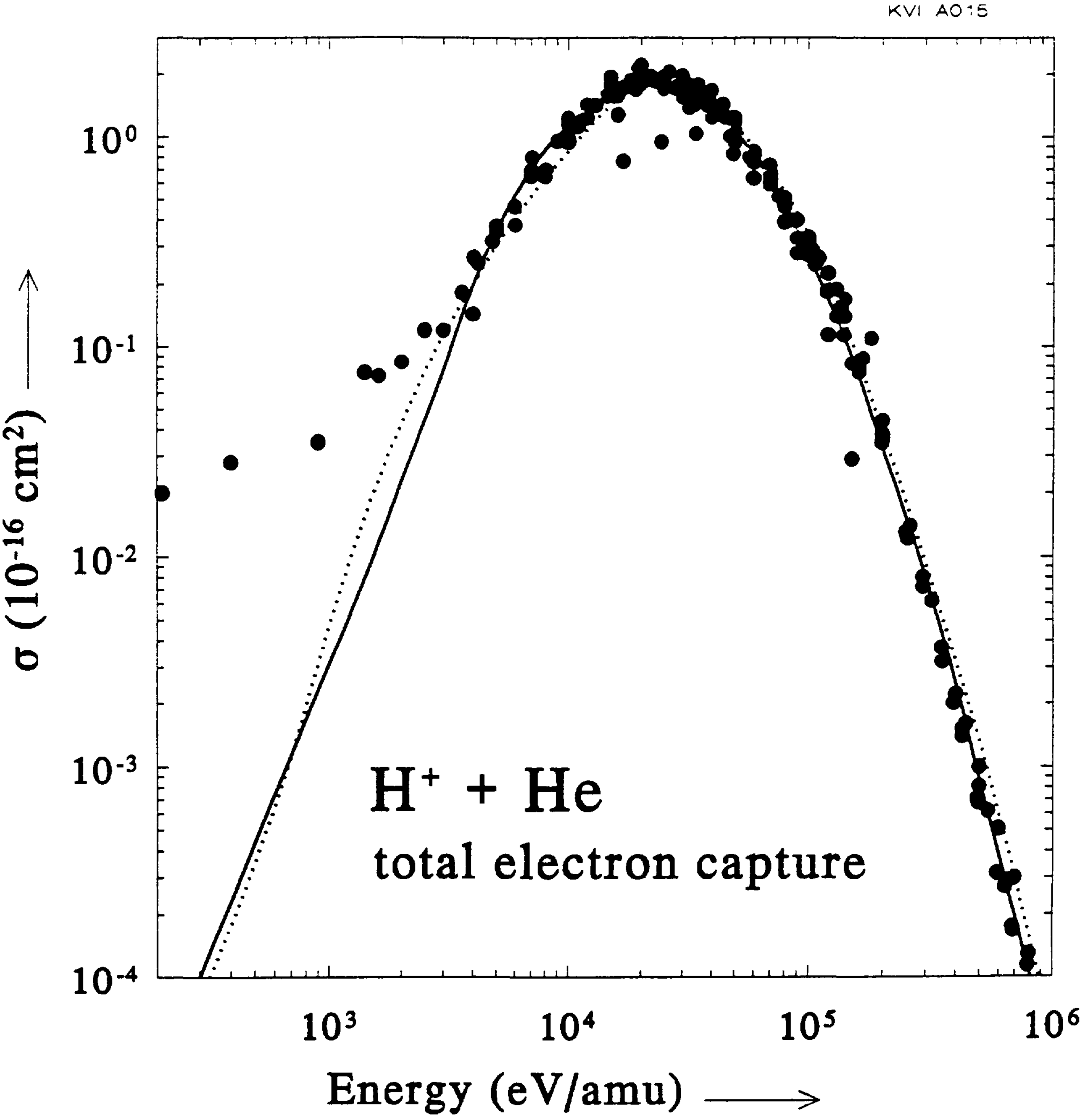
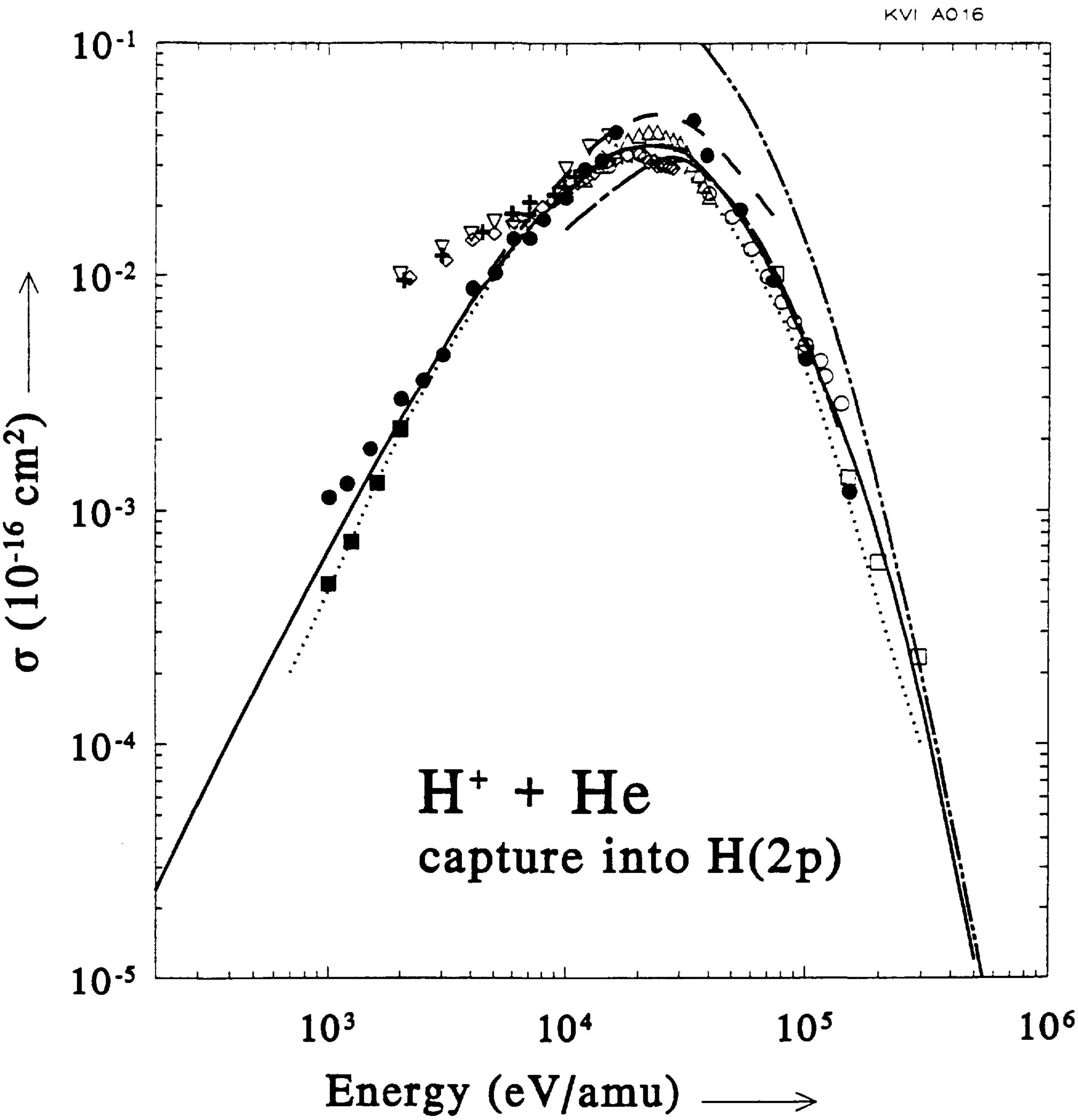


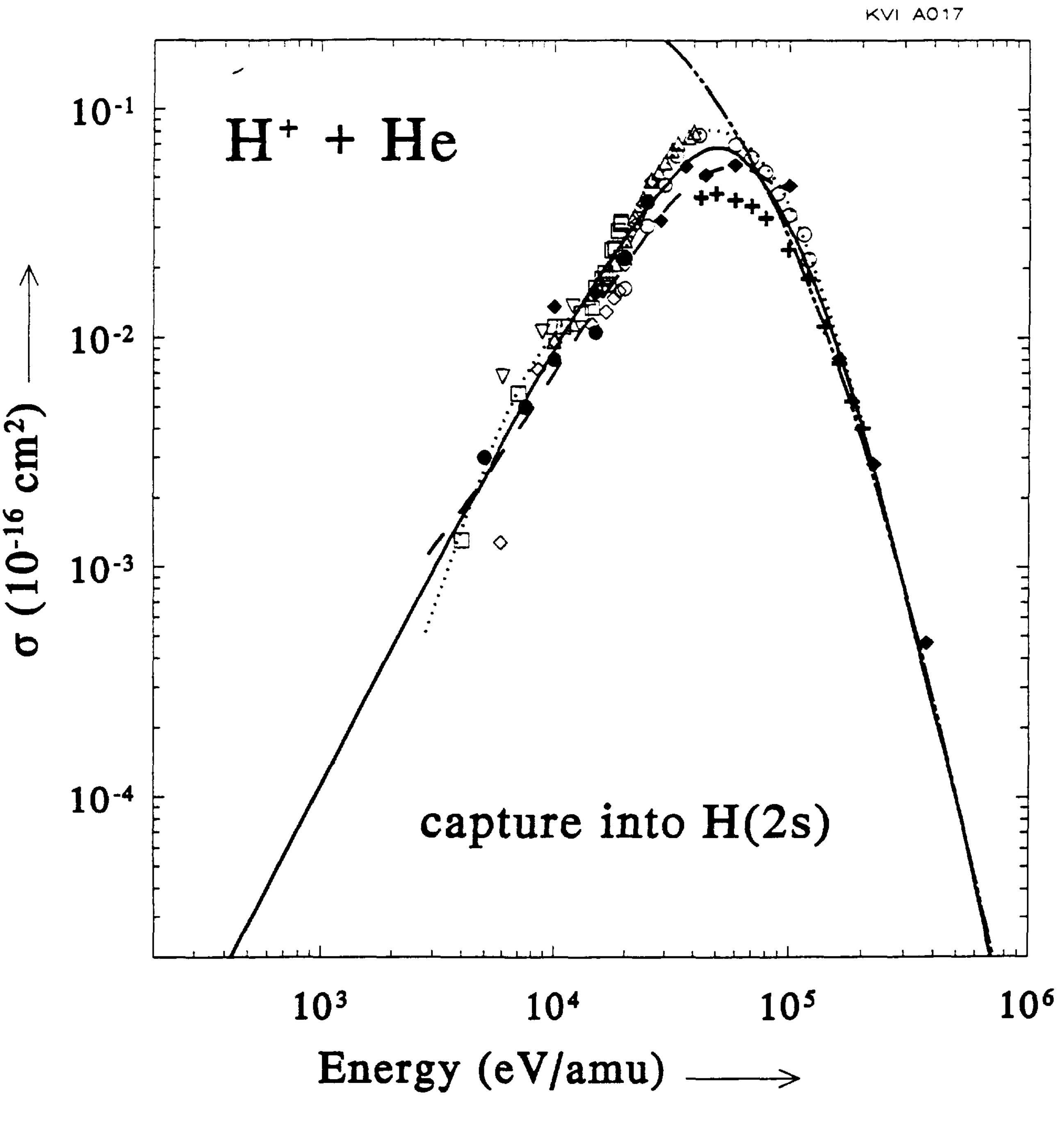
Figure 7. Scaling power γ ($n^{-\gamma}$) determined from the total $n = 2$ and $n = 3$ cross sections. ..... Redbook [44], —— this work.

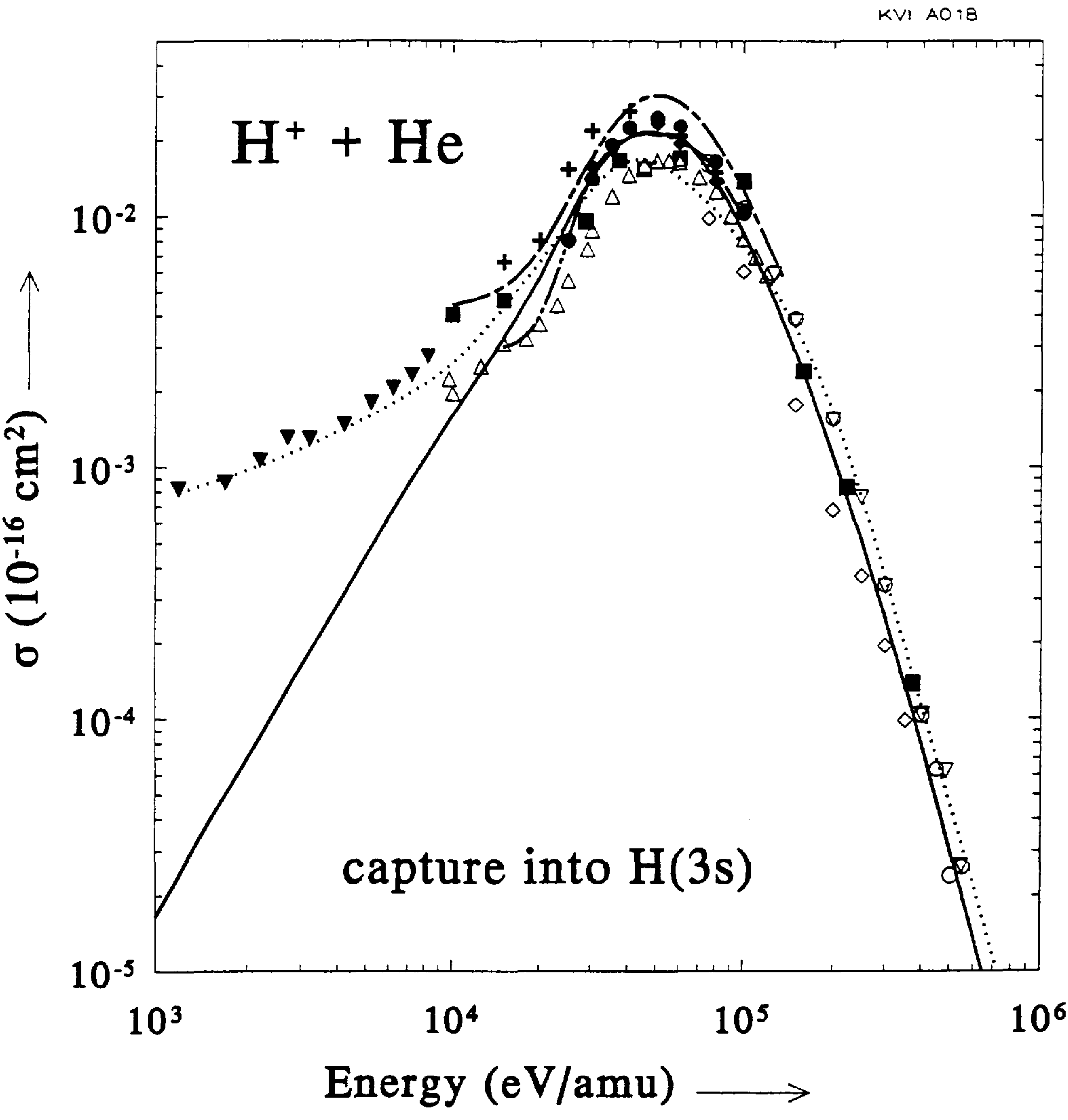


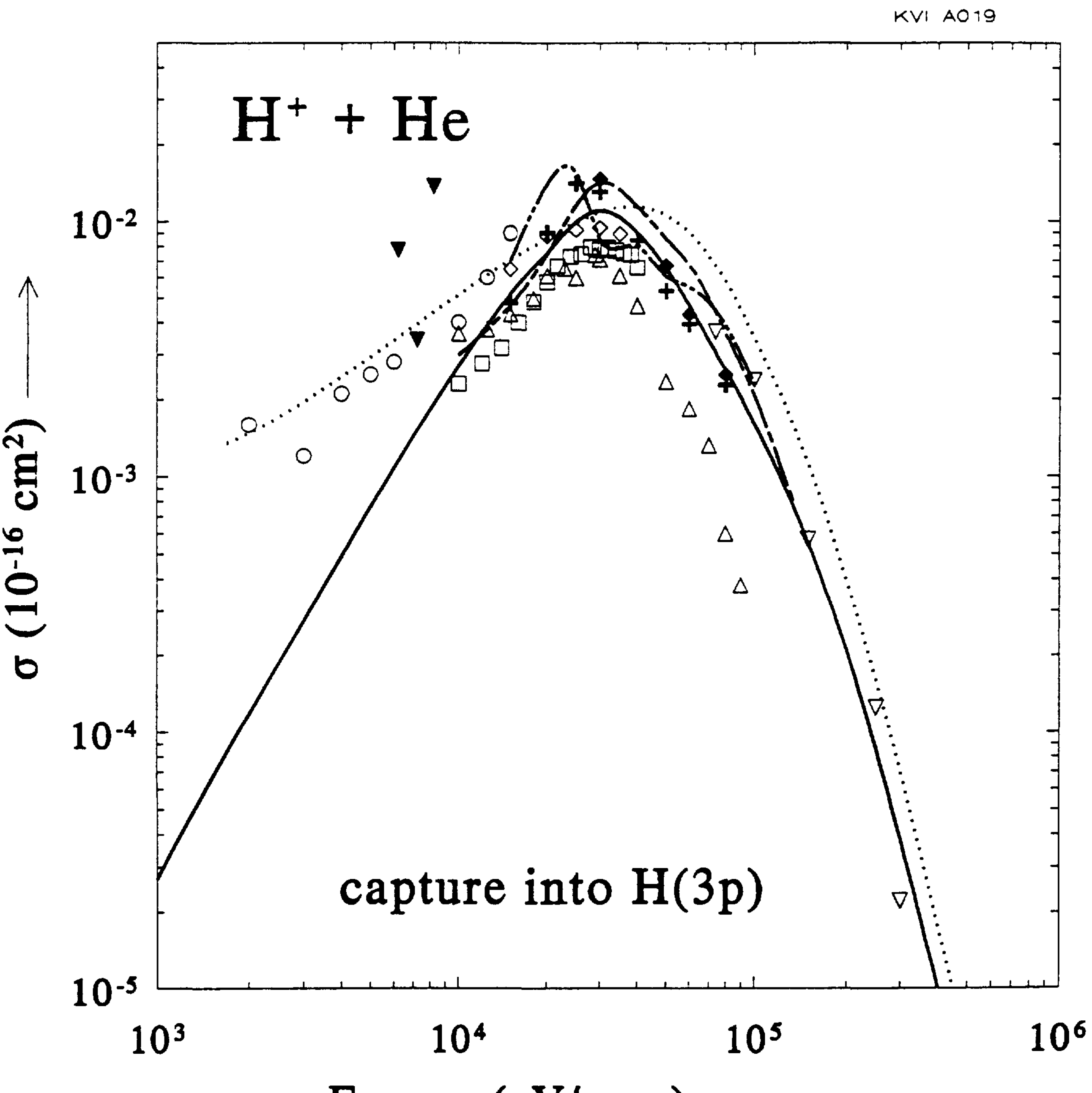
KVI A015
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
σ (10⁻¹⁶ cm²) →
10³
10⁴
10⁵
10⁶
Energy (eV/amu) →
H⁺ + He
total electron capture



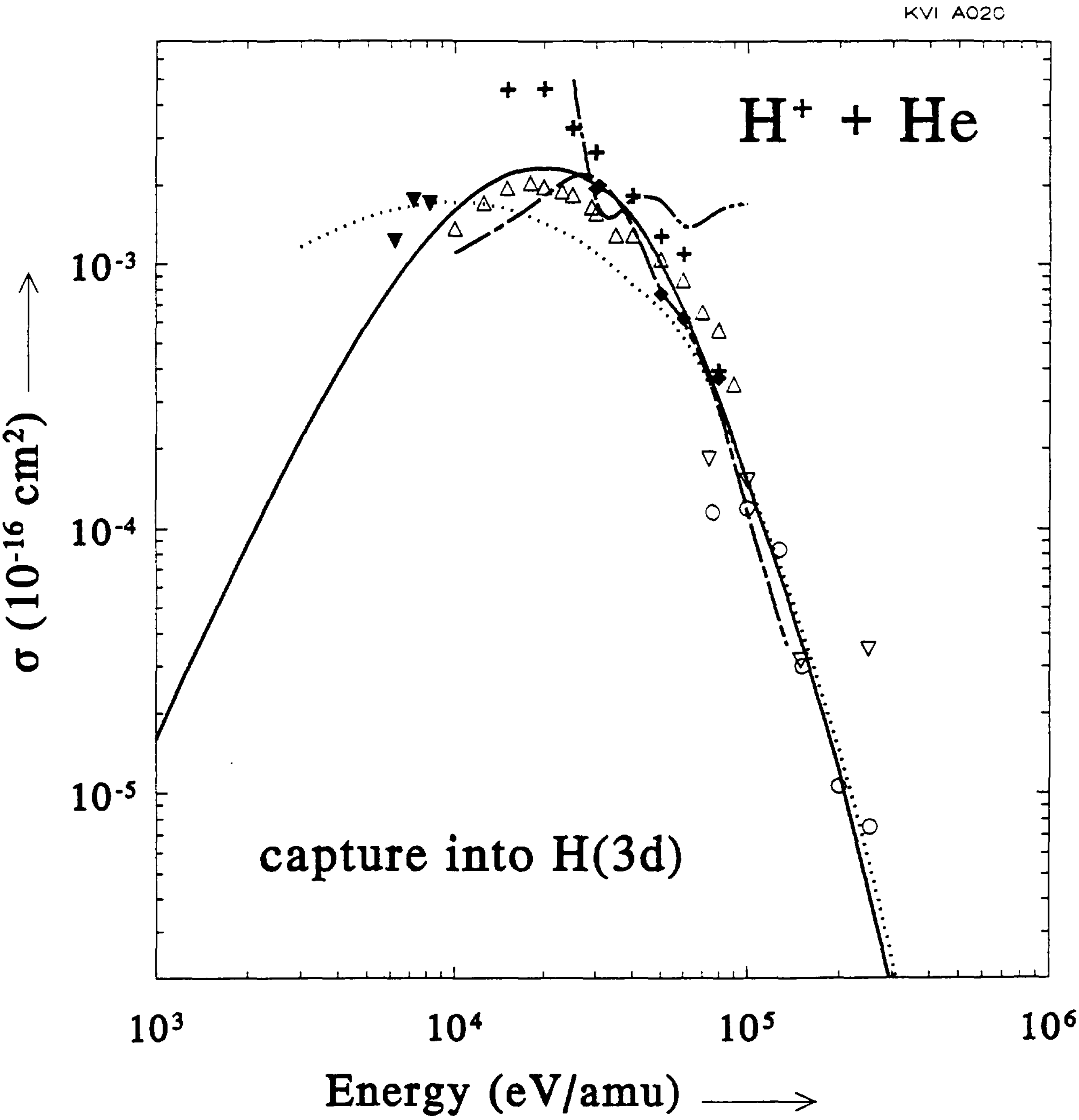
KVI A016
10-1
10-2
10-3
10-4
10-5
σ (10-16 cm2)
H+ + He
capture into H(2p)
10^3
10^4
10^5
10^6
Energy (eV/amu)

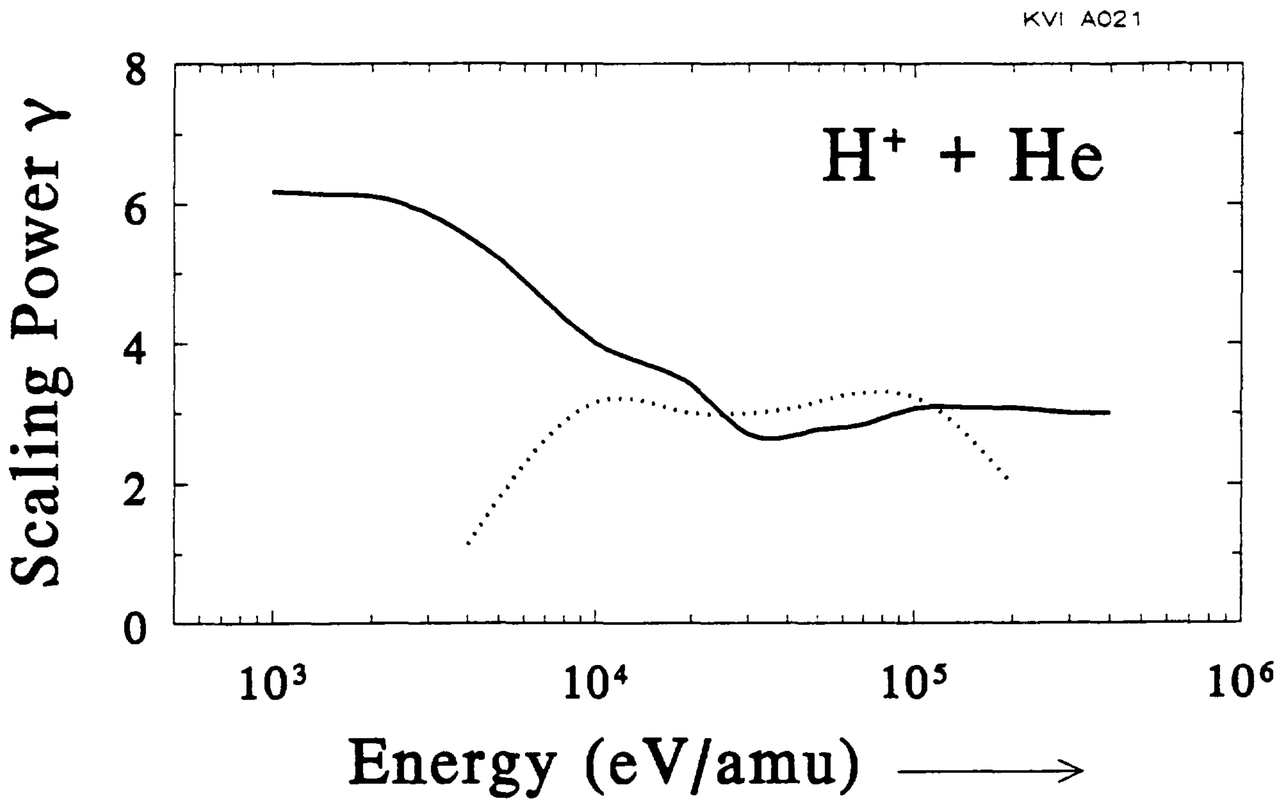

KVI A017
H⁺ + He
capture into H(2s)
σ (10⁻¹⁶ cm²) →
Energy (eV/amu) →
10⁻¹
10⁻²
10⁻³
10⁻⁴
10³
10⁴
10⁵
10⁶


KVI A018
H+ + He
capture into H(3s)
σ (10-16 cm2)
10-2
10-3
10-4
10-5
10³
10⁴
10⁵
10⁶
Energy (eV/amu)



KVI A019
H⁺ + He
capture into H(3p)
σ (10⁻¹⁶ cm²)
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10³
10⁴
10⁵
10⁶
Energy (eV/amu)


KVI A020
H+ + He
capture into H(3d)
σ (10-16 cm2)
10-3
10-4
10-5
10^3
10^4
10^5
10^6
Energy (eV/amu)


KVI A021
H+ + He
Scaling Power γ
0
2
4
6
8
10^3
10^4
10^5
10^6
Energy (eV/amu)

ANNEX

P.-H. REBUT, A. GIBSON, M. HUGUET, J.M. ADAMS[1], B. ALPER, H. ALTMANN, A. ANDERSEN[2], P. ANDREW[3], M. ANGELONE[4], S. ALI-ARSHAD, P. BAIGGER, W. BAILEY, B. BALET, P. BARABASCHI, P. BARKER, R. BARNSLEY[5], M. BARONIAN, D.V. BARTLETT, L. BAYLOR[6], A.C. BELL, G. BENALI, P. BERTOLDI, E. BERTOLINI, V. BHATNAGAR, A.J. BICKLEY, D. BINDER, H. BINDSLEV[2], T. BONICELLI, S.J. BOOTH, G. BOSIA, M. BOTMAN, D. BOUCHER, P. BOUCQUEY, P. BREGER, H. BRELEN, H. BRINKSCHULTE, D. BROOKS, A. BROWN, T. BROWN, M. BRUSATI, S. BRYAN, J. BRZOZOWSKI[7], R. BUCHSE[22], T. BUDD, M. BURES, T. BUSINARO, P. BUTCHER, H. BUTTGEREIT, C. CALDWELL-NICHOLS, D.J. CAMPBELL, P. CARD, G. CELENTANO, C.D. CHALLIS, A.V. CHANKIN[8], A. CHERUBINI, D. CHIRON, J. CHRISTIANSEN, P. CHUILON, R. CLAESEN, S. CLEMENT, E. CLIPSHAM, J.P. COAD, I.H. COFFEY[9], A. COLTON, M. COMISKEY[10], S. CONROY, M. COOKE, D. COOPER, S. COOPER, J.G. CORDEY, W. CORE, G. CORRIGAN, S. CORTI, A.E. COSTLEY, G. COTTRELL, M. COX[11], P. CRIPWELL[12], O. Da COSTA, J. DAVIES, N. DAVIES, H. de BLANK, H. de ESCH, L. de KOCK, E. DEKSNIS, F. DELVART, G.B. DENNE-HINNOV, G. DESCHAMPS, W.J. DICKSON[13], K.J. DIETZ, S.L. DMITRENKO, M. DMITRIEVA[14], J. DOBBING, A. DOGLIO, N. DOLGETTA, S.E. DORLING. P.G. DOYLE, D.F. DÜCHS, H. DUQUENOY, A. EDWARDS, J. EHRENBERG, A. EKEDAHL, T. ELEVANT[7], S.K. ERENTS[11], L.G. ERIKSSON, H. FAJEMIROKUN[12], H. FALTER, J. FREILING[15], F. FREVILLE, C. FROGER, P. FROISSARD, K. FULLARD, M. GADEBERG, A. GALETSAS, T. GALLAGHER, D. GAMBIER, M. GARRIBBA, P. GAZE, R. GIANNELLA, R.D. GILL, A GIRARD, A. GONDHALEKAR, D. GOODALL[11], C. GORMEZANO, N.A. GOTTARDI, C. GOWERS, B.J. GREEN, B. GRIEVSON, R. HAANGE, A. HAIGH, C.J. HANCOCK, P.J. HARBOUR, T. HARTRAMPF, N.C. HAWKES[11], P. HAYNES[11], J.L. HEMMERICH, T. HENDER[11], J. HOEKZEMA, D. HOLLAND, M. HONE, L. HORTON, J. HOW, M. HUART, I. HUGHES, T.P. HUGHES[10], M. HUGON, Y. HUO[16], K. IDA[17], B. INGRAM, M. IRVING, J. JACQUINOT, H. JAECKEL, J.F. JAEGER, G. JANESCHITZ, Z. JANKOVICZ[18], O.N. JARVIS, F. JENSEN, E.M. JONES, H.D. JONES, L.P.D.F. JONES, S. JONES[19], T.T.C. JONES, J.-F. JUNGER, F. JUNIQUE, A. KAYE, B.E. KEEN, M. KEILHACKER, G.J. KELLY, W. KERNER, A. KHUDOLEEV[21], R. KONIG, A. KONSTANTELLOS, M. KOVANEN[20], G. KRAMER[15], P. KUPSCHUS, R. LÄSSER, J.R. LAST, B. LAUNDY, L. LAURO-TARONI, M. LAVEYRY, K. LAWSON[11], M. LENNHOLM, J. LINGERTAT[22], R.N. LITUNOVSKI, A. LOARTE, R. LOBEL, P. LOMAS, M. LOUGHLIN, C. LOWRY, J. LUPO, A.C. MAAS[15], J. MACHUZAK[19], B. MACKLIN, G. MADDISON[11], C.F. MAGGI[23], G. MAGYAR, W. MANDL[22], V. MARCHESE, G. MARCON, F. MARCUS, J. MART, D. MARTIN, E. MARTIN, R. MARTIN-SOLIS[24], P. MASSMANN, G. MATTHEWS, H. McBRYAN, G. McCRACKEN[11], J. McKIVITT, P. MERIGUET, P. MIELE, A. MILLER, J. MILLS, S.F. MILLS, P. MILLWARD, P. MILVERTON, E. MINARDI[4], R. MOHANTI[25], P.L. MONDINO, D. MONTGOMERY[26], A. MONTVAI[27], P. MORGAN, H. MORSI, D. MUIR, G. MURPHY, R. MYRNÄS[28], F. NAVE[29], G. NEWBERT, M. NEWMAN, P. NIELSEN, P. NOLL, W. OBERT, D. O'BRIEN, J. ORCHARD, J. O'ROURKE, R. OSTROM, M. OTTAVIANI, M. PAIN, F. PAOLETTI, S. PAPASTERGIOU, W. PARSONS, D. PASINI, D. PATEL, A. PEACOCK, N. PEACOCK[11], R.J.M. PEARCE, D. PEARSON[12], J.F. PENG[16], R. PEPE DE SILVA, G. PERINIC, C. PERRY, M. PETROV[21], M.A. PICK, J. PLANCOULAINE, J.-P POFFÉ, R. PÖHLCHEN, F. PORCELLI, L. PORTE[13], R. PRENTICE, S. PUPPIN, S. PUTVINSKII[8], G. RADFORD[30], T. RAIMONDI, M.C. RAMOS DE ANDRADE, R. REICHLE, J. REID, S. RICHARDS, E. RIGHI, F. RIMINI, D. ROBINSON[11], A. ROLFE, R.T. ROSS, L. ROSSI, R. RUSS, P. RUTTER, H.C. SACK, G. SADLER, G. SAIBENE, J.L. SALANAVE, G. SANAZZARO, A. SANTAGIUSTINA, R. SARTORI, C. SBORCHIA, P. SCHILD, M. SCHMID, G. SCHMIDT[31], B. SCHUNKE, S.M. SCOTT, L. SERIO, A SIBLEY, R. SIMONINI, A.C.C. SIPS, P. SMEULDERS, R. SMITH, R. STAGG, M. STAMP, P. STANGEBY[3], R. STANKIEWICZ[32], D.F. START, C.A. STEED, D. STORK, P.E. STOTT, P. STUBBERFIELD, D. SUMMERS, H. SUMMERS[13], L. SVENSSON, J.A. TAGLE[33], M. TALBOT, A. TANGA, A. TARONI, C. TERELLA, A TERRINGTON, A TESINI, P.R. THOMAS, E. THOMPSON, K. THOMSEN, F. TIBONE, A. TISCORNIA, P. TREVALION, B. TUBBING, P. VAN BELLE, H. VAN DER BEKEN, G. VLASES, M. VON HELLERMANN, T. WADE, C. WALKER, R. WALTON[31], D. WARD, M.L. WATKINS, N. WATKINS, M.J. WATSON, S. WEBER[34], J. WESSON, T.J. WIJNANDS, J. WILKS, D. WILSON, T. WINKEL, R. WOLF, D. WONG, C. WOODWARD, Y. WU[35], M. WYKES, D. YOUNG, I.D. YOUNG, L. ZANNELLI, A. ZOLFAGHARI[19], W. ZWINGMANN

[1] Harwell Laboratory, UKAEA, Harwell, Didcot, Oxfordshire, UK.
[2] Risø National Laboratory, Roskilde, Denmark.
[3] Institute for Aerospace Studies, University of Toronto, Downsview, Ontario, Canada.
[4] ENEA Frascati Energy Research Centre, Frascati, Rome, Italy.
[5] University of Leicester, Leicester, UK.
[6] Oak Ridge National Laboratory, Oak Ridge, TN, USA.
[7] Royal Institute of Technology, Stockholm, Sweden.
[8] I.V. Kurchatov Institute of Atomic Energy, Moscow, Russian Federation.
[9] Queens University, Belfast, UK.
[10] University of Essex, Colchester, UK.
[11] Culham Laboratory, UKAEA, Abingdon, Oxfordshire, UK.
[12] Imperial College of Science, Technology and Medicine, University of London, London, UK.
[13] University of Strathclyde, Glasgow, UK.
[14] Keldysh Institute of Applied Mathematics, Moscow, Russian Federation.
[15] FOM-Institute for Plasma Physics "Rijnhuizen", Nieuwegein, Netherlands.
[16] Institute of Plasma Physics, Academia Sinica, Hefei, Anhui Province, China.
[17] National Institute for Fusion Science, Nagoya, Japan.
[18] Soltan Institute for Nuclear Studies, Otwock/Świerk, Poland.
[19] Plasma Fusion Center, Massachusetts Institute of Technology, Boston, MA, USA.
[20] Nuclear Engineering Laboratory, Lappeenranta University, Finland.
[21] A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russian Federation.
[22] Max-Planck-Institut für Plasmaphysik, Garching, Germany.
[23] Department of Physics, University of Milan, Milan, Italy.
[24] Universidad Complutense de Madrid, Madrid, Spain.
[25] North Carolina State University, Raleigh, NC, USA.
[26] Dartmouth College, Hanover, NH, USA.
[27] Central Research Institute for Physics, Budapest, Hungary.
[28] University of Lund, Lund, Sweden.
[29] Laboratorio Nacional de Engenharia e Tecnologia Industrial, Sacavem, Portugal.
[30] Institute of Mathematics, University of Oxford, Oxford, UK.
[31] Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA.
[32] RCC Cyfronet, Otwock/Świerk, Poland,
[33] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain.
[34] Freie Universität, Berlin, Germany.
[35] Insitute for Mechanics, Academia Sinica, Beijing, China.