

NATIONAL INSTITUTE FOR FUSION SCIENCE**Comparison of Recombination Rate Coefficients
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from Hydrogen through Nickel**

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Comparison of Recombination Rate Coefficients given by Empirical Formulas for Ions from Hydrogen through Nickel

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Abstract

Recombination rate coefficients based on several empirical formulae are compared for ions of H, He, C, N, O, Ne, Na, Mg, Al, Si, S, P, Cl, Ar, Ca, Fe and Ni. The total rate coefficients including radiative recombination and dielectronic recombination are shown in graphs.

Key words

recombination rate coefficients, radiative recombination, dielectronic recombination, plasma, ions, empirical formulae

1. Introduction

Recombination rate coefficients as well as ionization rate coefficients are important in understanding ionization balance in both laboratory and astrophysical plasmas. We compared ionization rate coefficients by several empirical formulas for various ions in Ref.1. From both experimental and theoretical viewpoints, recombination is less well-studied than ionization. Experimental data is not plentiful. In this report we compare recombination rate coefficients given by empirical formulas which are commonly used for laboratory and astrophysical plasmas. We compare values for the total recombination rate coefficient which is the sum of radiative recombination and dielectric recombination at low density limit. We do not compare three body recombination rate coefficients since they are not important at low density plasmas and they can be easily derived from ionization rate coefficients. As we will see in the graphs of this paper, the dielectronic recombination rate coefficients are confused for L and M shell ions. The empirical formulas examined here are not new. However we hope our comparison will stimulate an improvement of this data in the future.

Recently detailed calculations for dielectronic recombination have been published as well as the experimental data². We do not include these individual data in our comparison but we hope new empirical formulas based on these new data can be made in the near future.

2. Empirical formula

We have compared the following six empirical formulas. The rate coefficients given here are the sum over all the excited states of a final ion from the ground state of an initial ion.

2.1. Aldrovandi and Pequingot³

Radiative and dielectronic recombination rate coefficients are calculated for all non-hydrogenic ions of He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar and Ca.

The results are given for the Maxwell averaged radiative recombination rate coefficient:

$$\alpha_r = A_r (T_e/10^4)^{-\eta} \quad (1)$$

where T_e is the electron temperature in K. The dielectronic recombination rate coefficient is given by

$$\alpha_{di} = A_{di} T_e^{-3/2} \exp(-T_0/T_e) (1 + B_{di} \exp(-T_i/T_e)) \quad (2)$$

A_r , η , A_{di} , T_0 , B_{di} , T_i are fit parameters in Eqs.(1) and (2). The fit values are given in Tables in Ref.3 for each ion.

2.2 Mewe

Atomic data by Mewe^{4, 5} are widely used especially for astrophysical studies, solar flares and X-ray astronomy. The radiative recombination rate coefficient is approximated by

$$\alpha_{Z,z}^r = 10^{-10} \alpha_z^{2\eta+1} \Delta T_e^{-\eta} \quad \text{cm}^3 \text{ s}^{-1} \quad (3)$$

where α , η and Δ are given in table II in Ref.4. Z and z are the nuclear charge and ionic charge of the ion respectively.

The dielectronic recombination rate coefficient for $z < Z - 4$ is approximated by

$$\alpha_{Z,z}^d = 10^{-3} T_e^{-3/2} (z^2 + 13.4)^{-1/2} \sum \alpha_i z^{\beta_i} \exp(-10^4 g_i \delta_i / T_e) \quad \text{cm}^3 \text{ s}^{-1} \quad (4)$$

where the parameters α_i etc. are given in table III in Ref. 4. For higher z the results are presented in Ref.5.

The elements included are H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe and Ni. For other elements, P and Cl, the parameters are scaled (K. Masai⁶) and used for the graphs in this report.

2.3 Hulse

The atomic transport code called MIST

by R. Hulse⁷ is often used in the modelling of magnetic confined fusion plasmas. The atomic data from MIST were kindly given to us by Prof. T. Amano in National Institute for Fusion Science in 1980's and we use that data in our comparison.

2.4 Arnaud et al.

Arnaud and Rothenflug⁸ evaluated cross sections for ions of H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, Ni which are major species in astrophysical plasmas. Later Arnaud and Raymond⁹ updated the cross section for iron ions. They used parametric formulas and the values for parameters are given in tables in their papers. The parametric fits are valid only in a given temperature range.

Radiative recombination to H-like ions is calculated using the formula given by Seaton¹⁰,

$$\alpha_r = 5.197 \times 10^{-14} Z\lambda^{1/2} \{0.4288 + 0.5\text{Ln}(\lambda) + 0.469\lambda^{-1/3}\} \text{ cm}^3 \text{ s}^{-1} \quad (5)$$

where $\lambda = 157890 Z^2/T(\text{K})$ and Z is the nuclear charge. For non hydrogenic ions Eq. (1) from Ref. 3 is used.

The dielectronic recombination rate coefficients are fitted by Eq. (2) except for recombination of He-like ions. For the dielectronic recombination of He-like ions to Li-like ions the formula given by Younger¹¹ is used,

$$\alpha_d = 7.6 \times 10^{-11} A(z) \exp(-D(z)/x) x^{3/2} \text{ cm}^3 \text{ s}^{-1} \quad (6)$$

where $x = kT/I(\text{Li})$ and $z = Z-2$

$$A(z) = (z+1)^3 / [z^2(z^2+13.4)^{1/2}(1+0.16(z+1) + 0.017(z+1)^2)]$$

$$D(z) = 3.0\{(z+1)^2/z^2\} / \{1+0.015z^3/(z+1)^2\}$$

$I(\text{Li})$ is the ionization potential of the Li-like ion.

For Fe ions they fit the rate coefficients with the formula,

$$\alpha_d = T^{-2/3} \sum_i c_i \exp(-E_i/kT) \text{ cm}^3 \text{ s}^{-1} \quad (7)$$

The parameters c_i and E_i are given in Table 3 in Ref.9.

2.5 Itikawa et al

Itikawa, Kato and Sakimoto¹² evaluated the rate coefficients for electron impact excitation, ionization and recombination for the analysis of X-ray spectra of H-like and He-like S, Ca and Fe ions from solar flares. For the radiative recombination processes they used formulas by Arnaud et al. For dielectronic recombination rate coefficients, several data are compared. They found large discrepancies between different data sources for L-shell ions such as Li \rightarrow Be and Be \rightarrow B like ions. The recommended data are fitted by Eq. (7) and the fit parameters are given for H-like, He-like, Li-like and Be-like ions as the initial ions. They adopted the data by Romanik¹³ for the dielectronic recombination of Li- and Be-like ions.

Figures 1, 2 and 3 show the recommended data by Itikawa et al. for S, Ca and Fe ions, respectively. The radiative recombination (RR) and dielectronic recombination (DR) are separately indicated in the figures. It is seen that DR process is important for low charged ions.

3. Graphs

The total recombination rate coefficients (radiative recombination and dielectronic recombination) by Aldrovandi and Pequignot³, Arnaud et al^{8,9}, Mewe et al⁵, Hulse⁷ and Itikawa et al¹². are compared by the element from H through Ni (H, He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, Ca, Fe, Ni) as a function of electron temperature.

4. Summary

From the comparison of the graphs large discrepancies are found especially for low charged ions. In order to discuss the ionization balance in plasma we need more reliable data for recombination. The discrepancies are mainly due to dielectronic recombination rate coefficients. Recently more accurate data are becoming available from both theoretical calculation and experimental measurements. We are making a database for these individual data (<http://dbshino.nifs.ac.jp>). It will be necessary to develop recommended data for recombination processes including the new data in the near future.

Acknowledgement

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Figure captions

Fig.1 The recombination rate coefficients by Itikawa et al¹⁰ for S ions of S¹²⁺ (Be-like → B-like), S¹³⁺ (Li-like → Be-like), S¹⁴⁺ (He-like → Li-like) and S¹⁵⁺ (H-like → He-like). The dotted line, dashed line and solid line indicate the radiative recombination, the dielectronic recombination and total recombination rate coefficients, respectively.

Fig.2 The recombination rate coefficients by Itikawa et al¹⁰ for Ca ions of Ca¹⁶⁺ (Be-like → B-like), Ca¹⁷⁺ (Li-like → Be-like), Ca¹⁸⁺ (He-like → Li-like) and Ca¹⁹⁺ (H-like → He-like). The dotted line, dashed line and solid line indicate the radiative recombination, the dielectronic recombination and total recombination rate coefficients, respectively.

Fig.3 The recombination rate coefficients by Itikawa et al¹⁰ for Ca ions of Fe²²⁺ (Be-like → B-like), Fe²³⁺ (Li-like → Be-like), Fe²⁴⁺ (He-like → Li-like) and Fe²⁵⁺ (H-like → He-like). The dotted line, dashed line and solid line indicate the radiative recombination, the dielectronic recombination and total recombination rate coefficients, respectively.

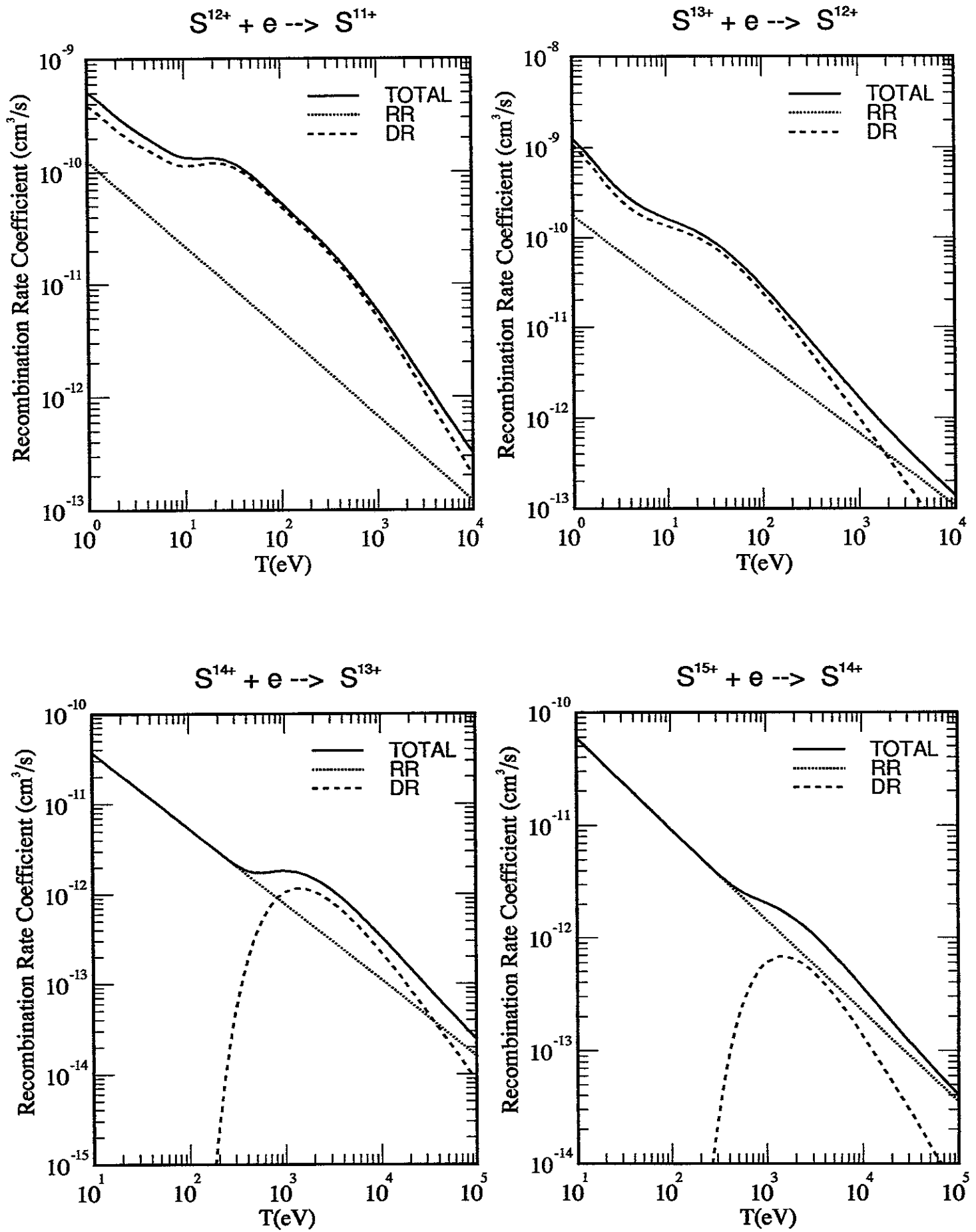


Fig.1

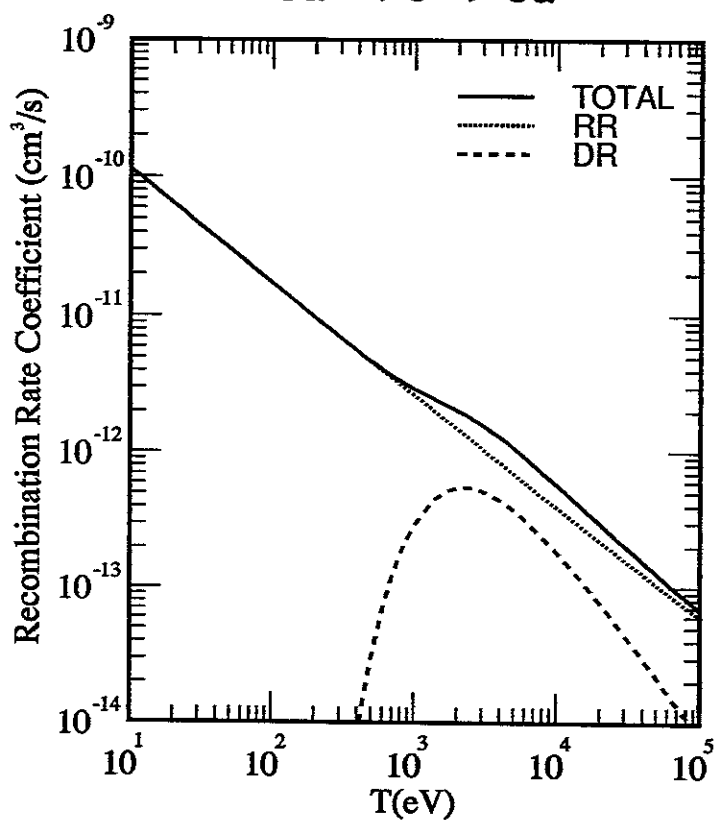
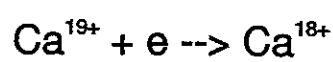
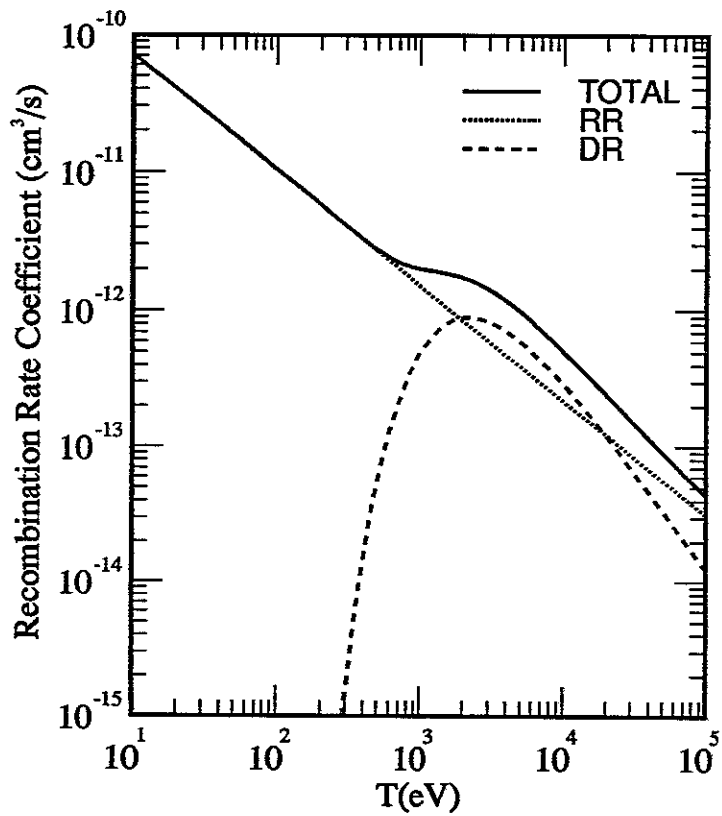
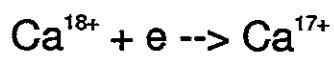
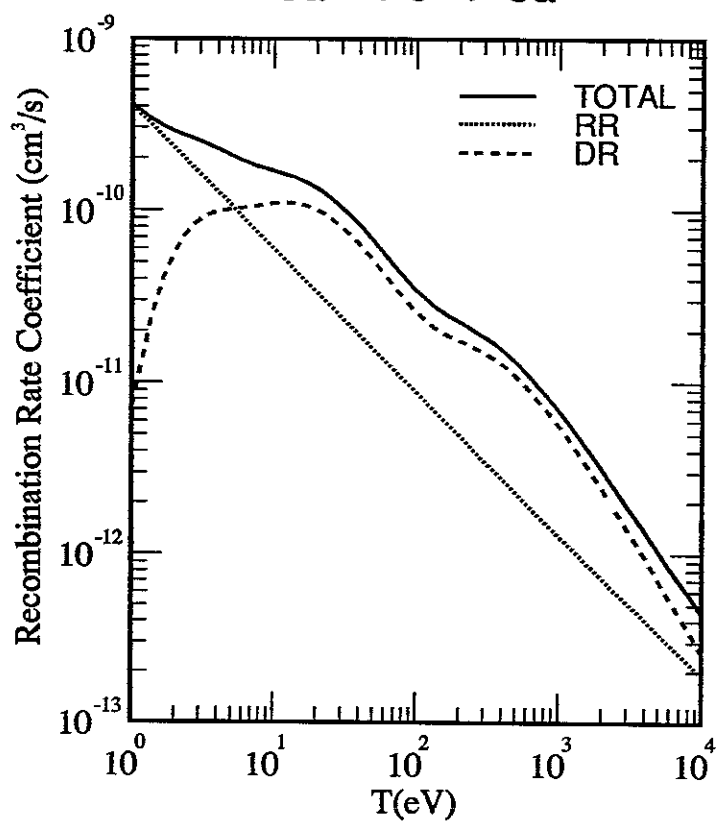
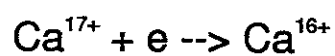
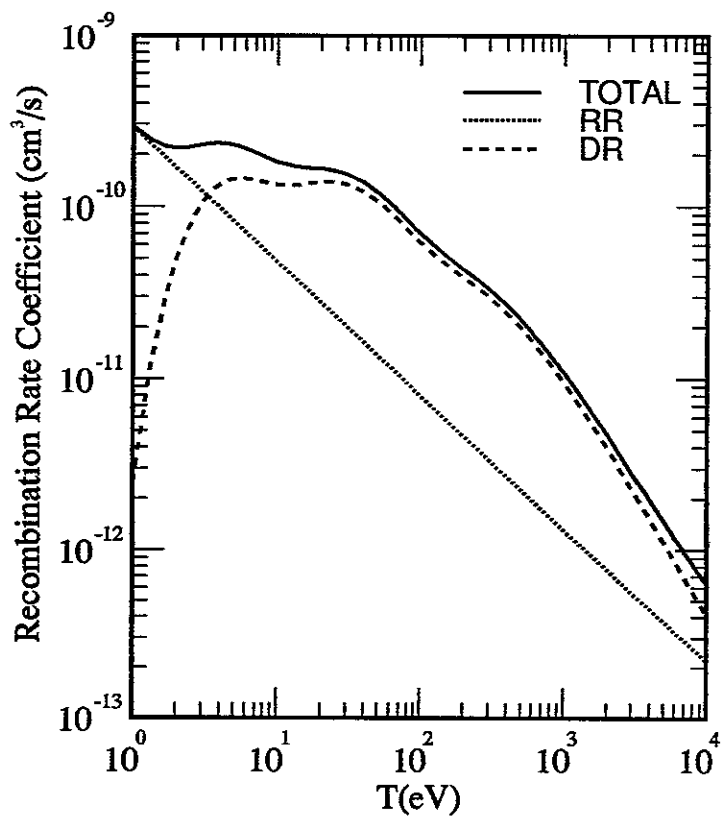
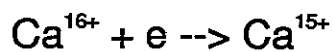


Fig.2

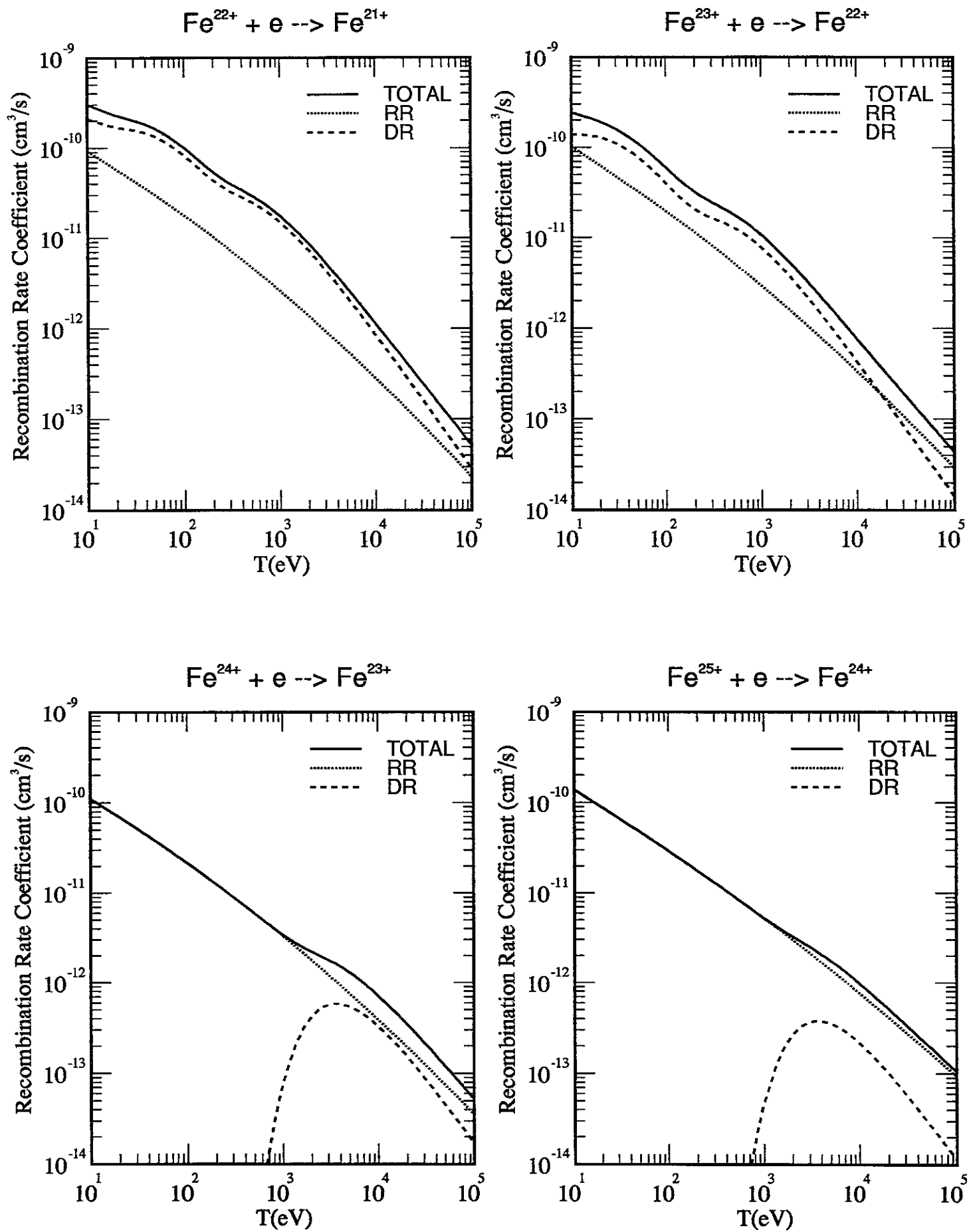
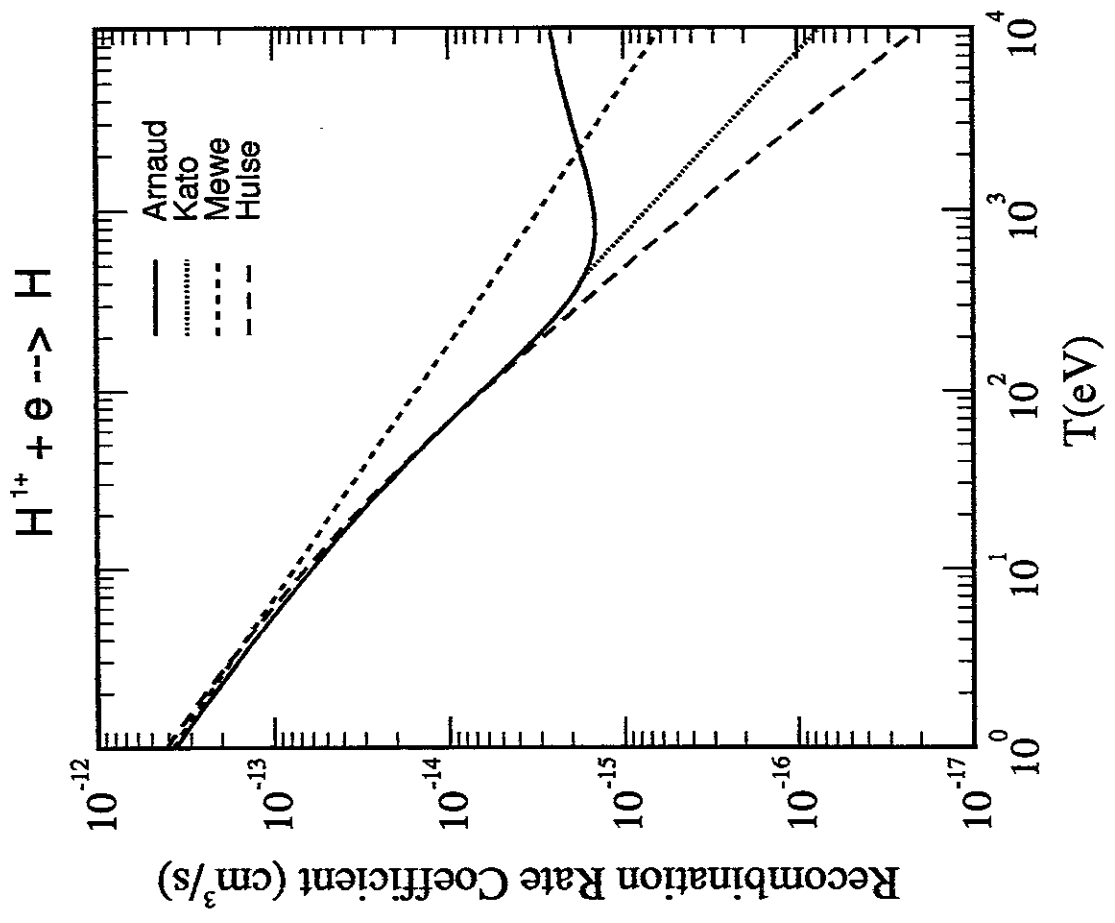
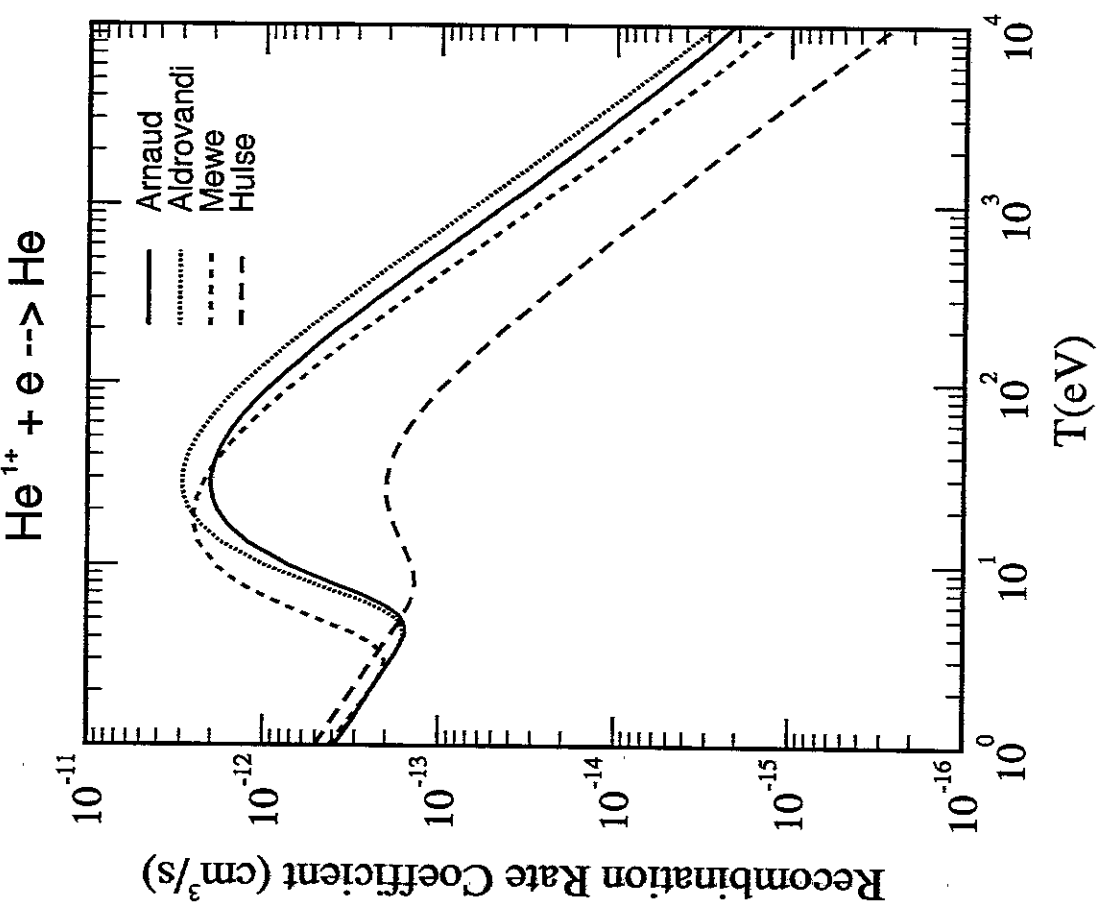
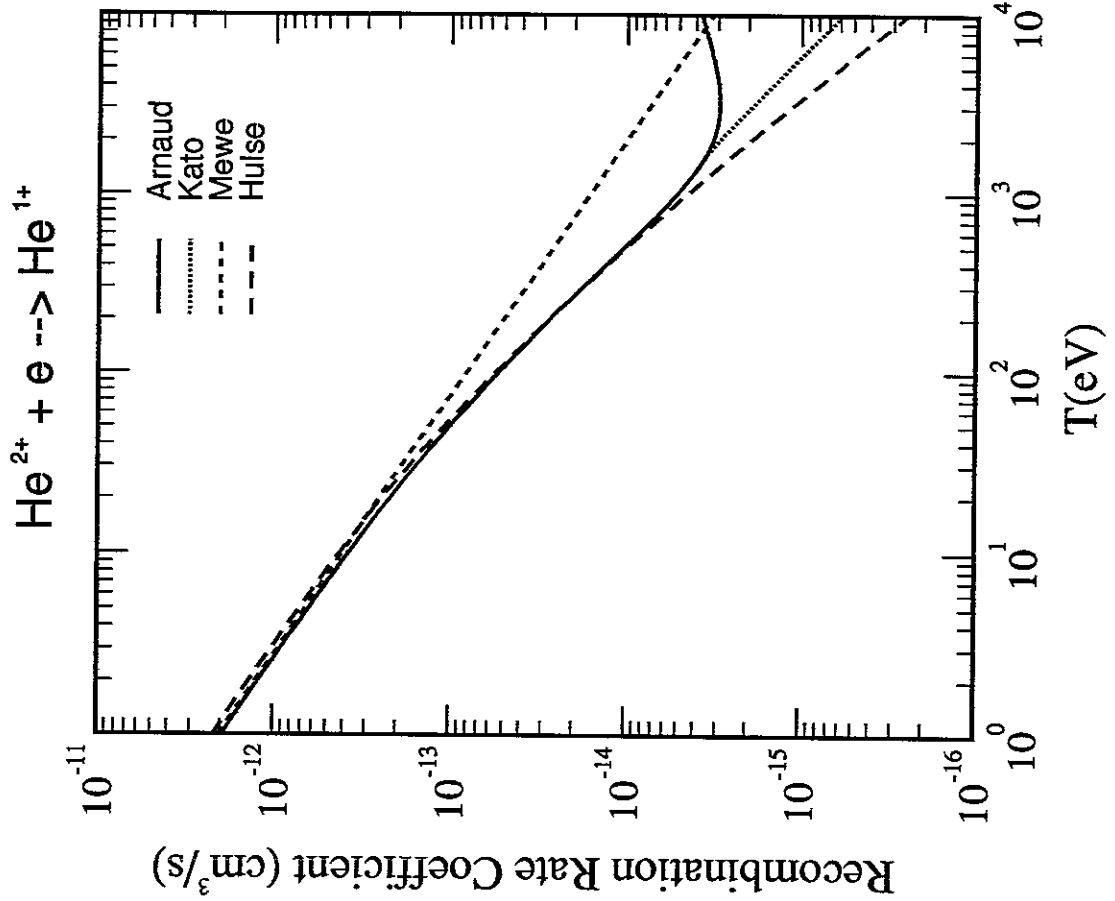
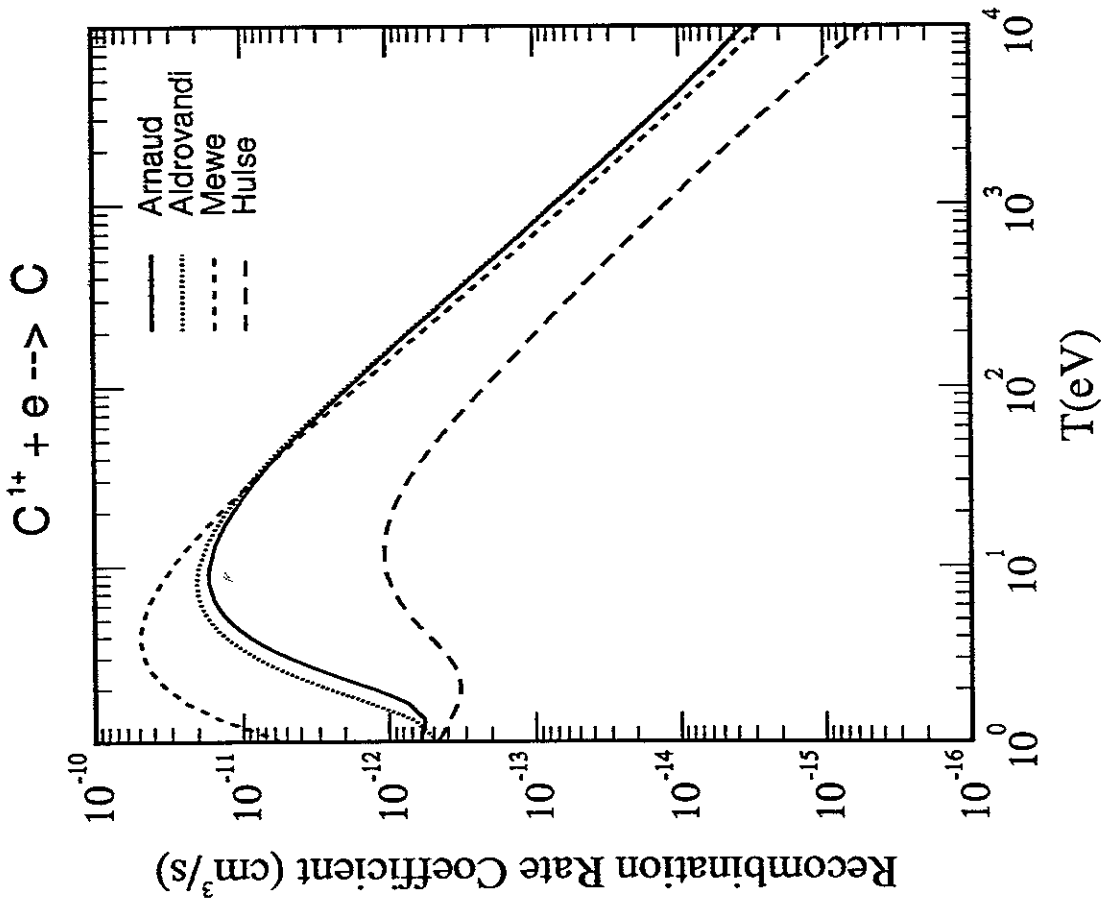
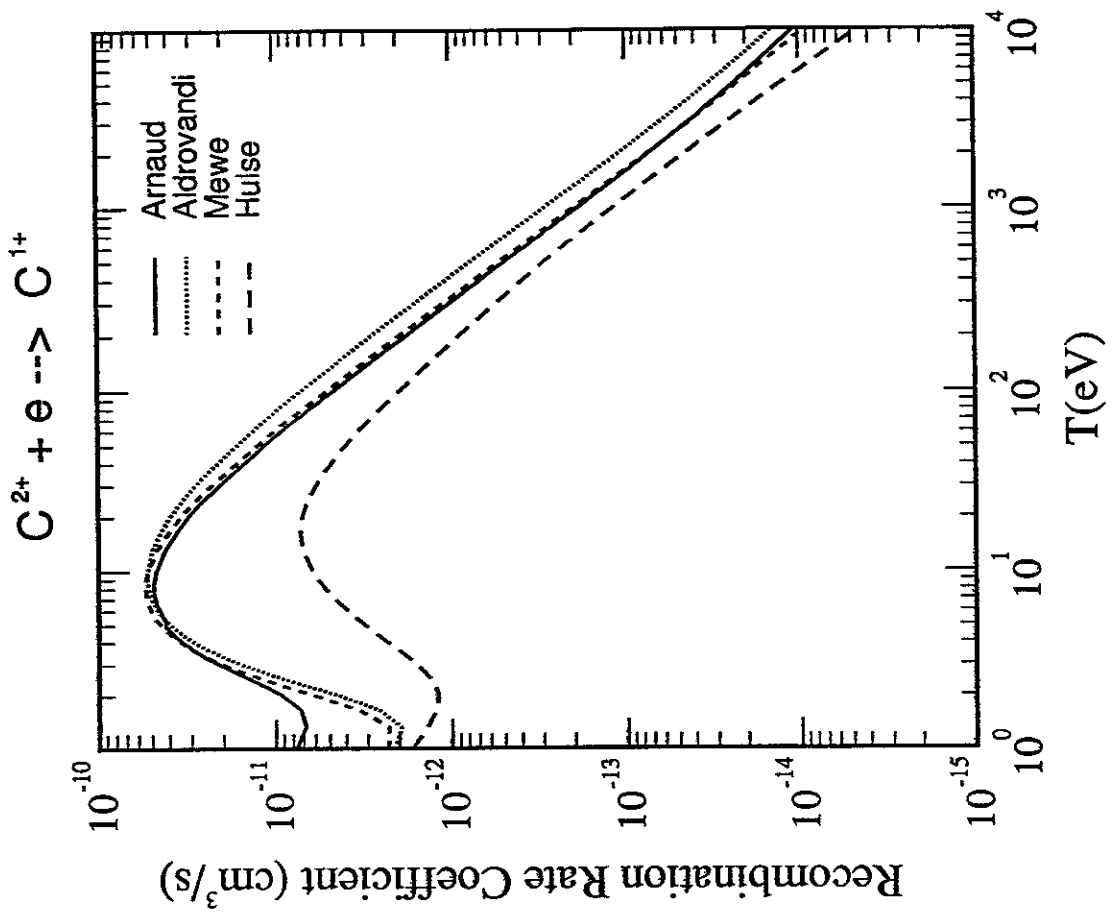


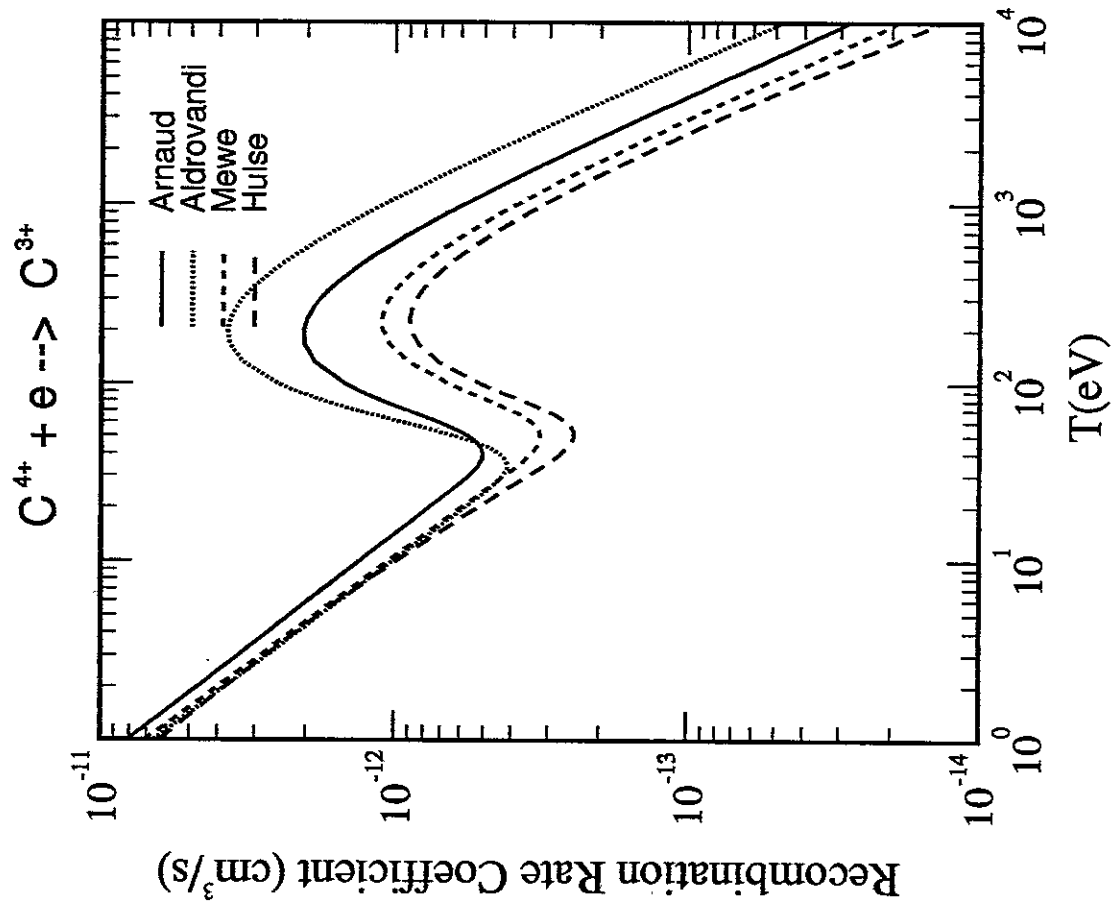
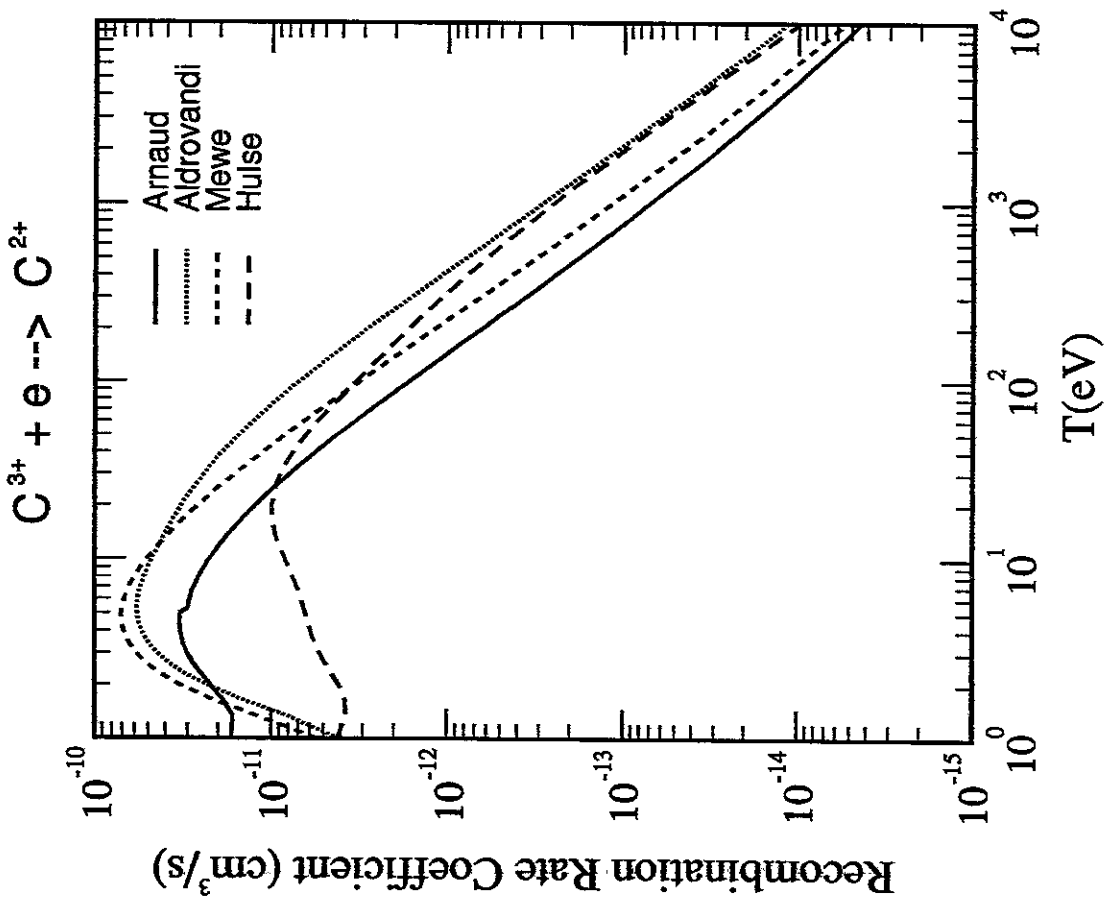
Fig.3

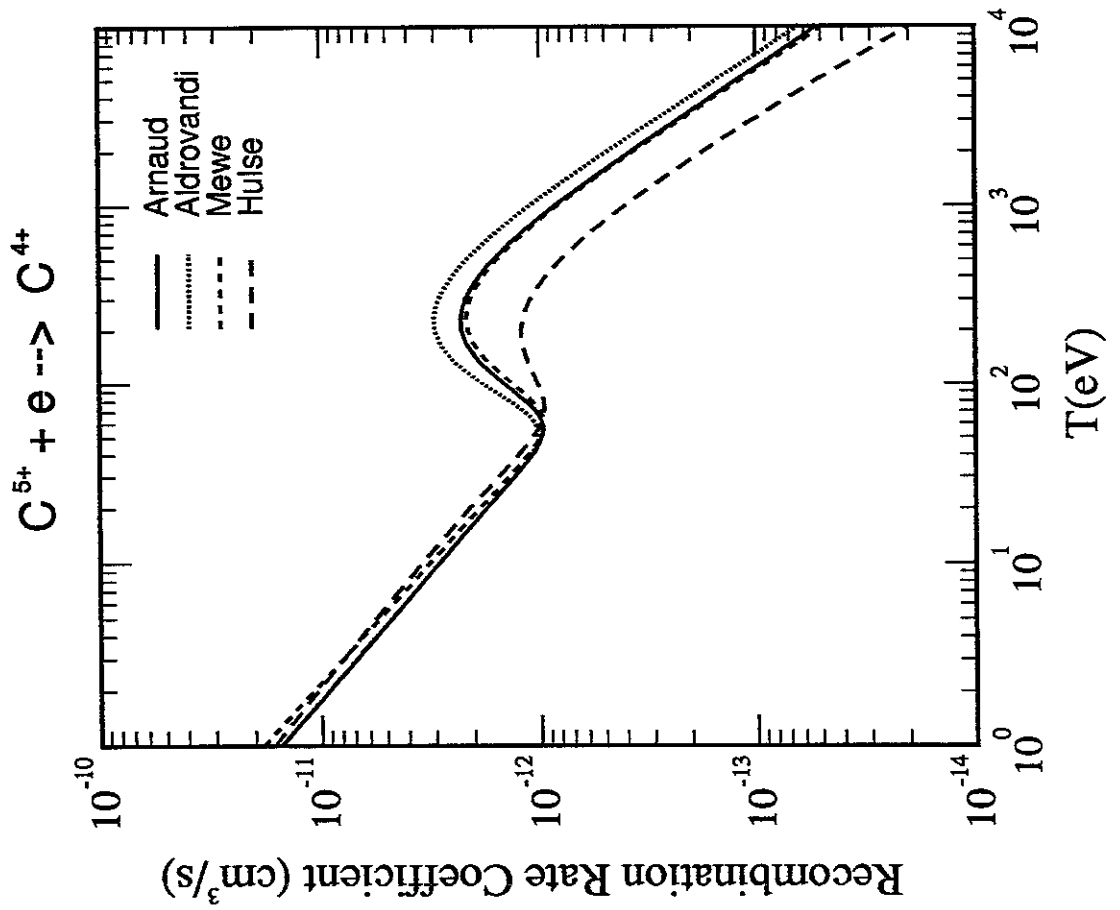
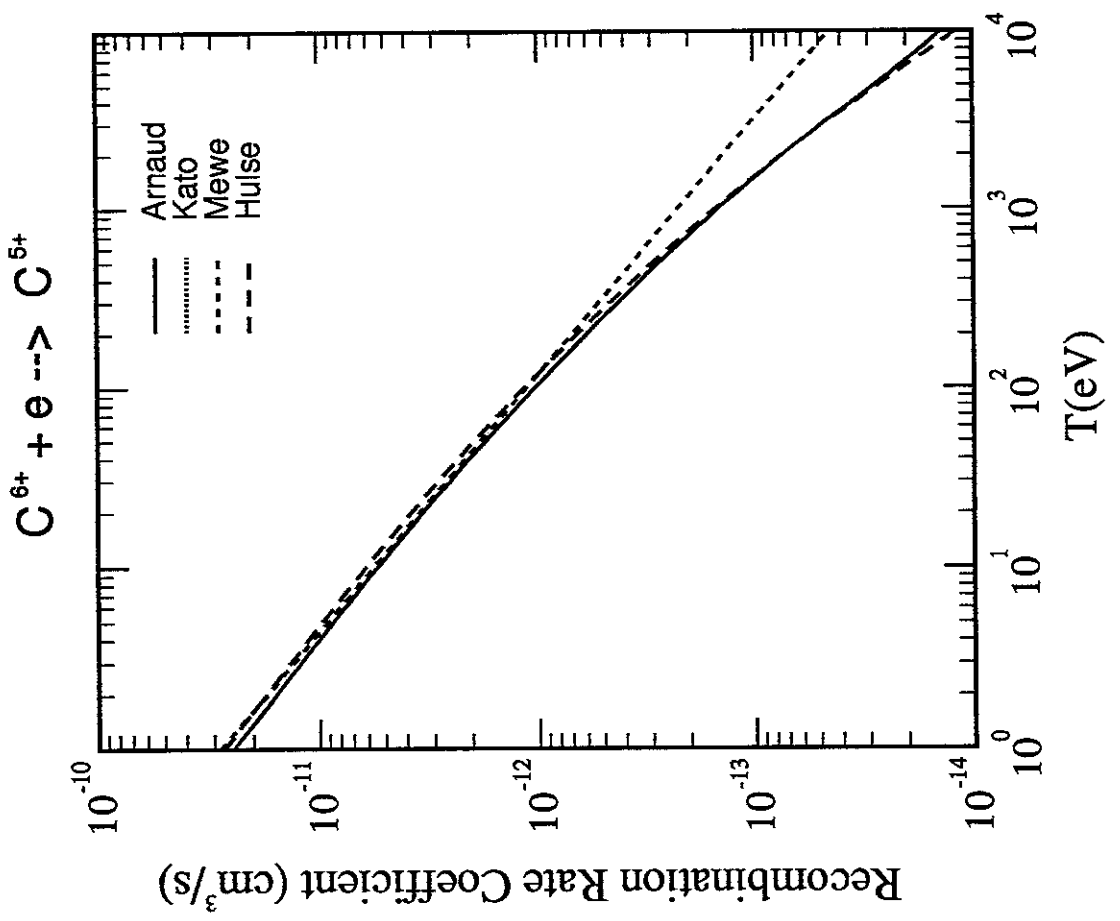
GRAPHS

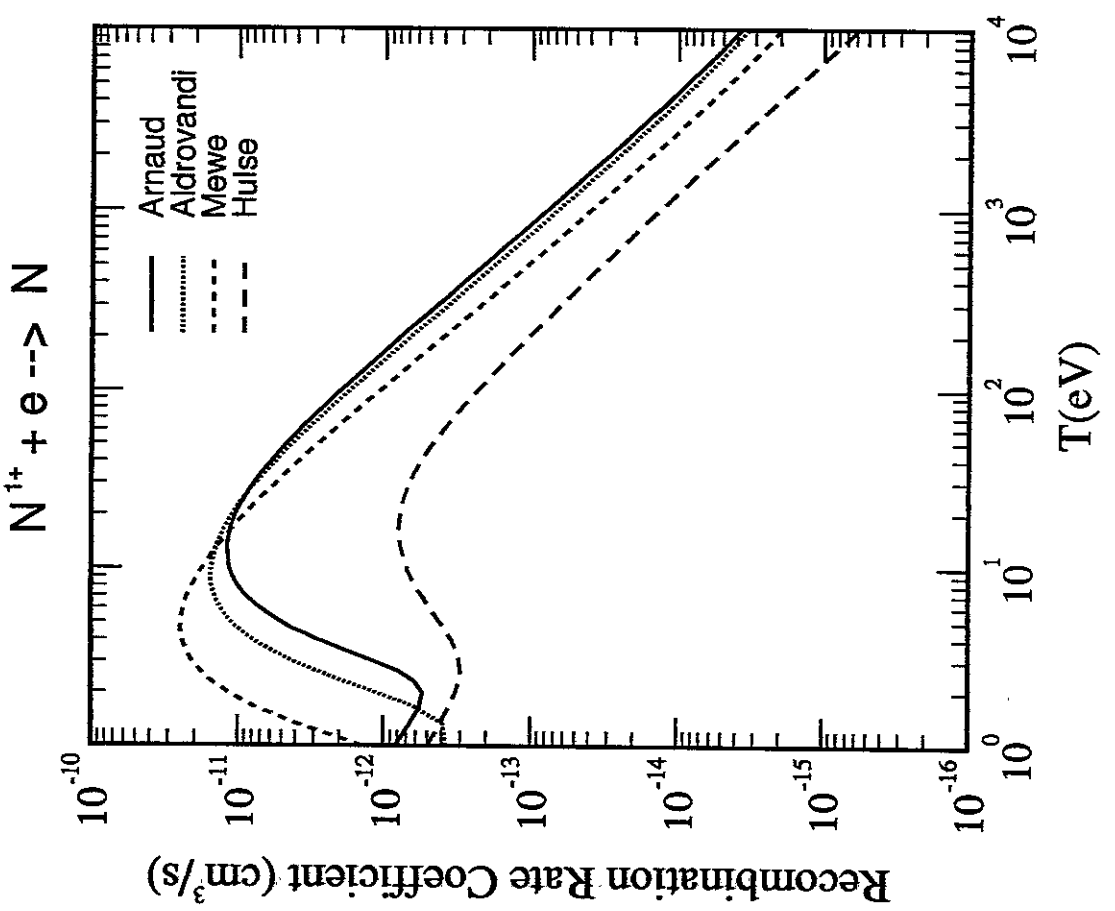
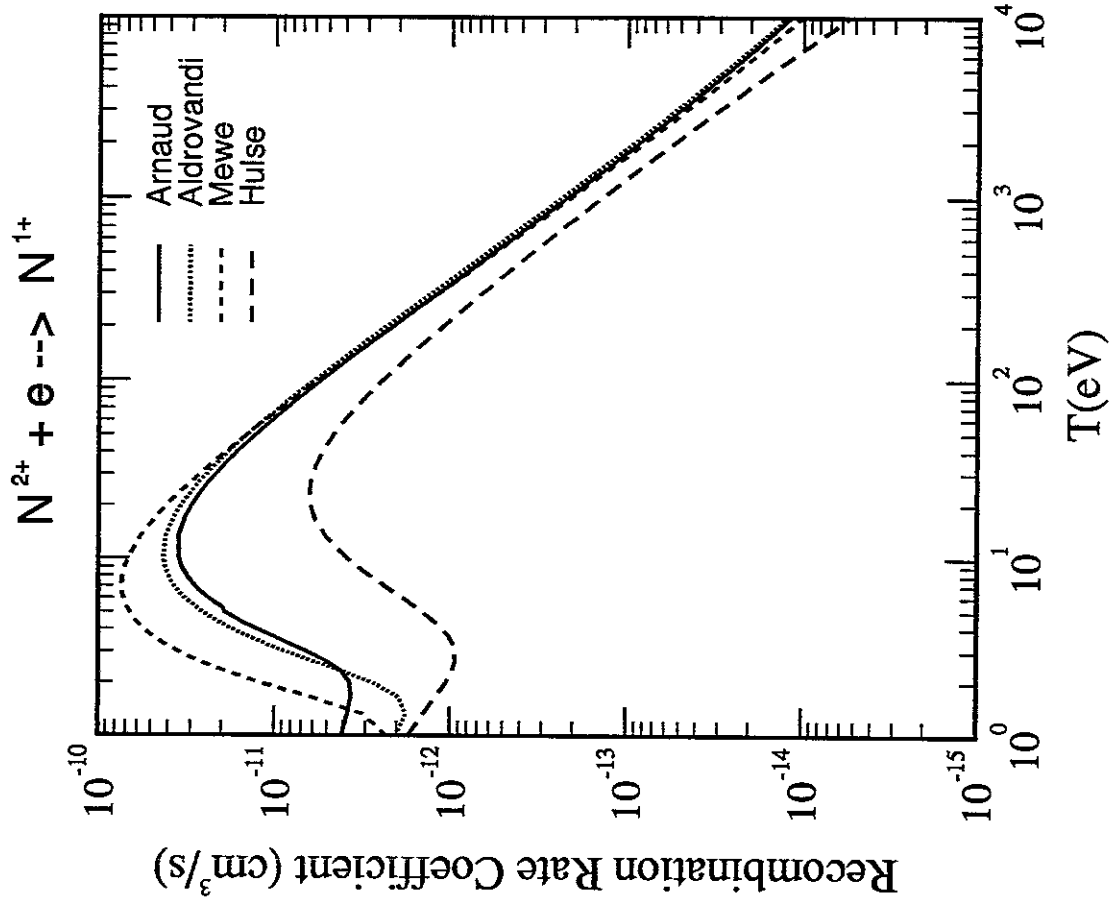


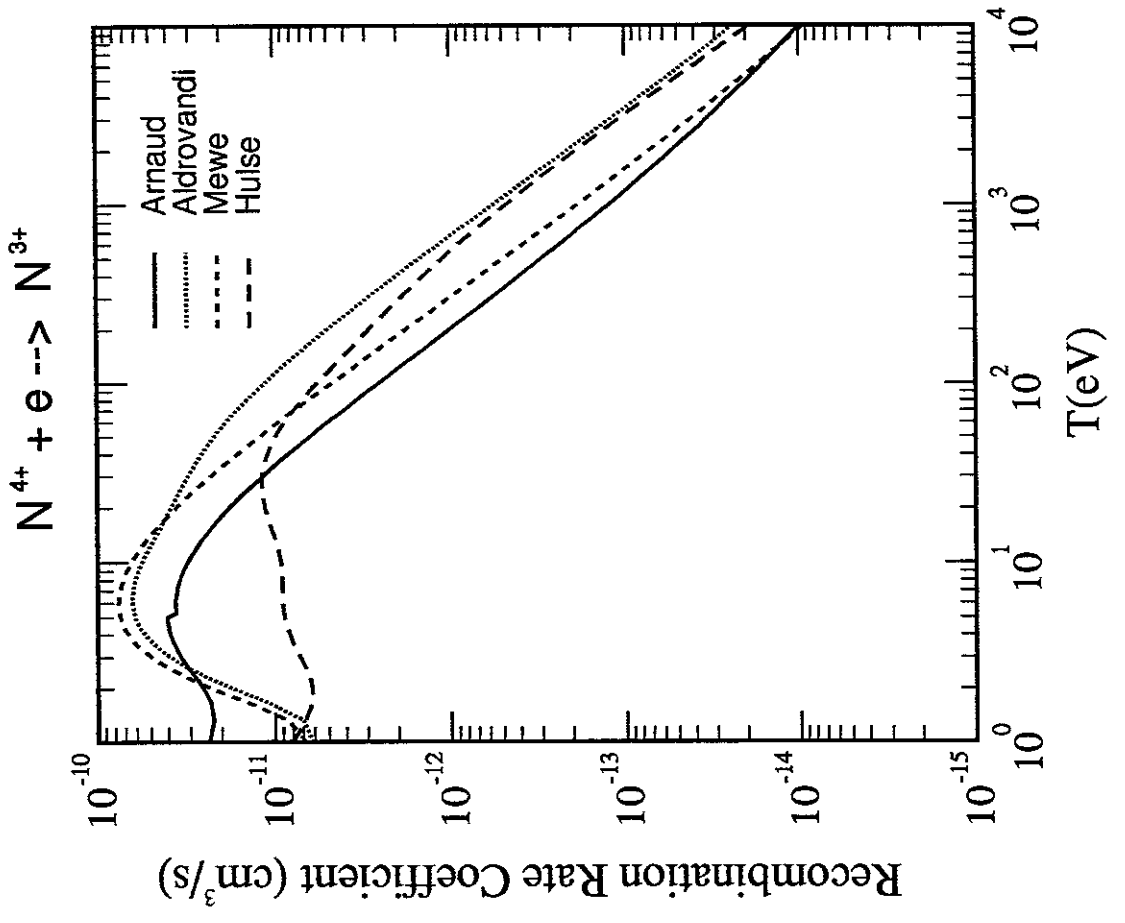
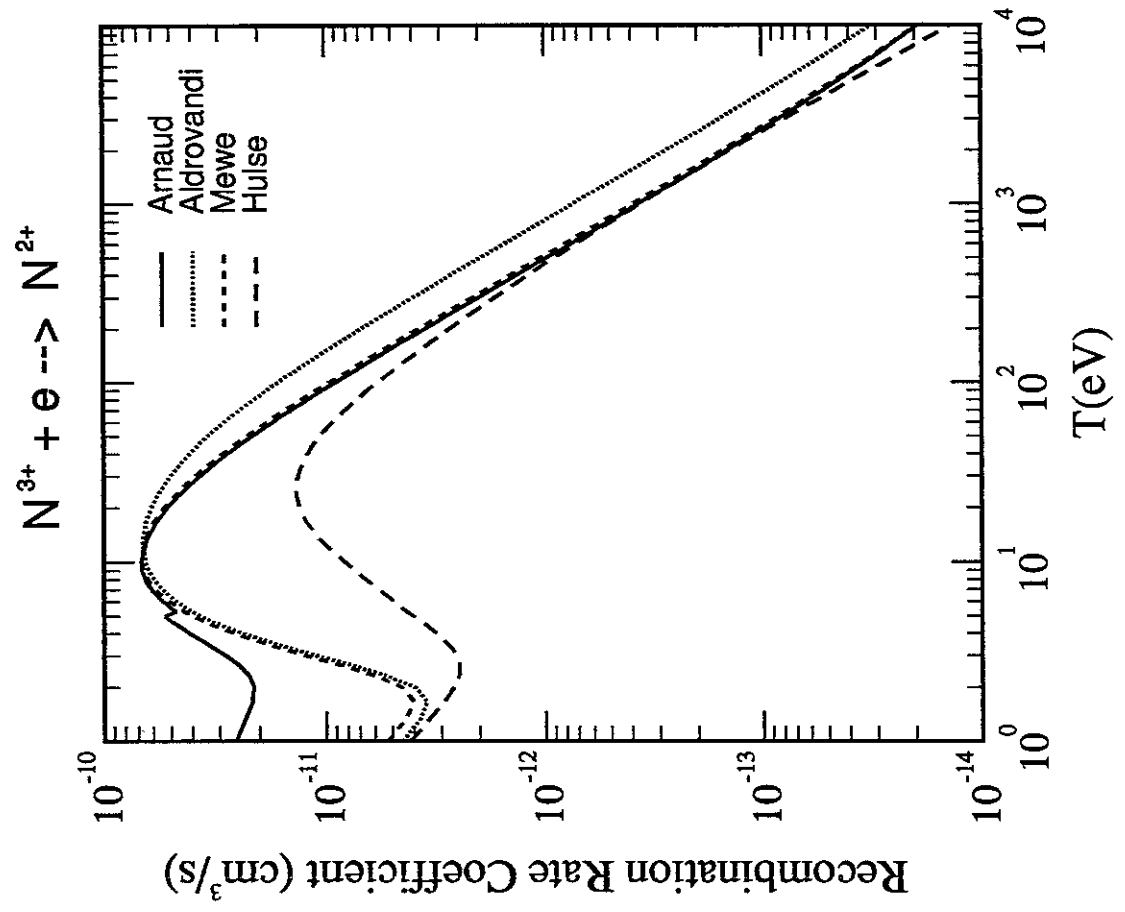


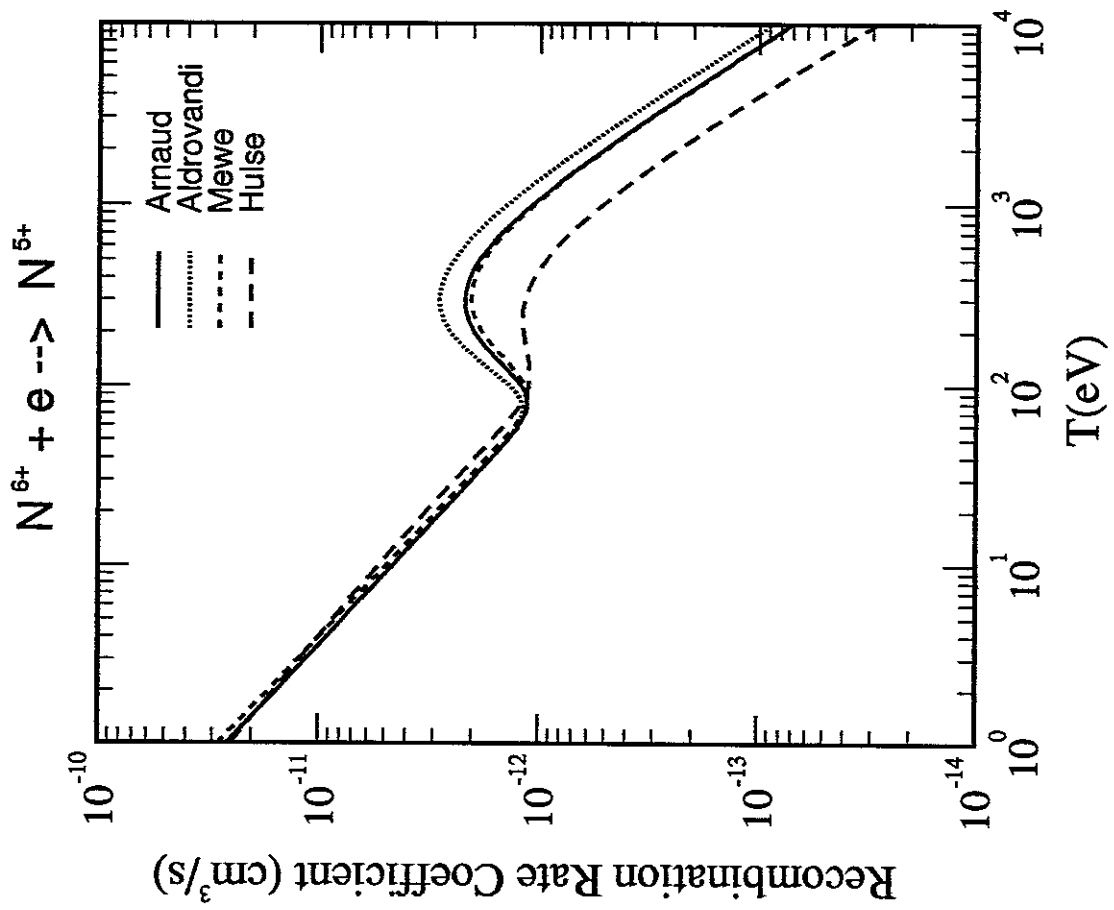
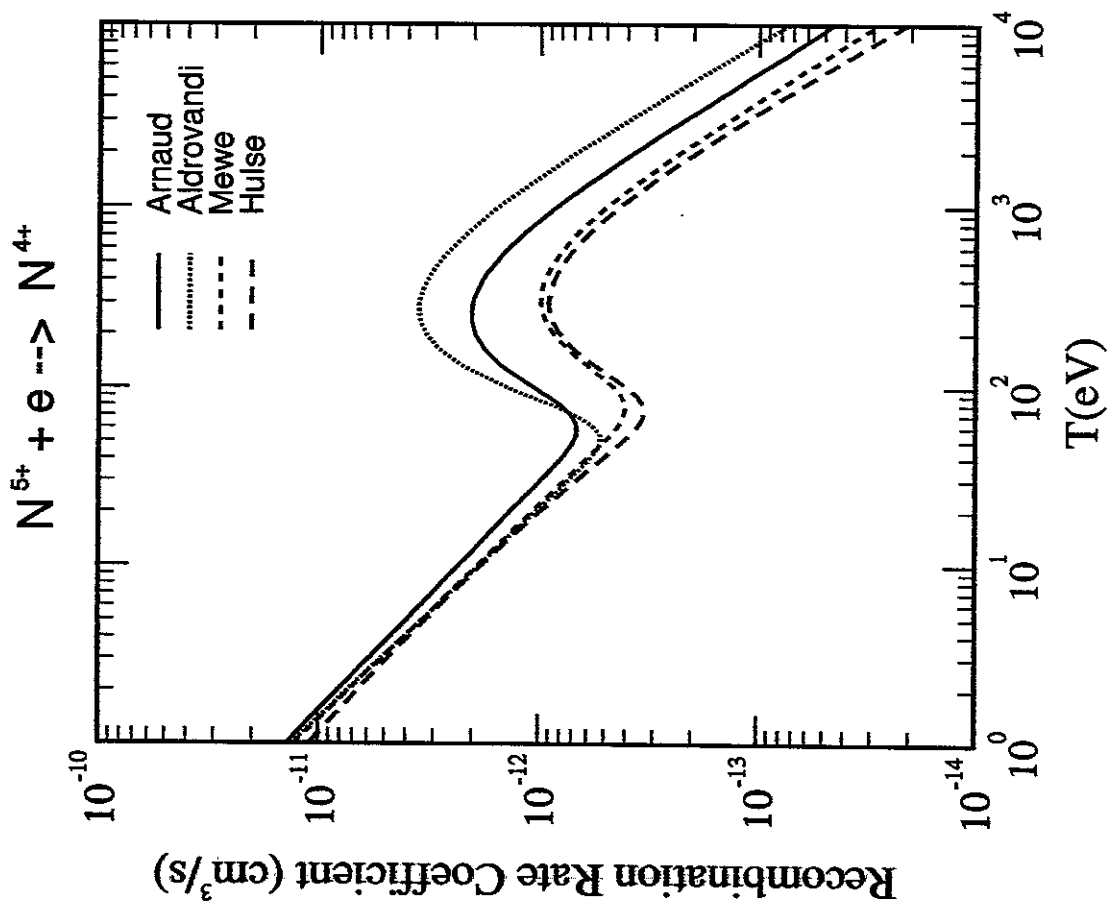


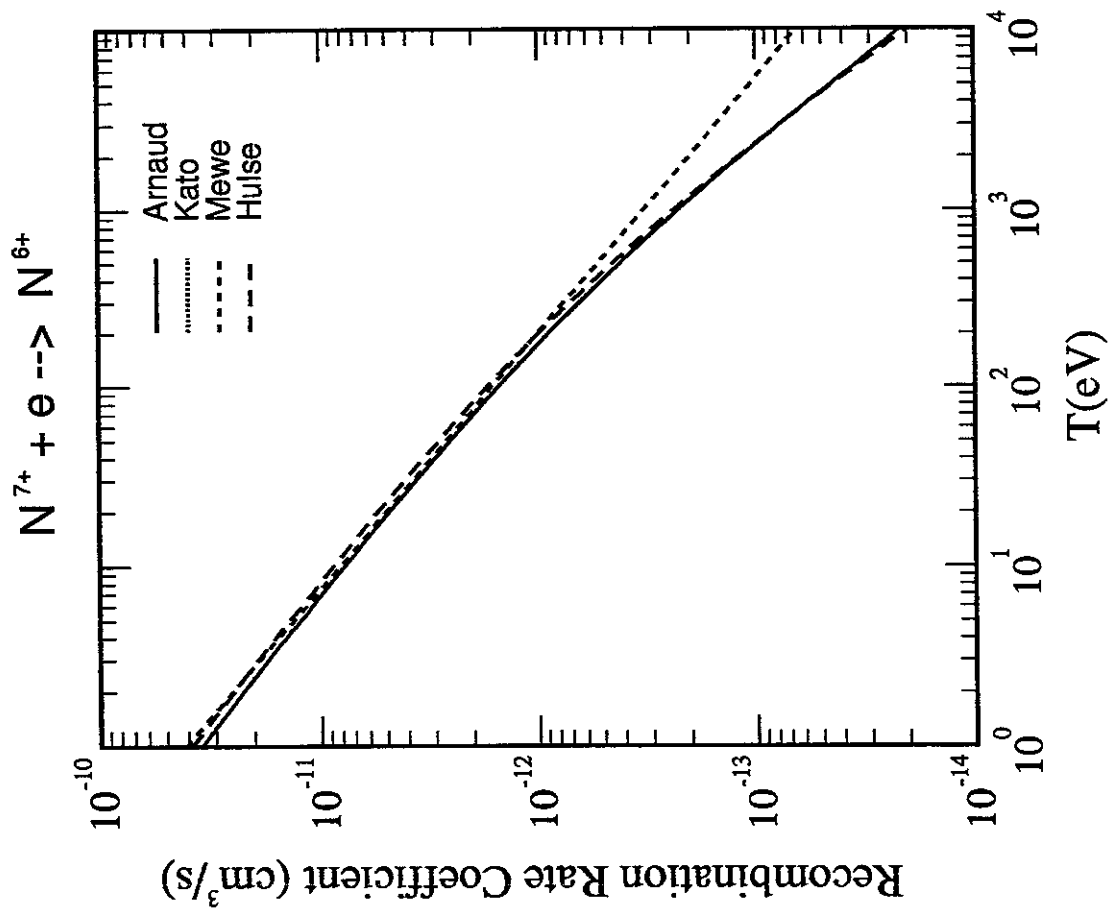


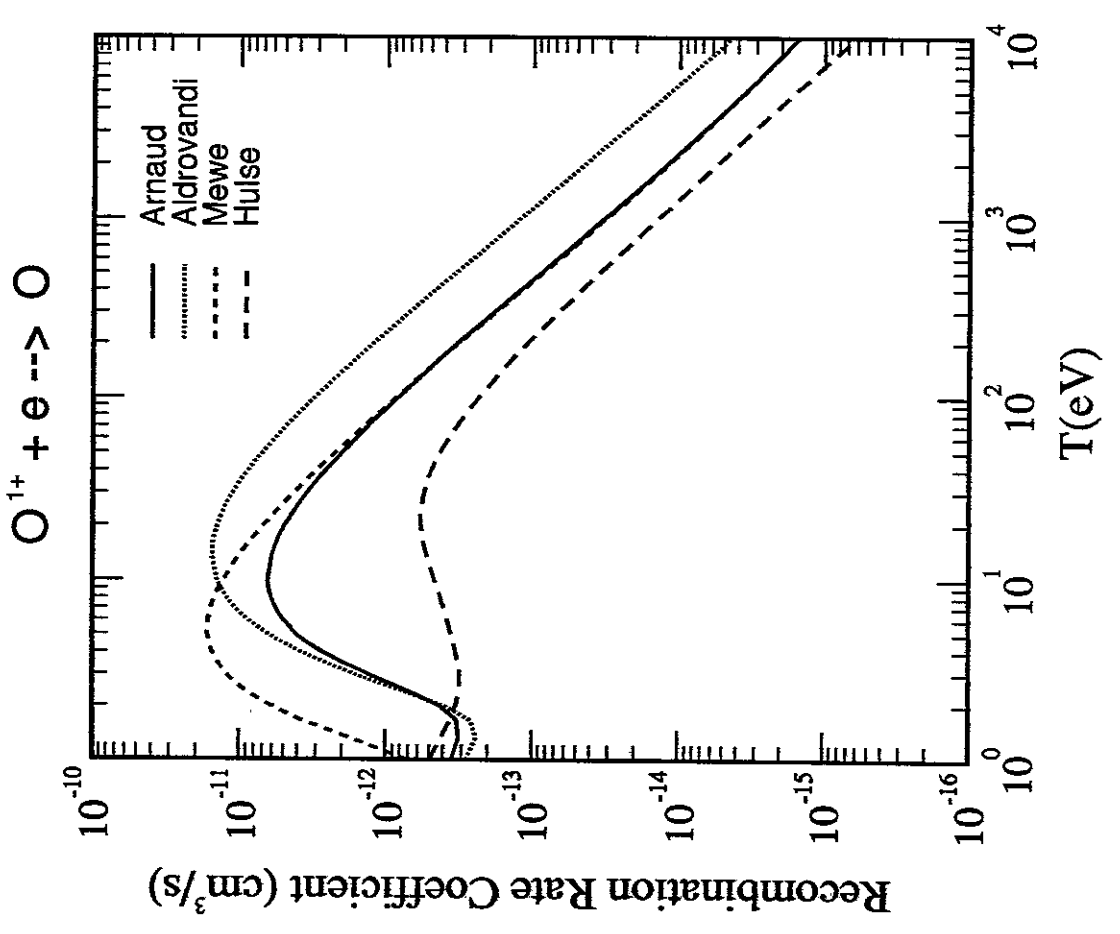
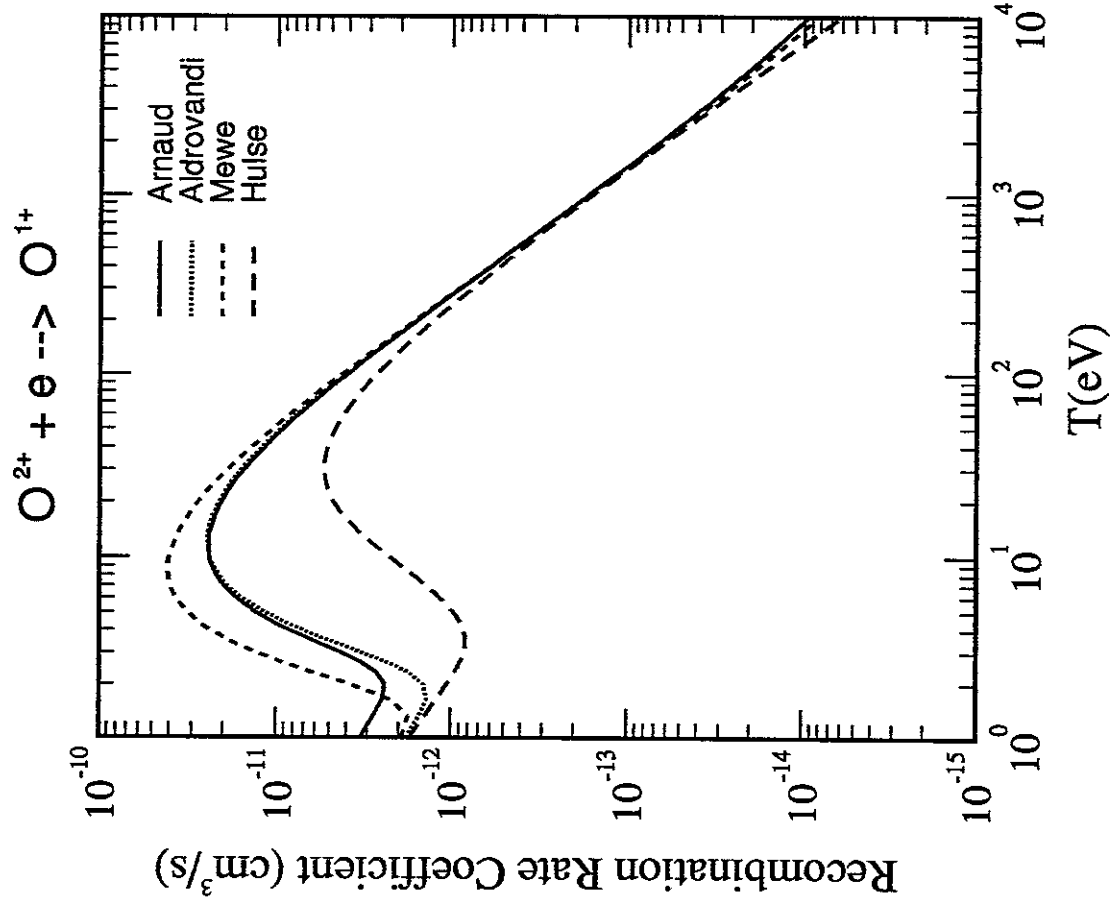


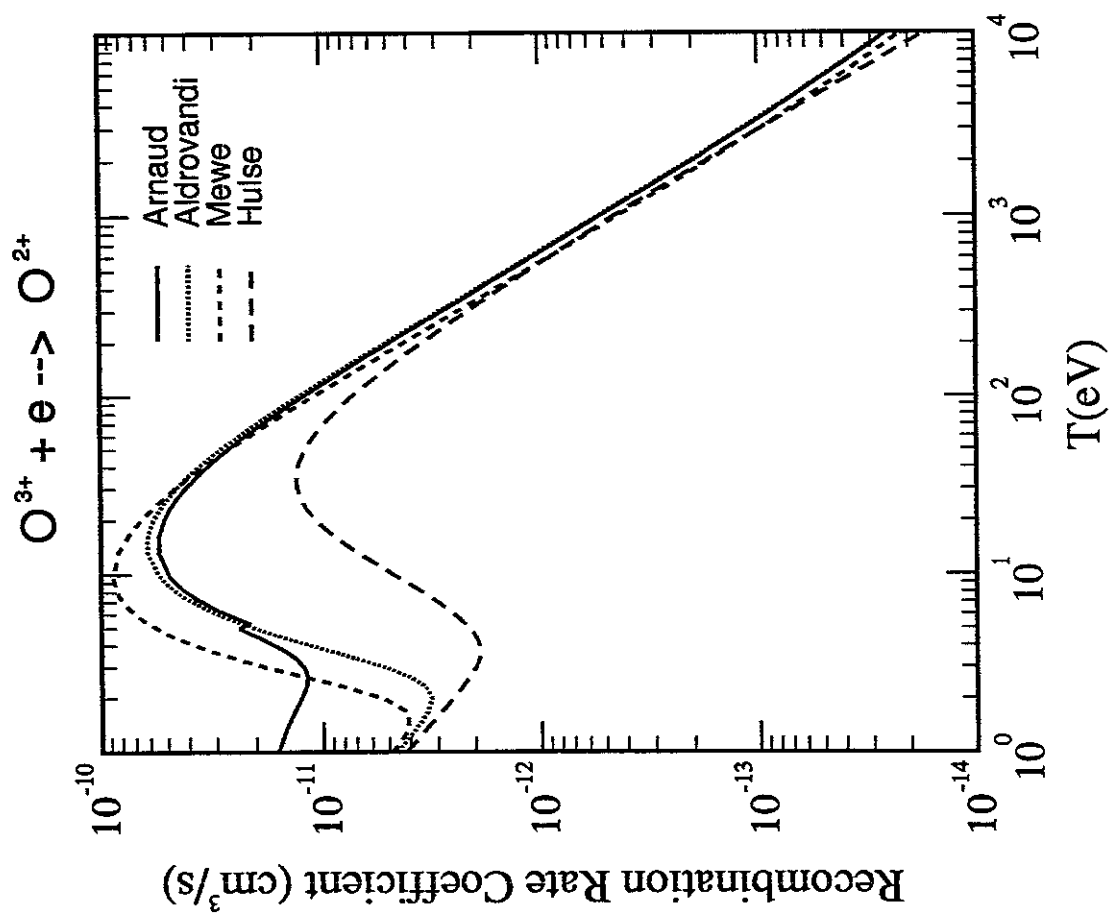
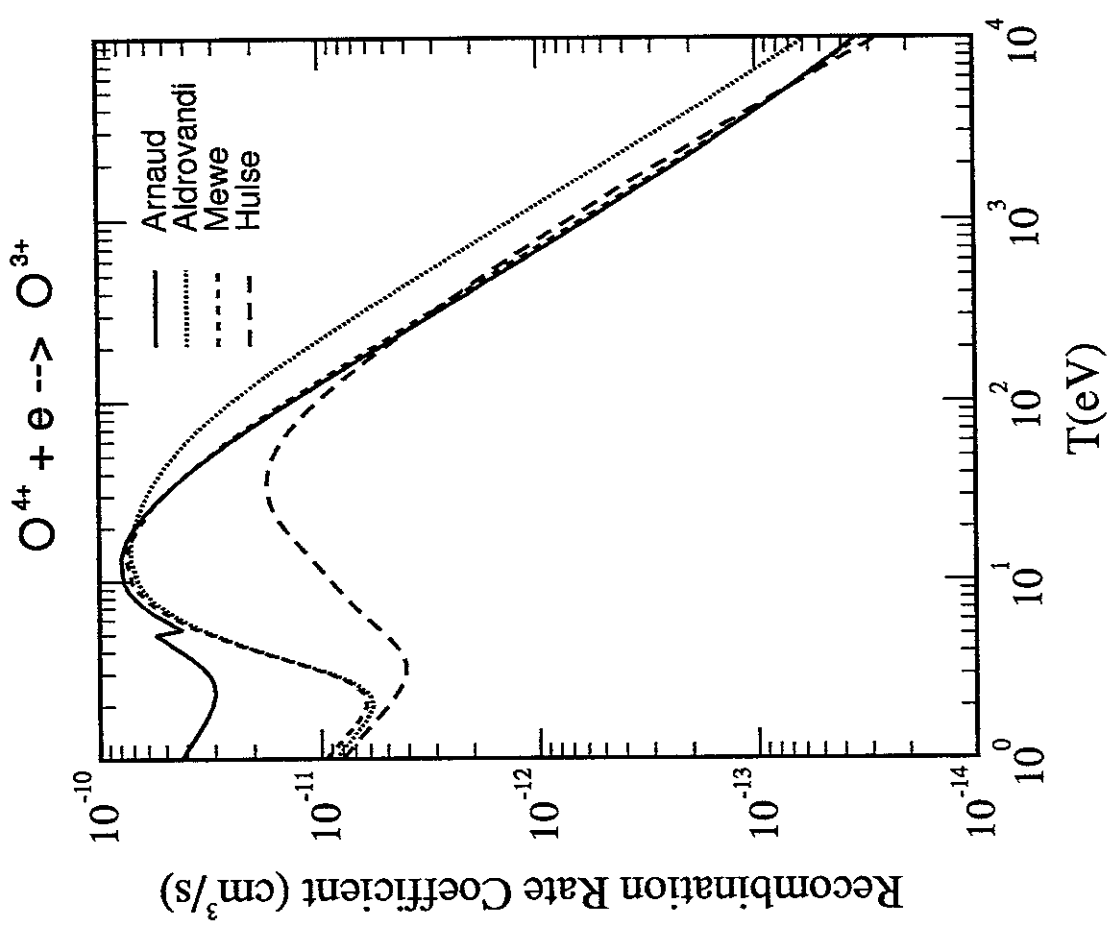


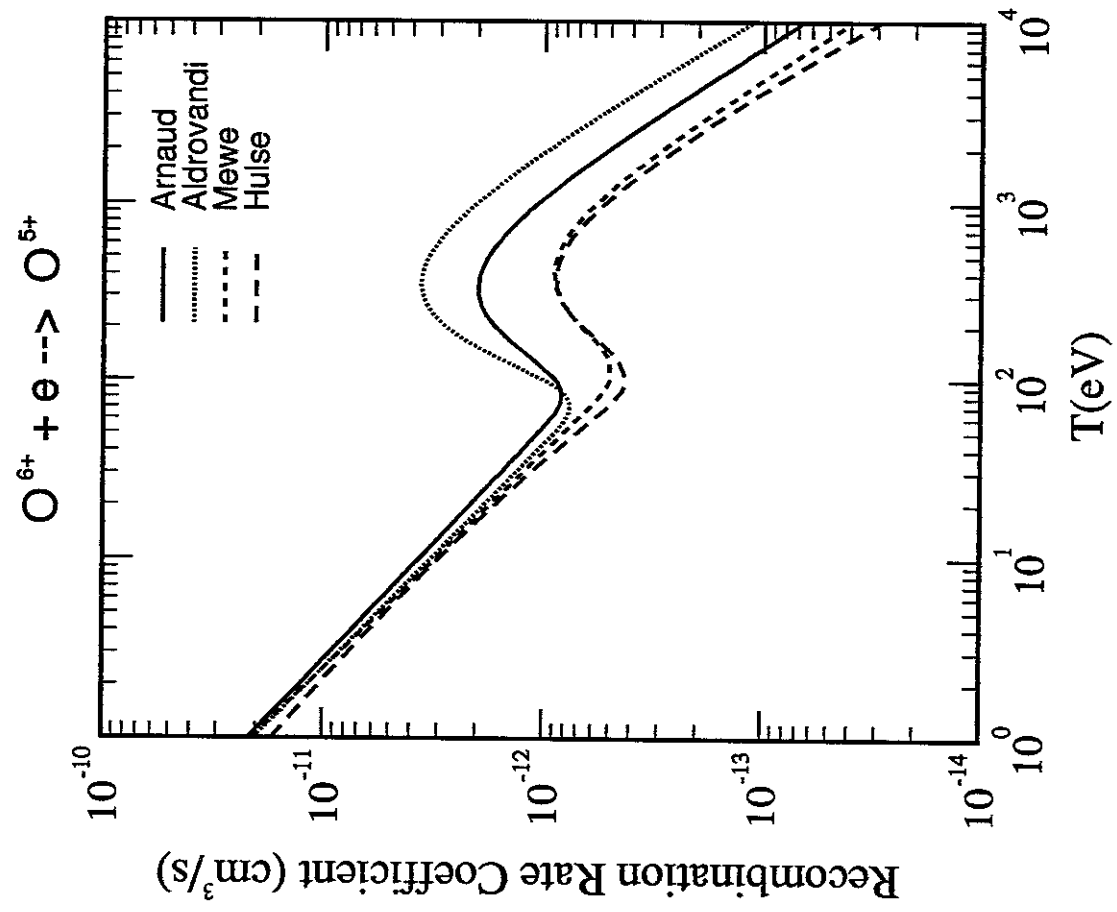
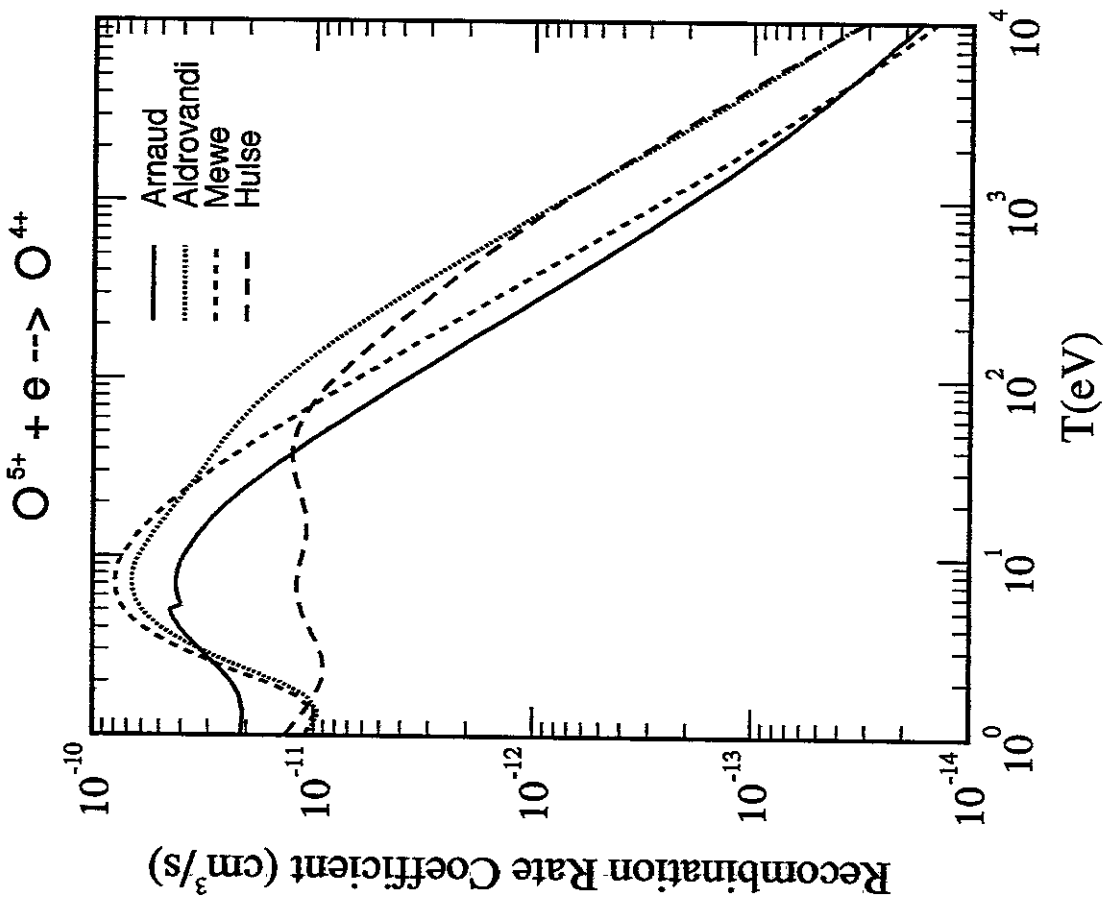


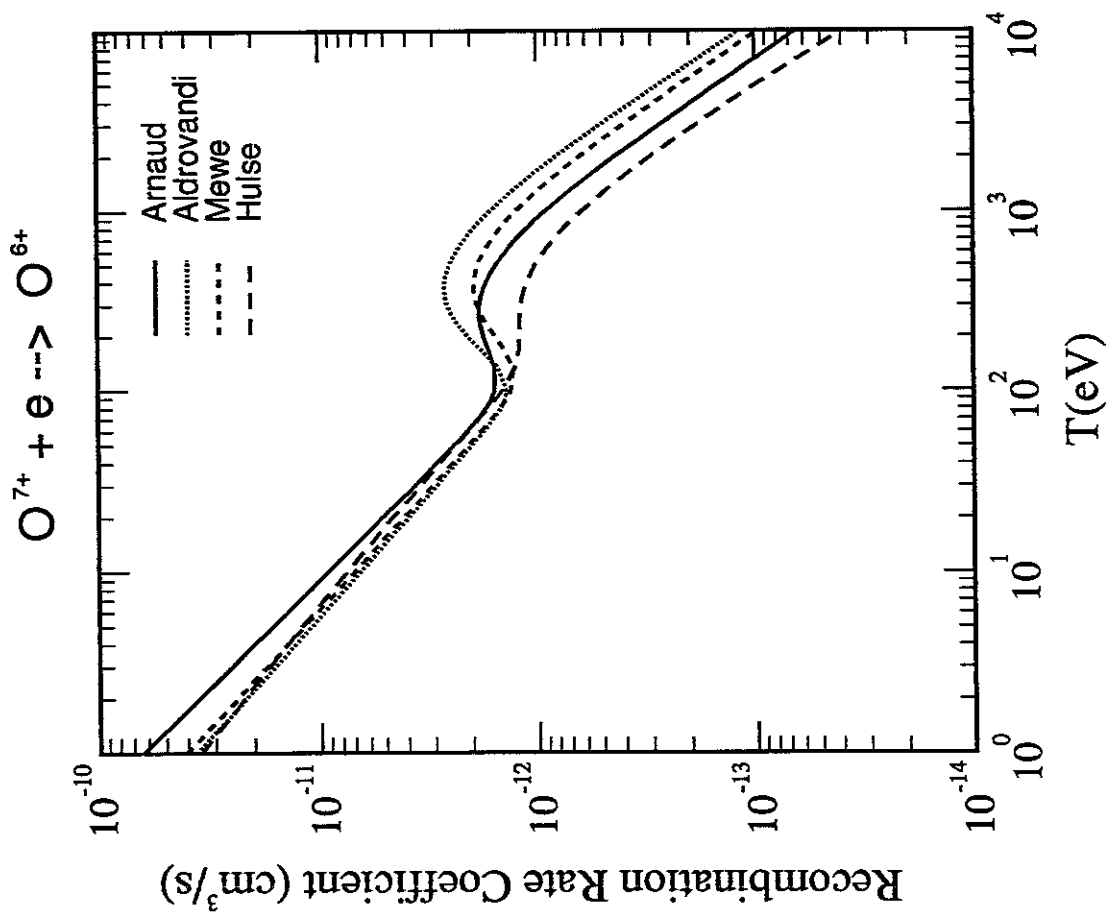
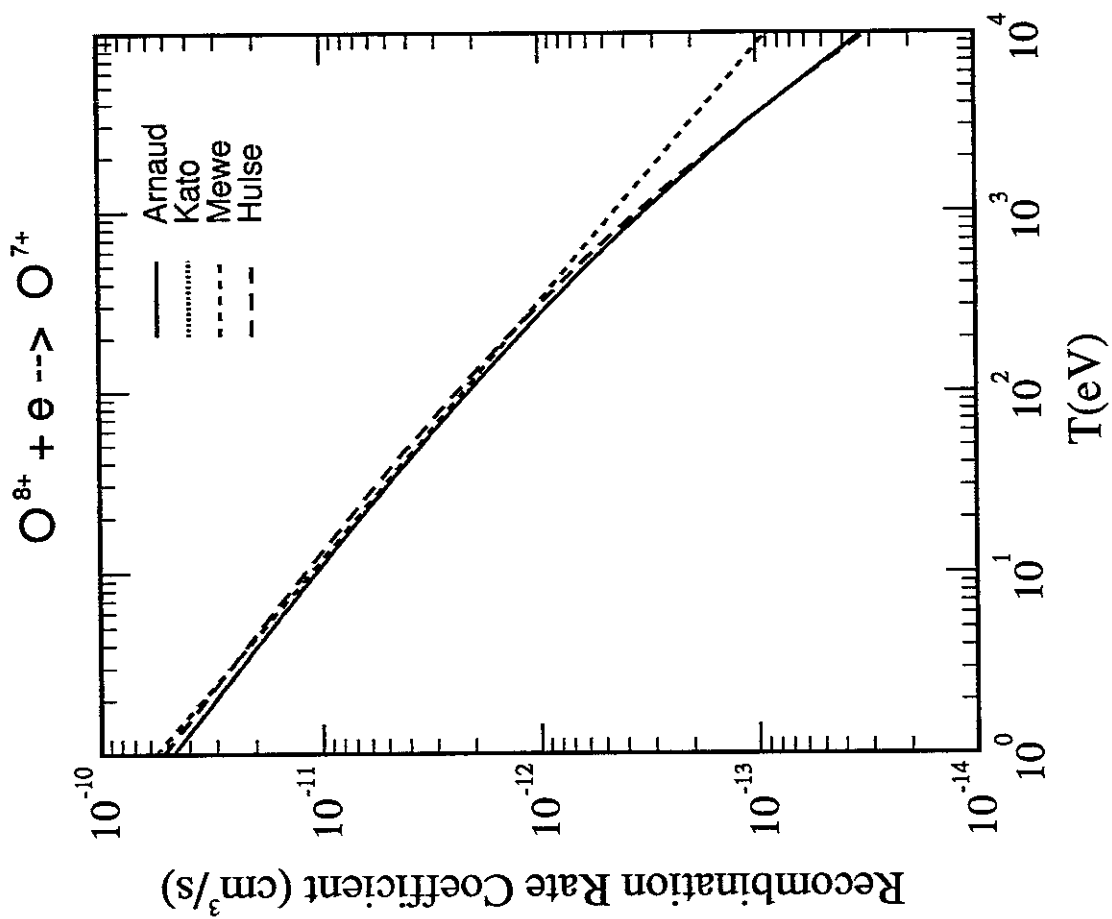


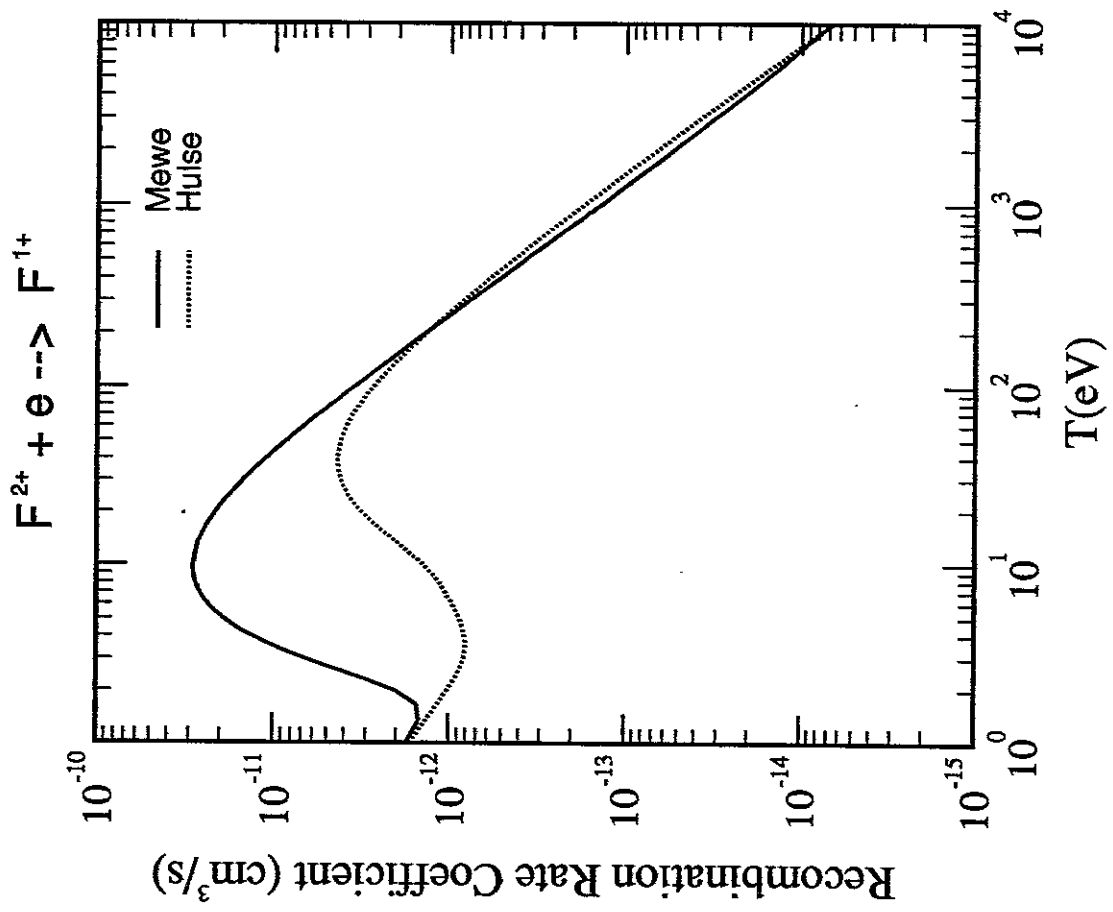
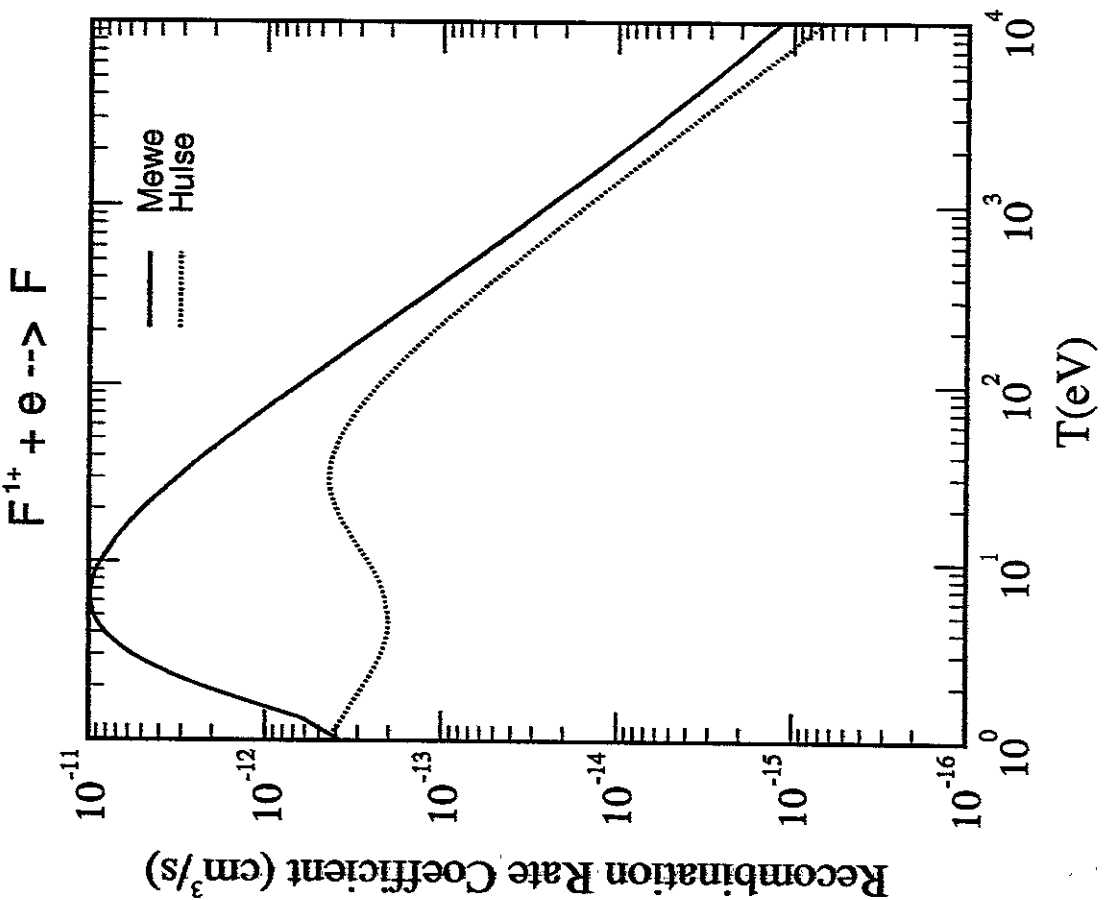


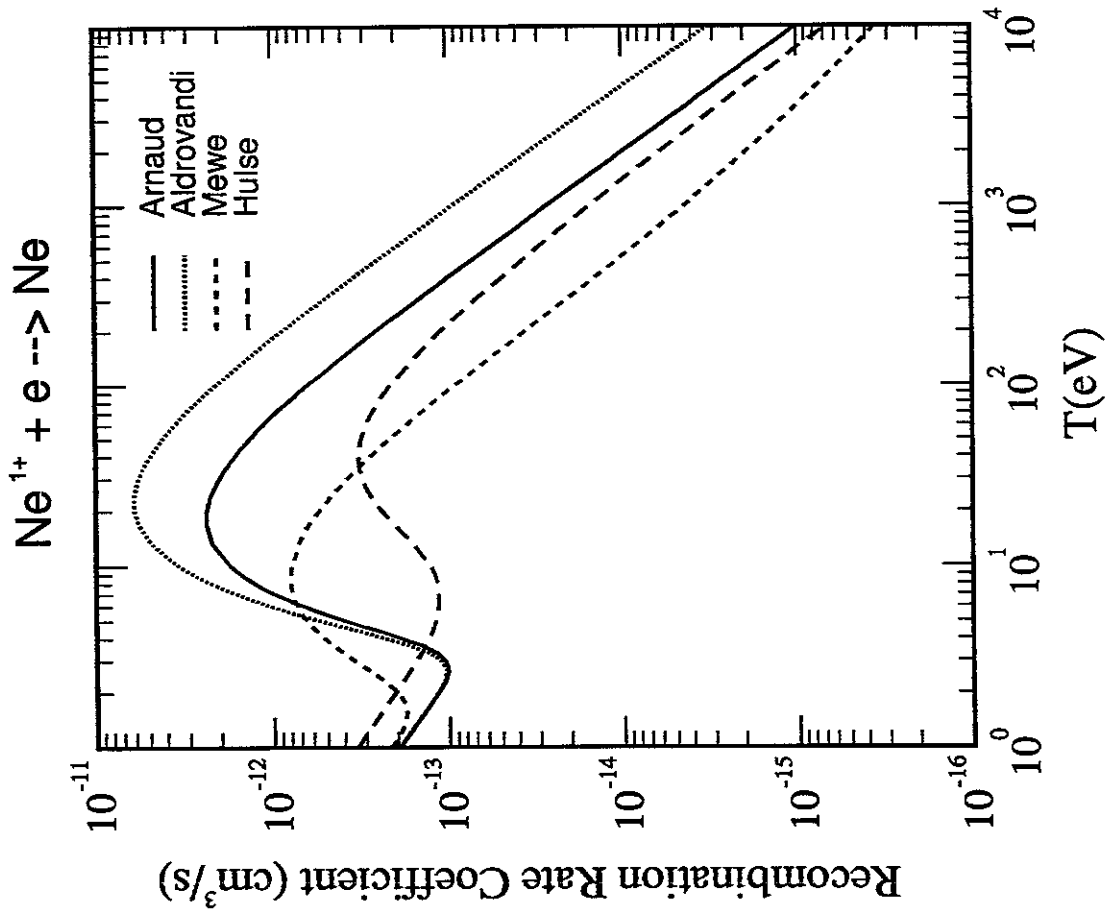
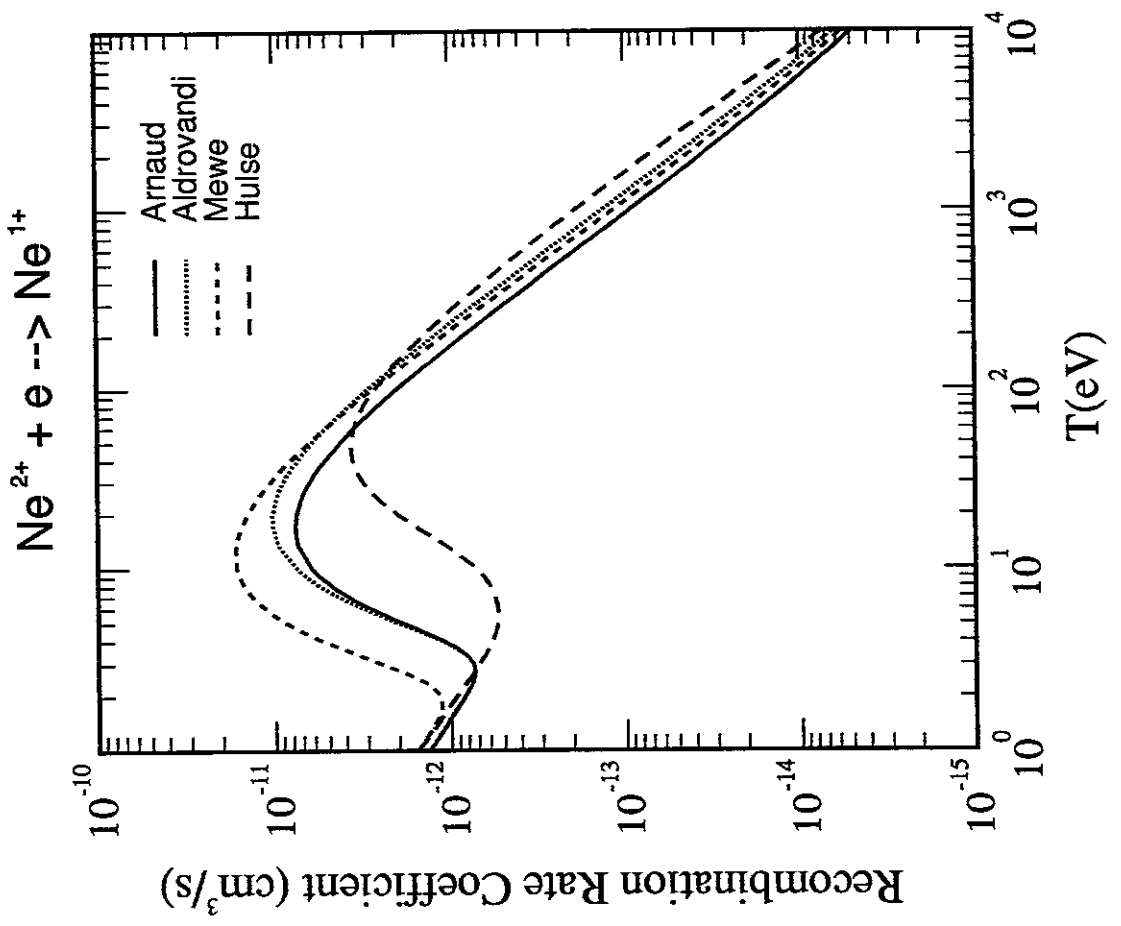


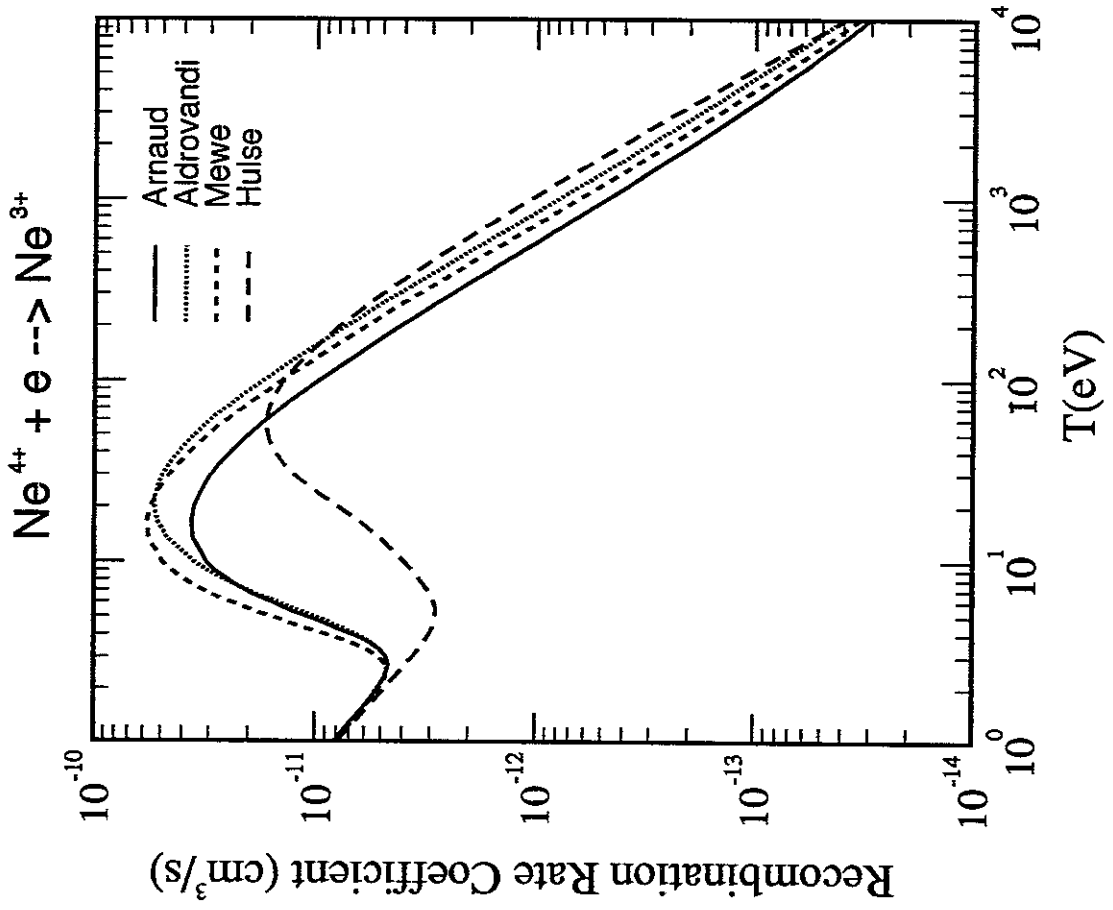
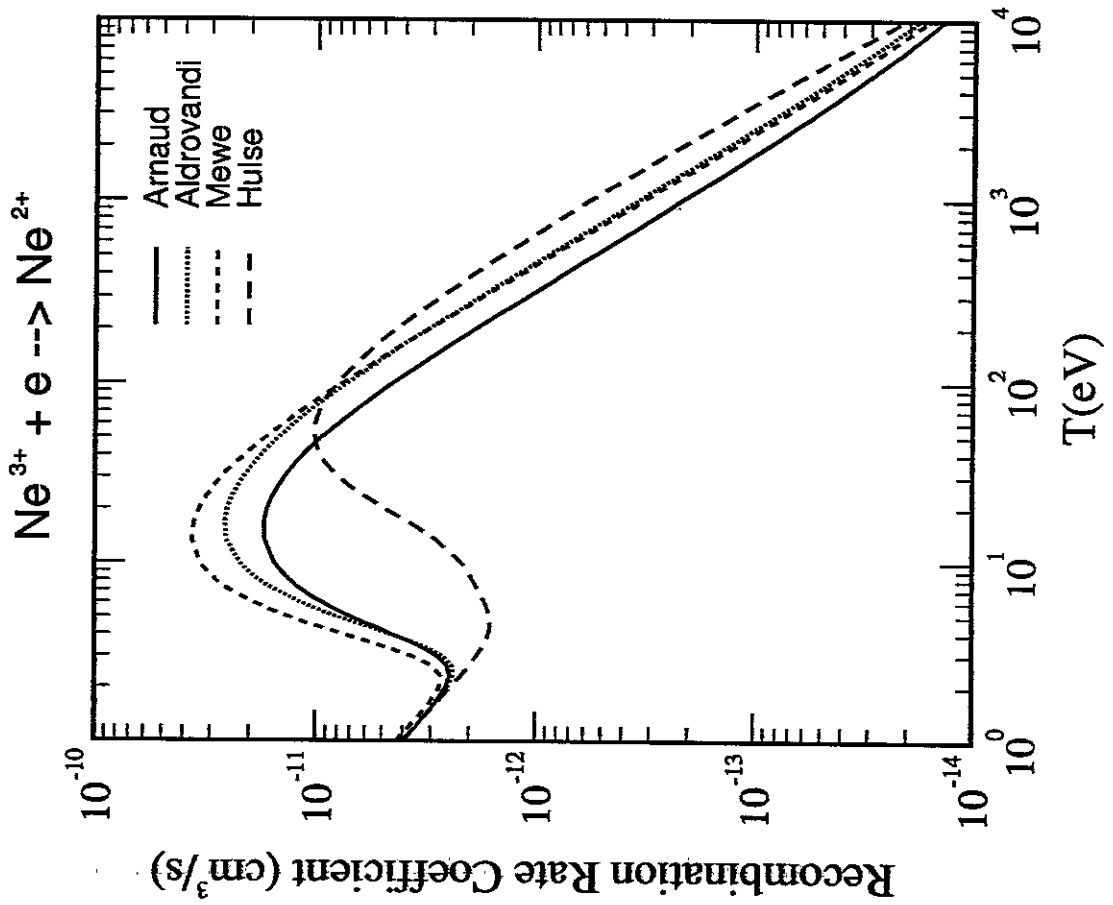


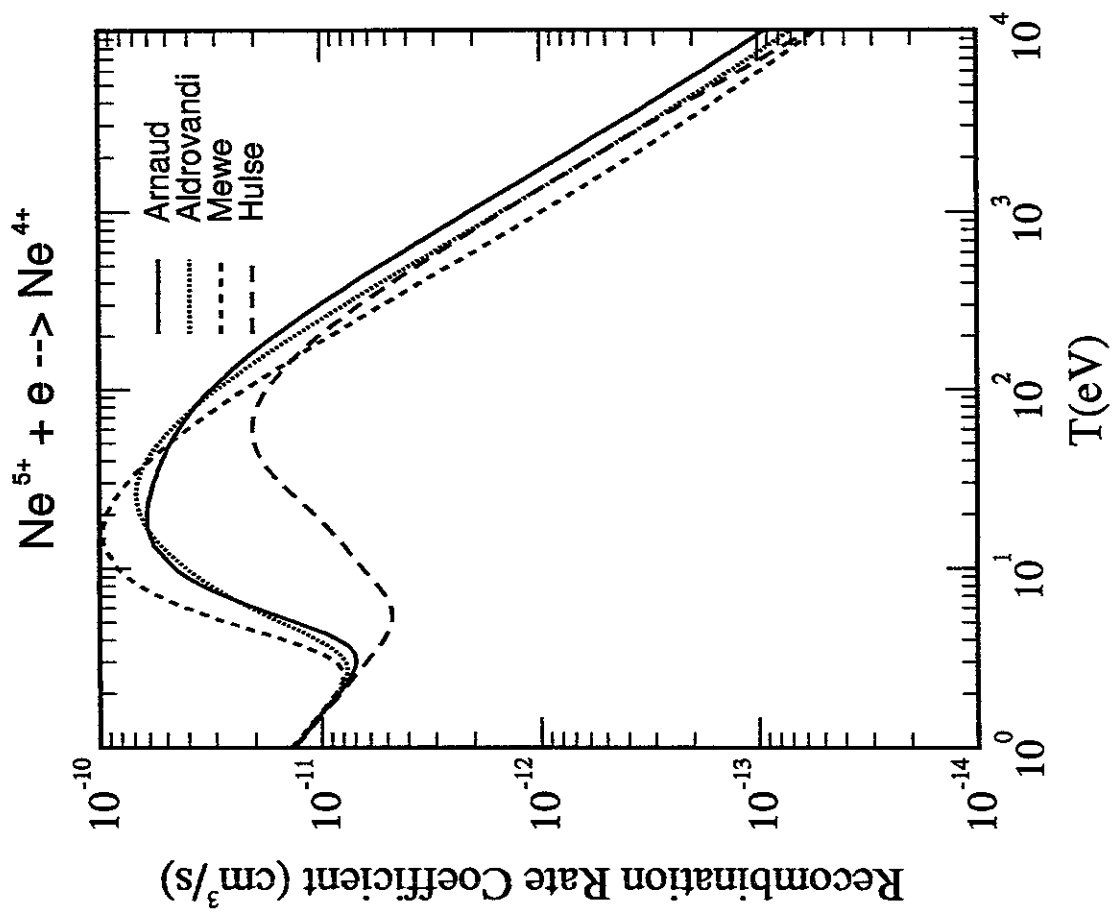
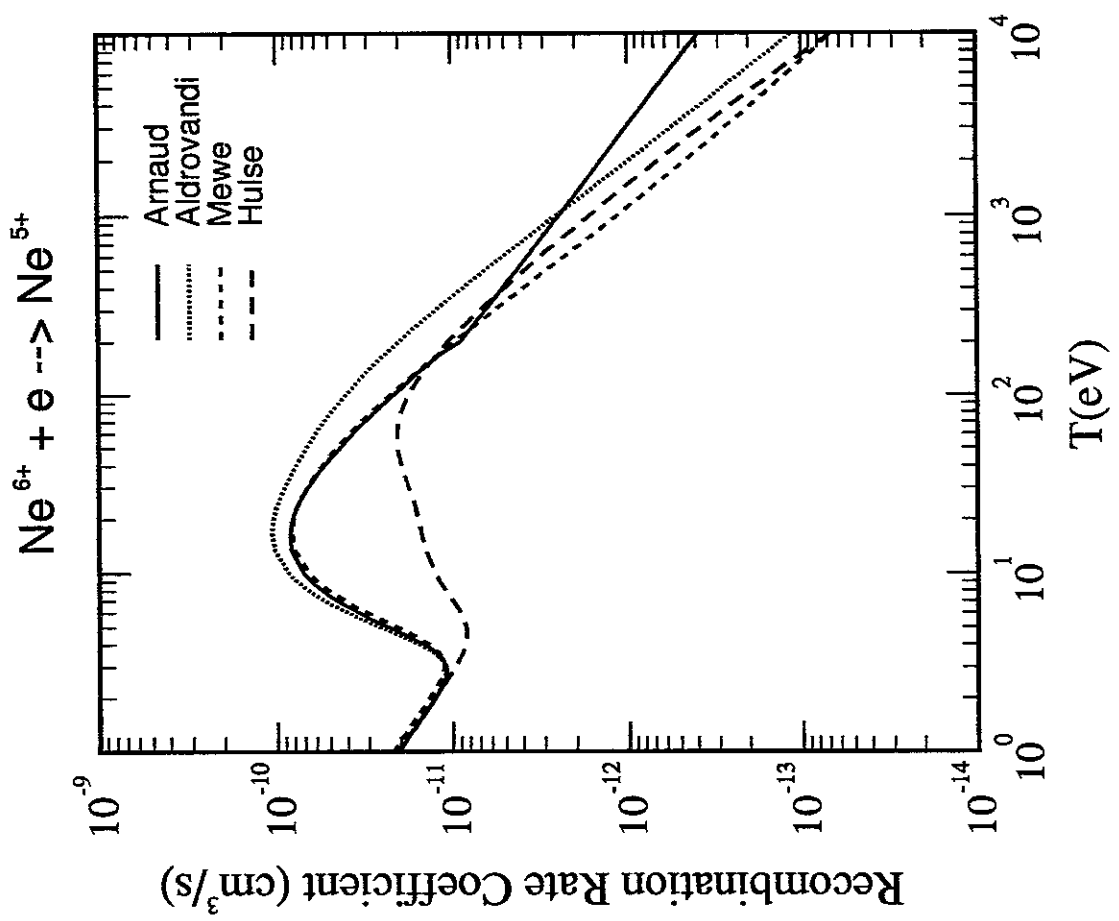


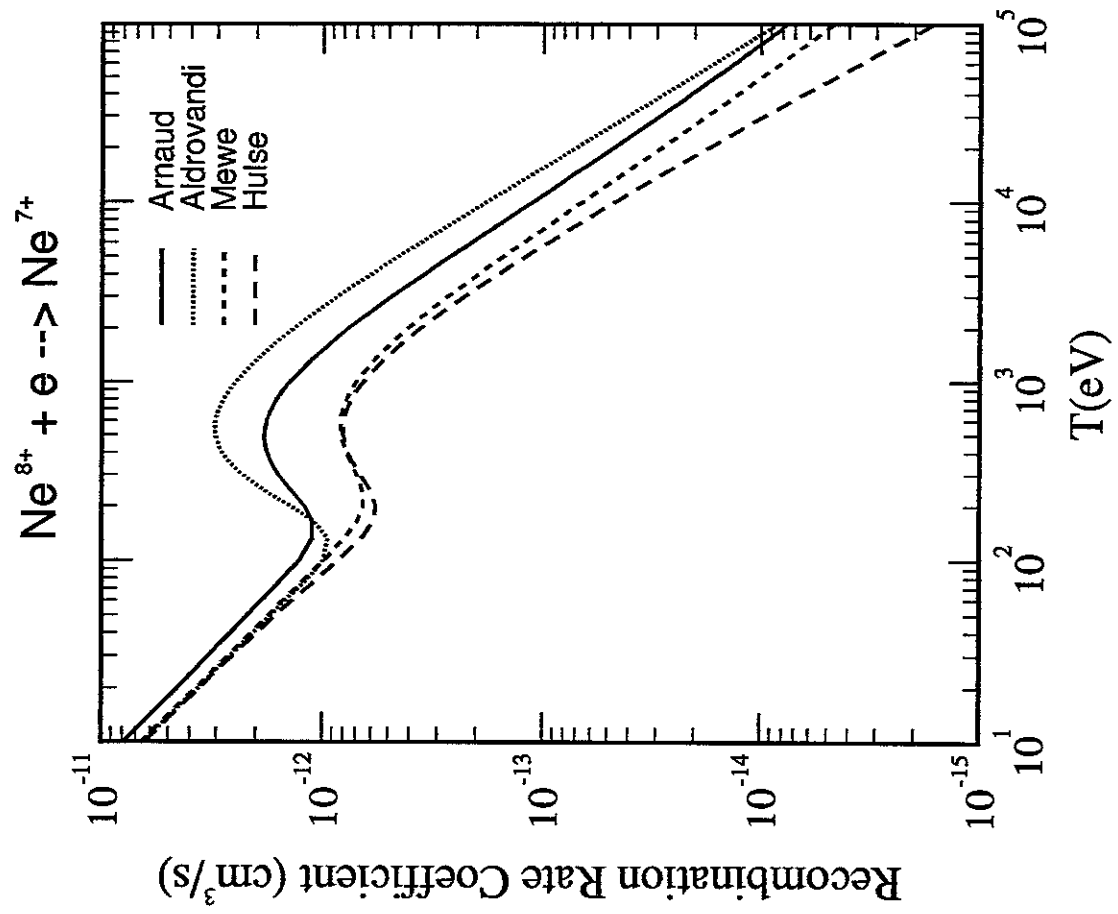
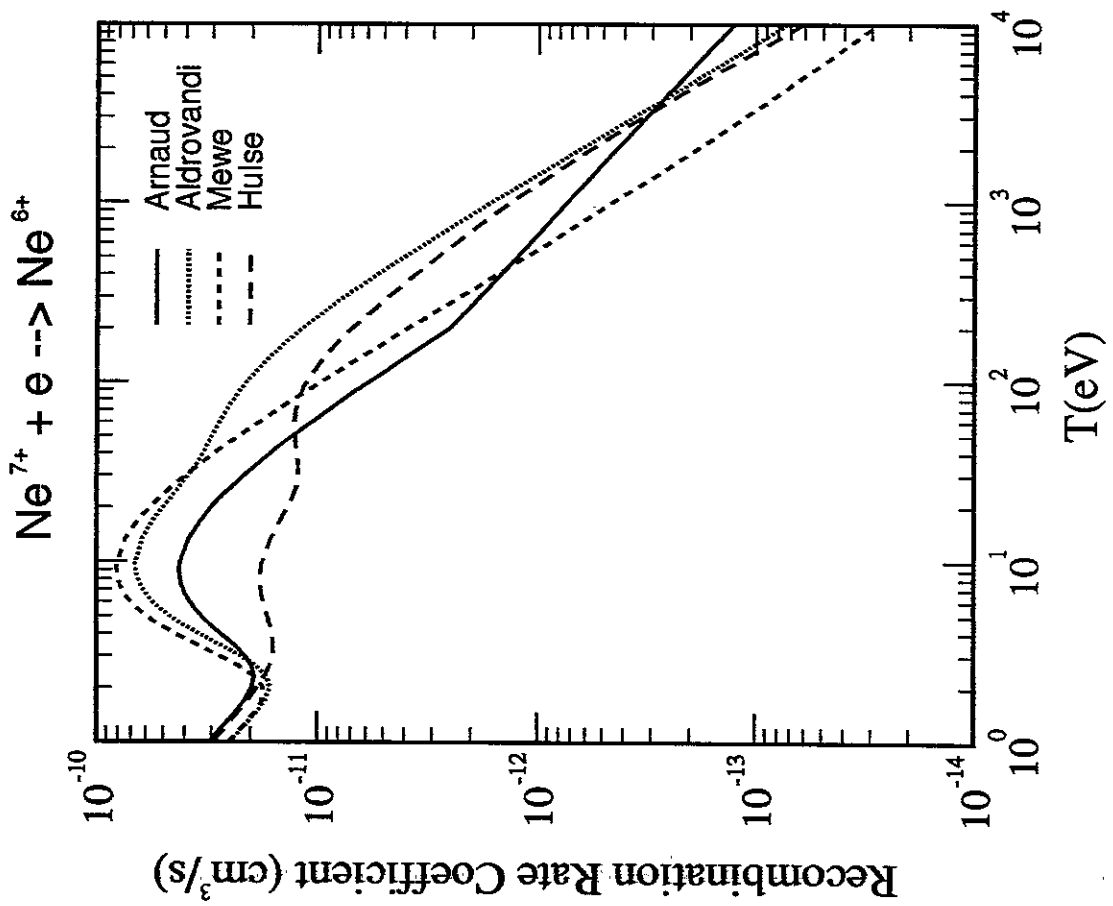


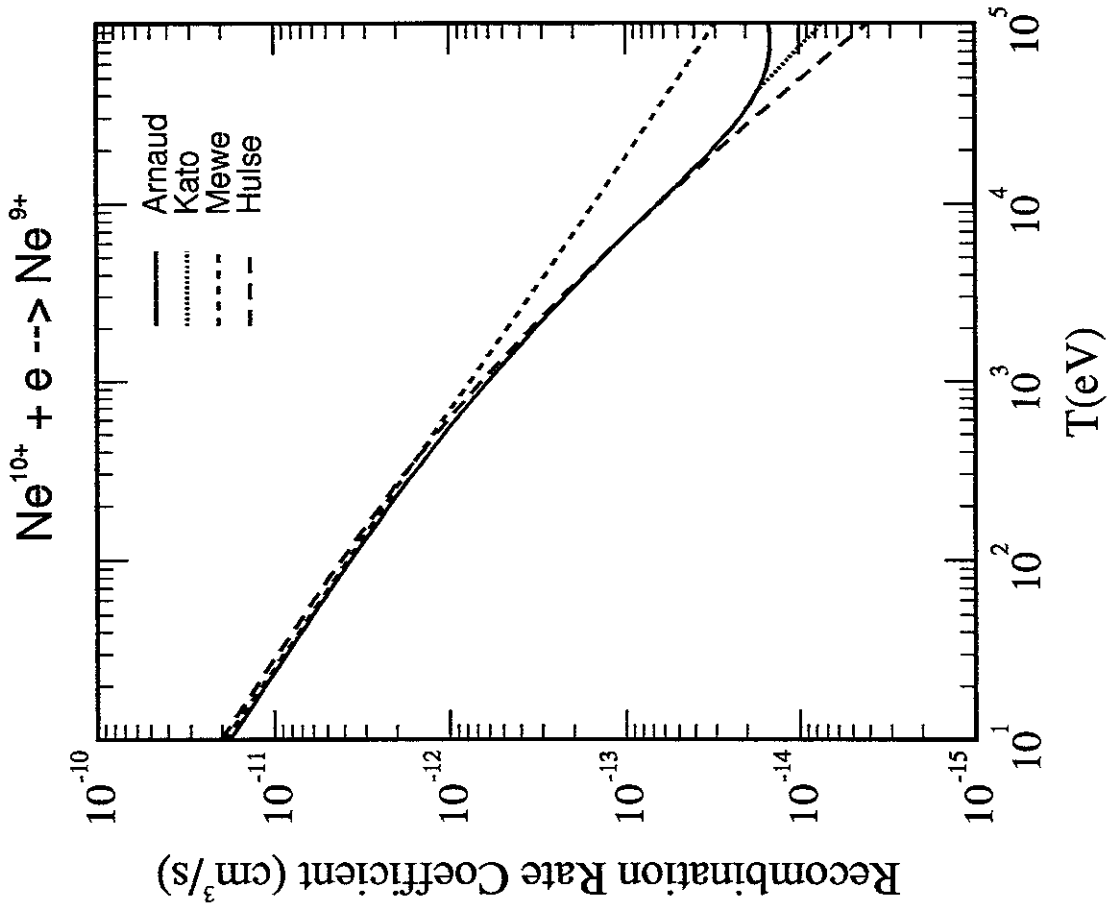
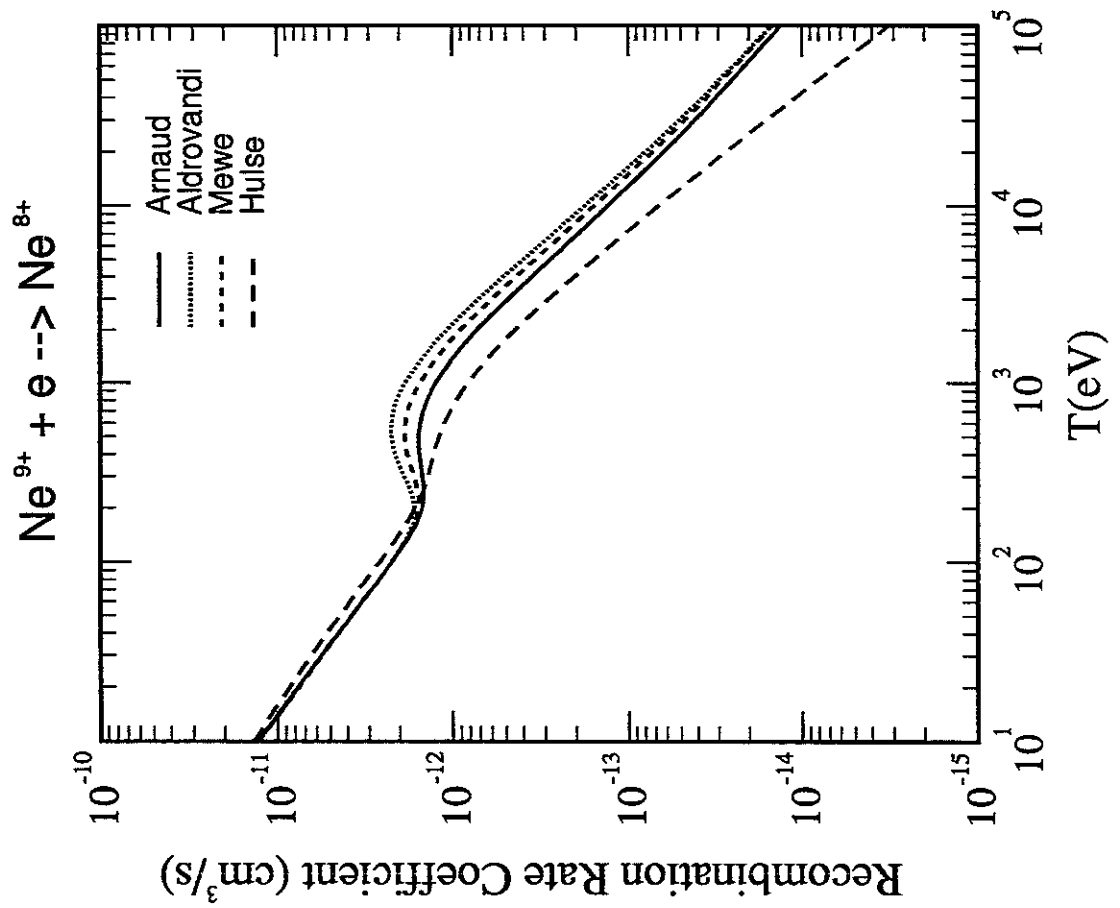


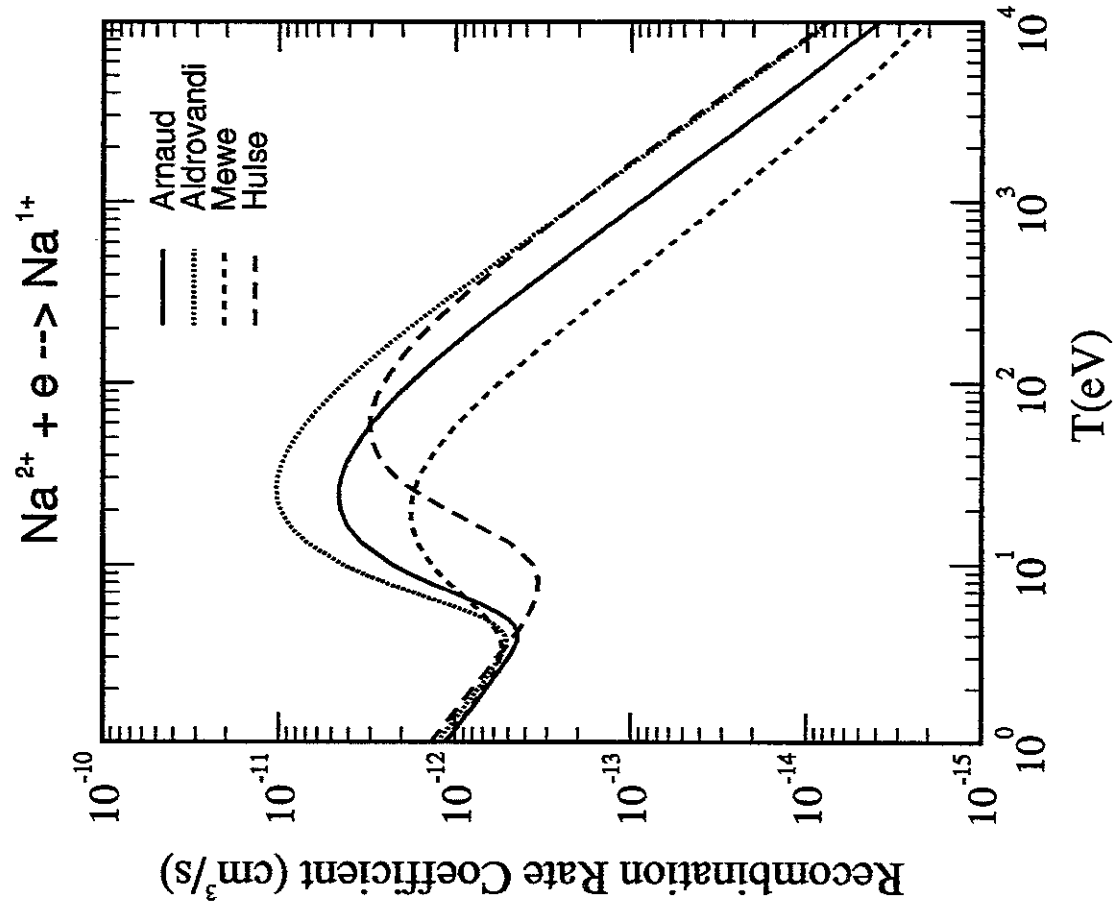
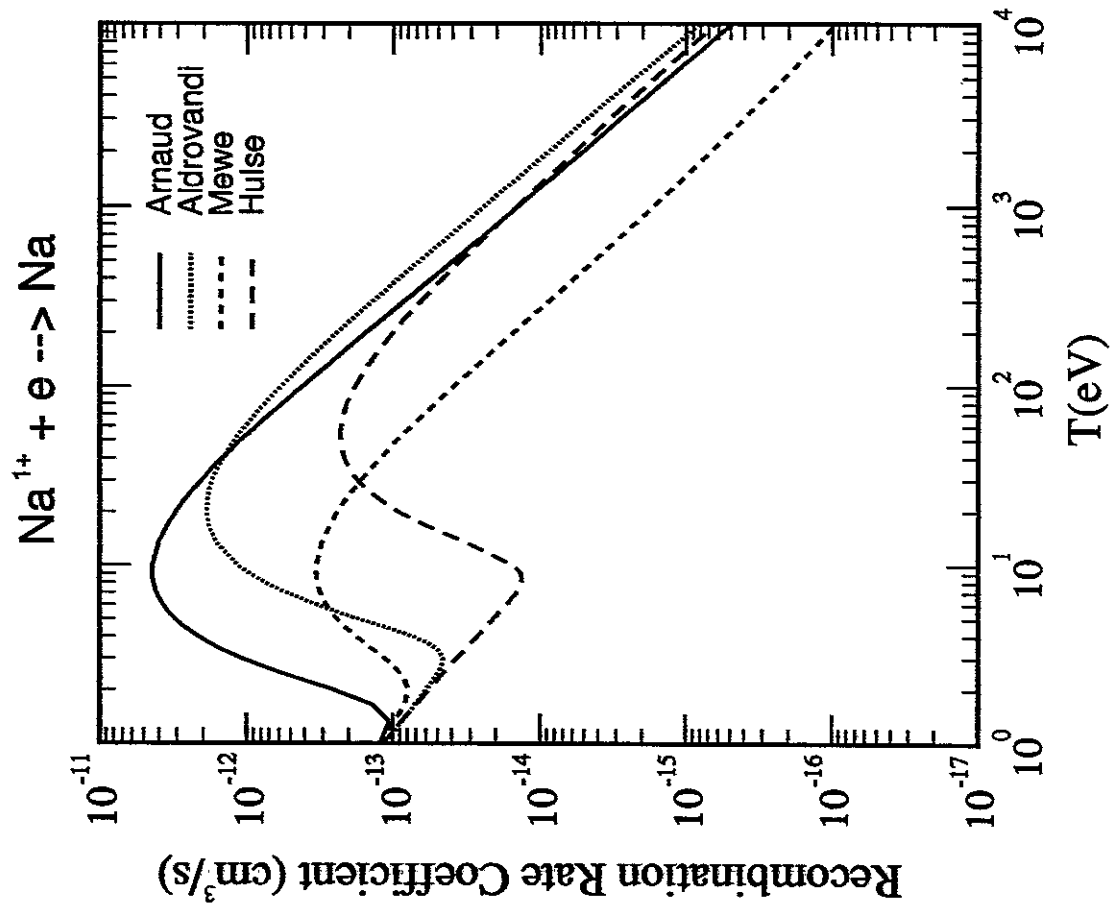


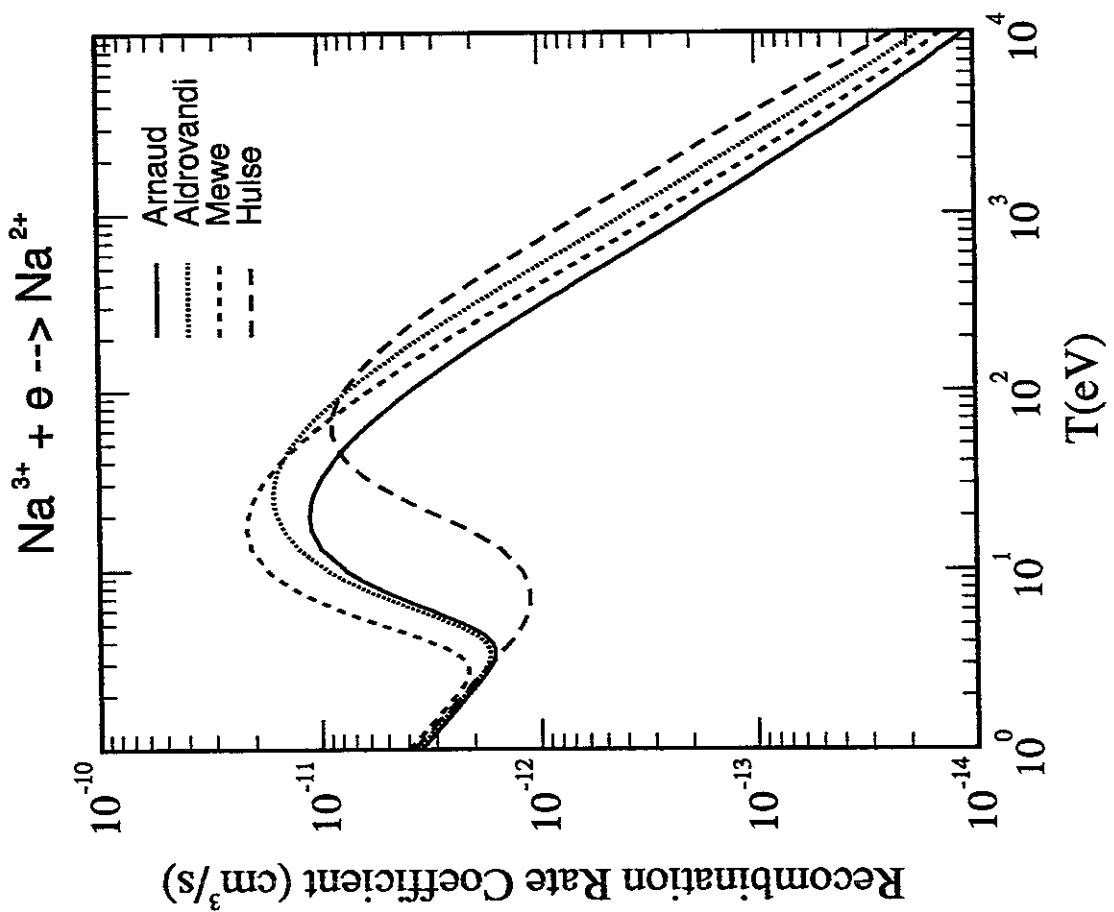
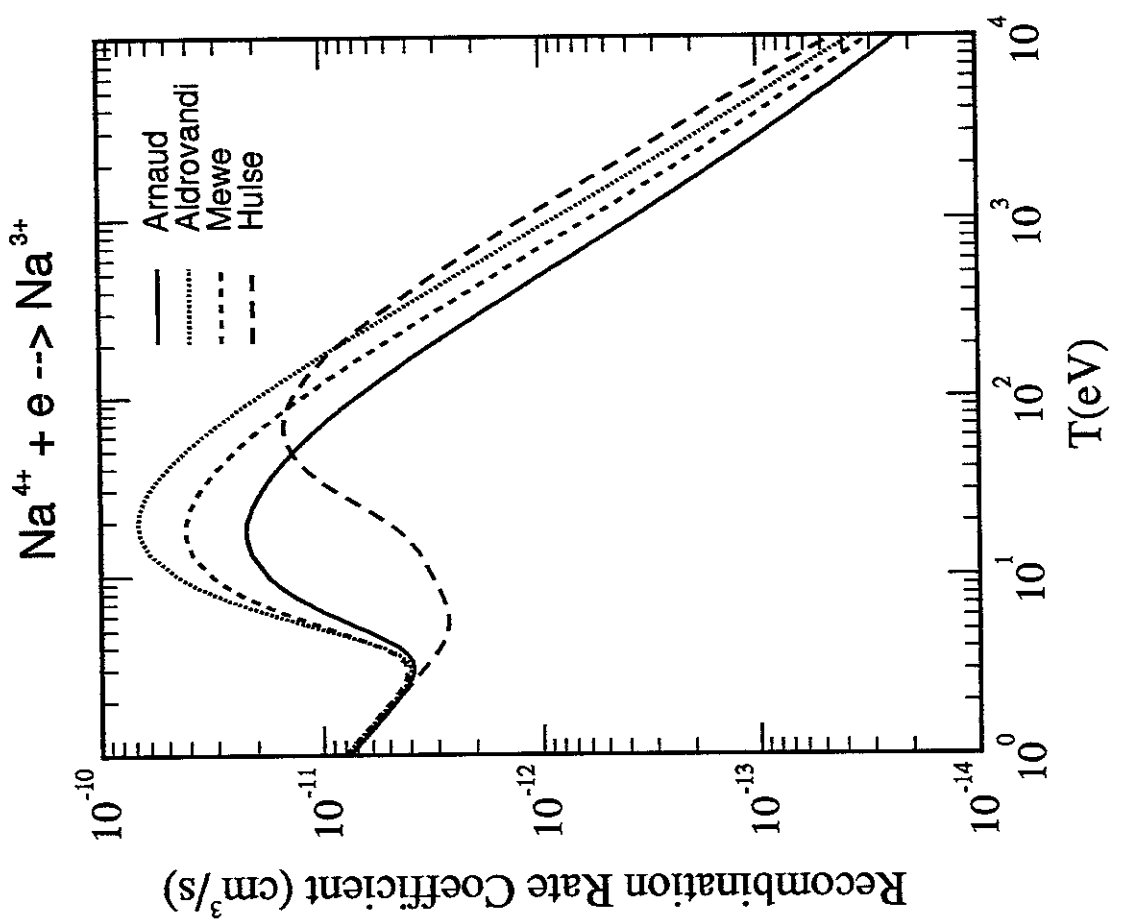


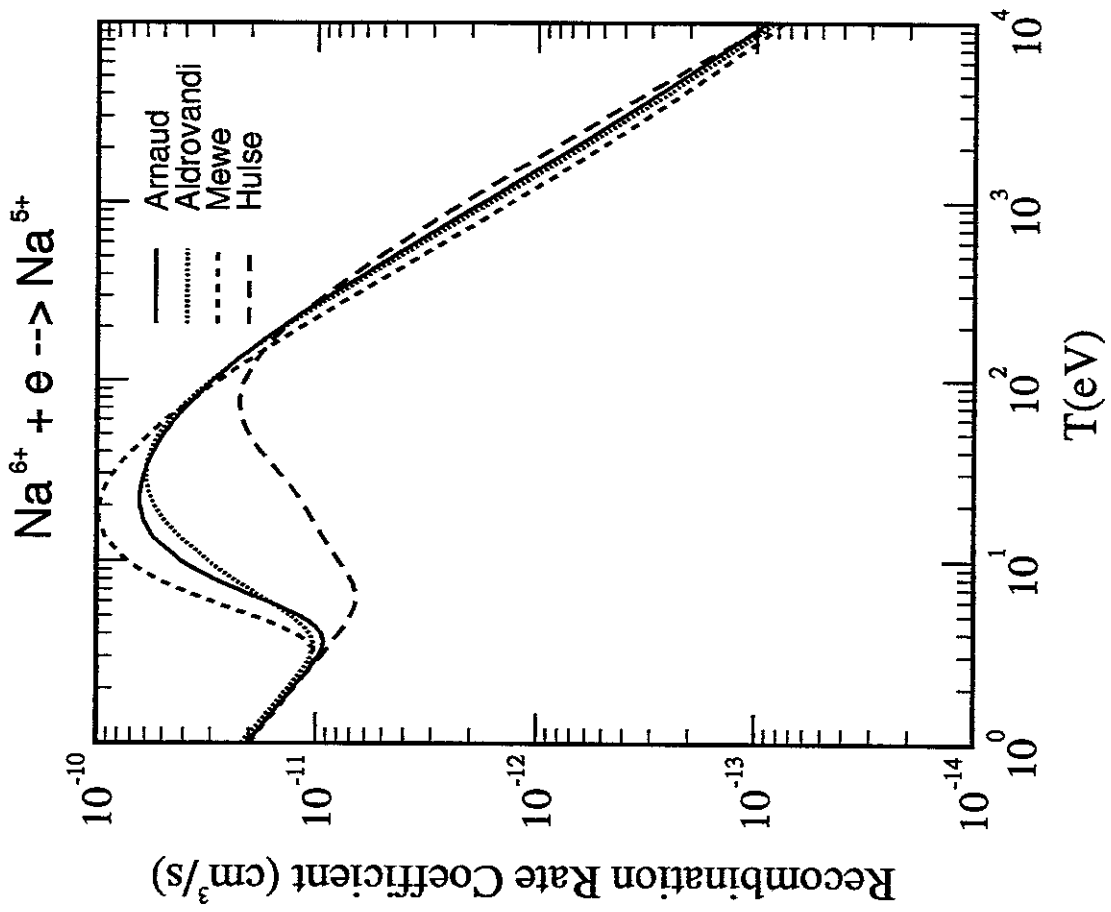
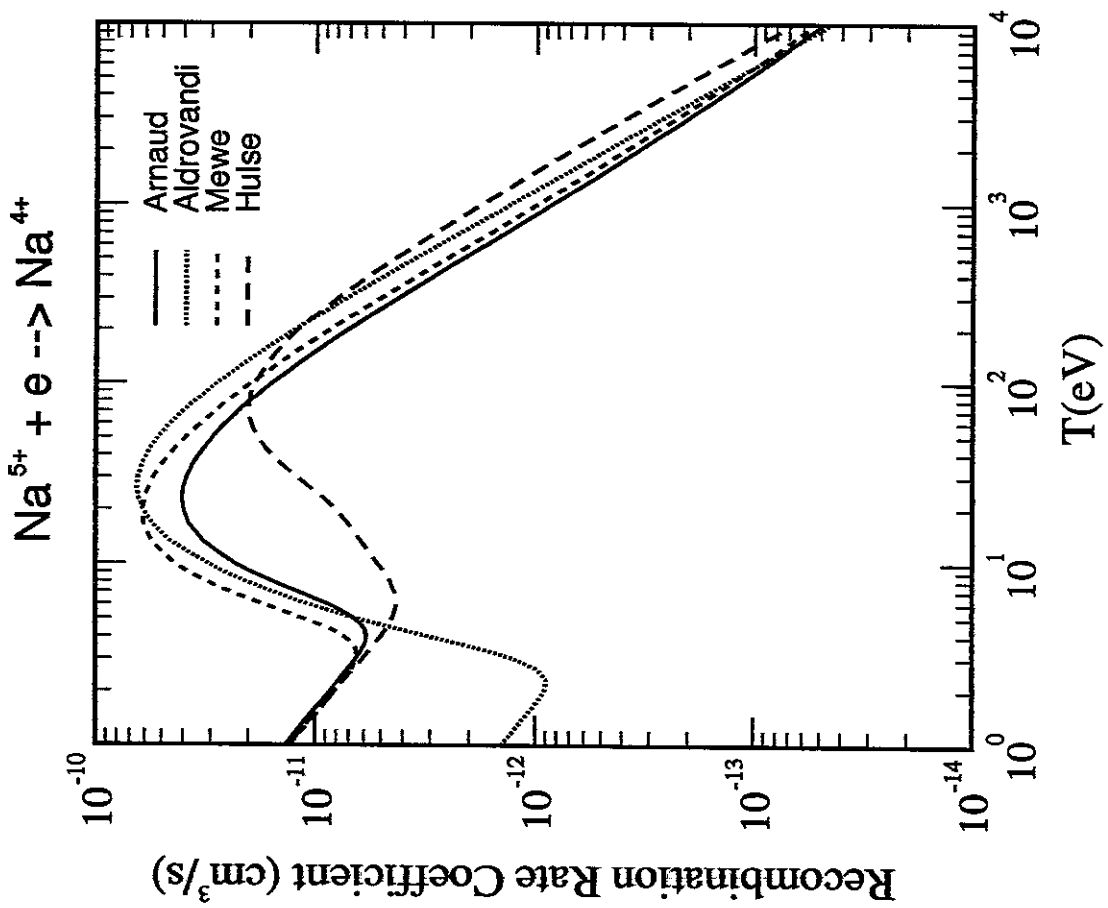


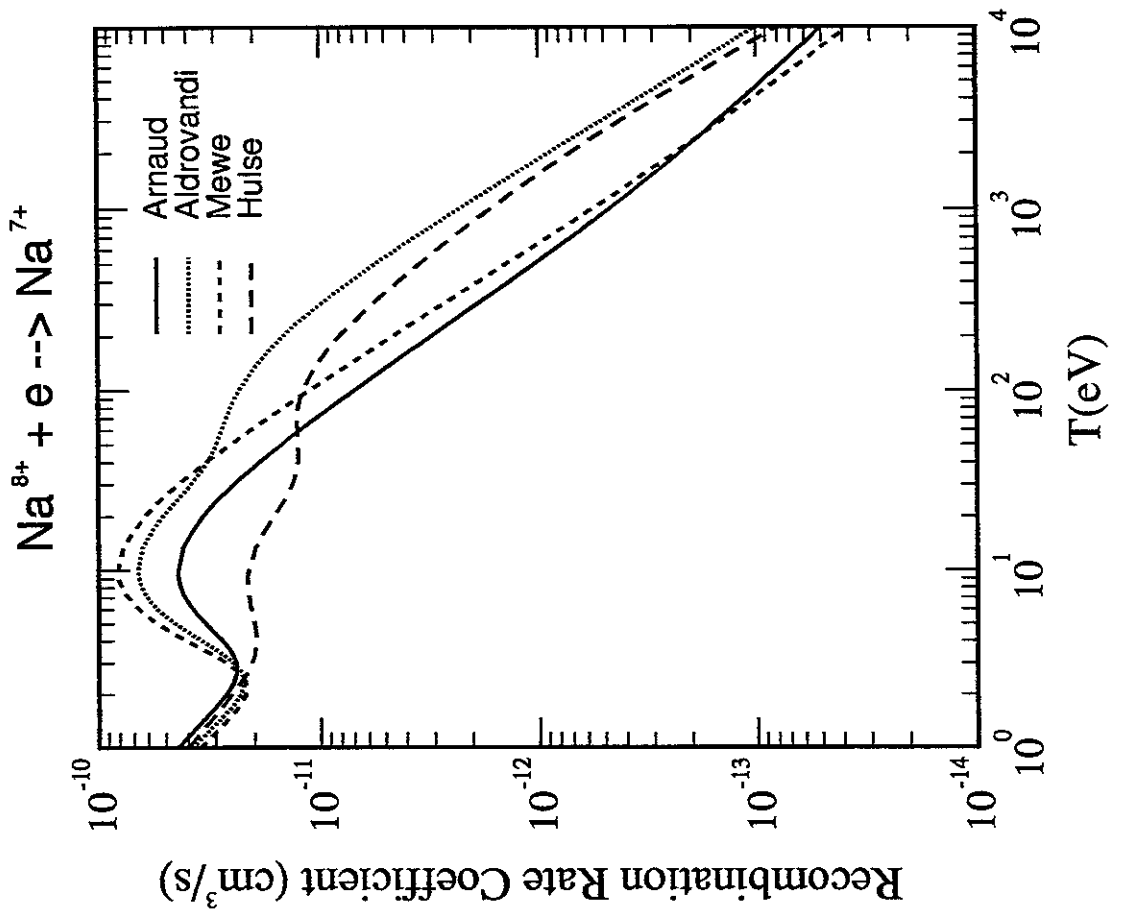
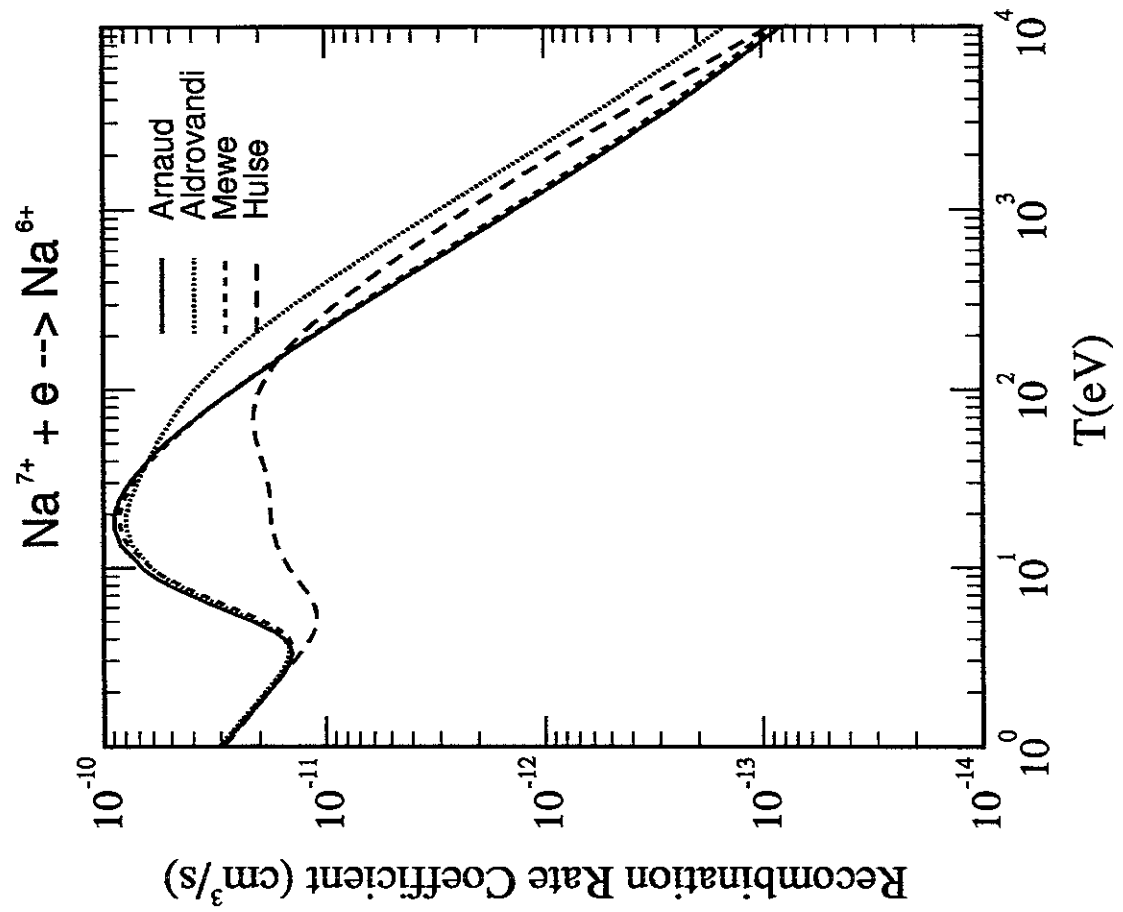


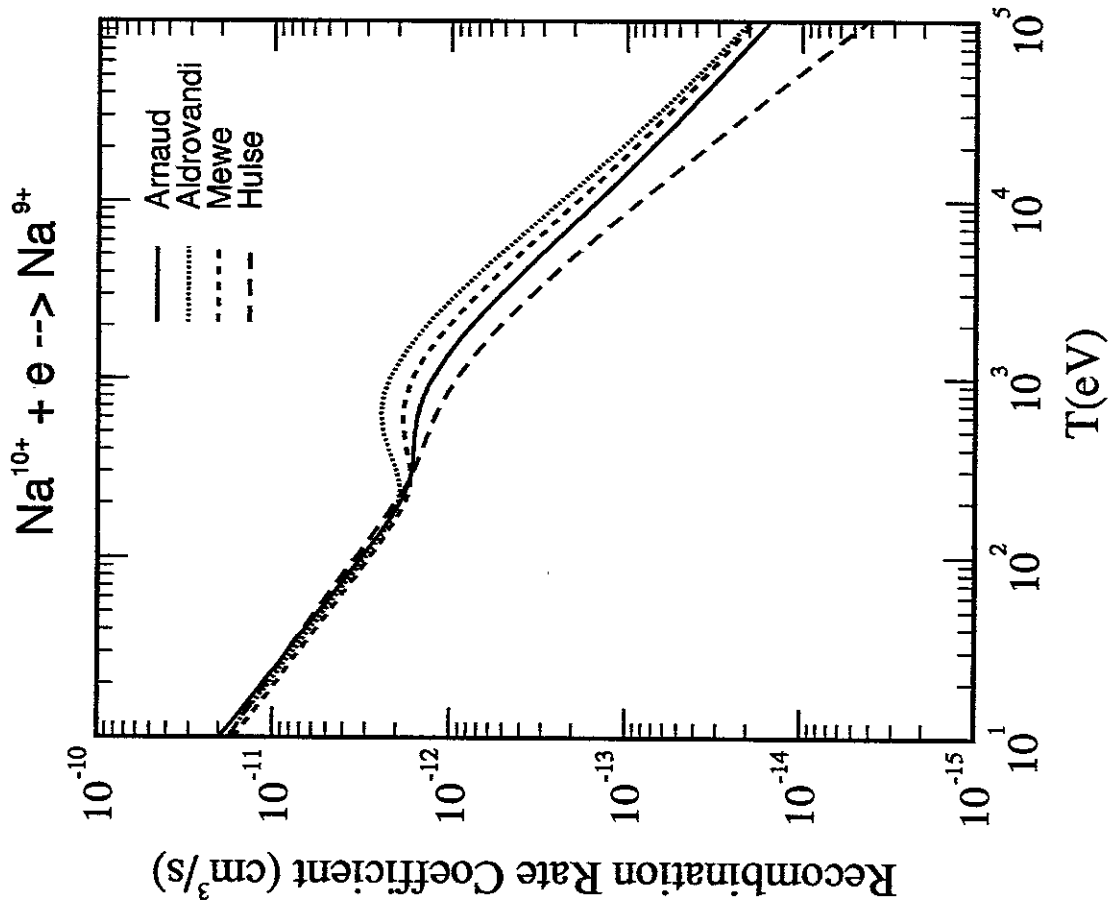
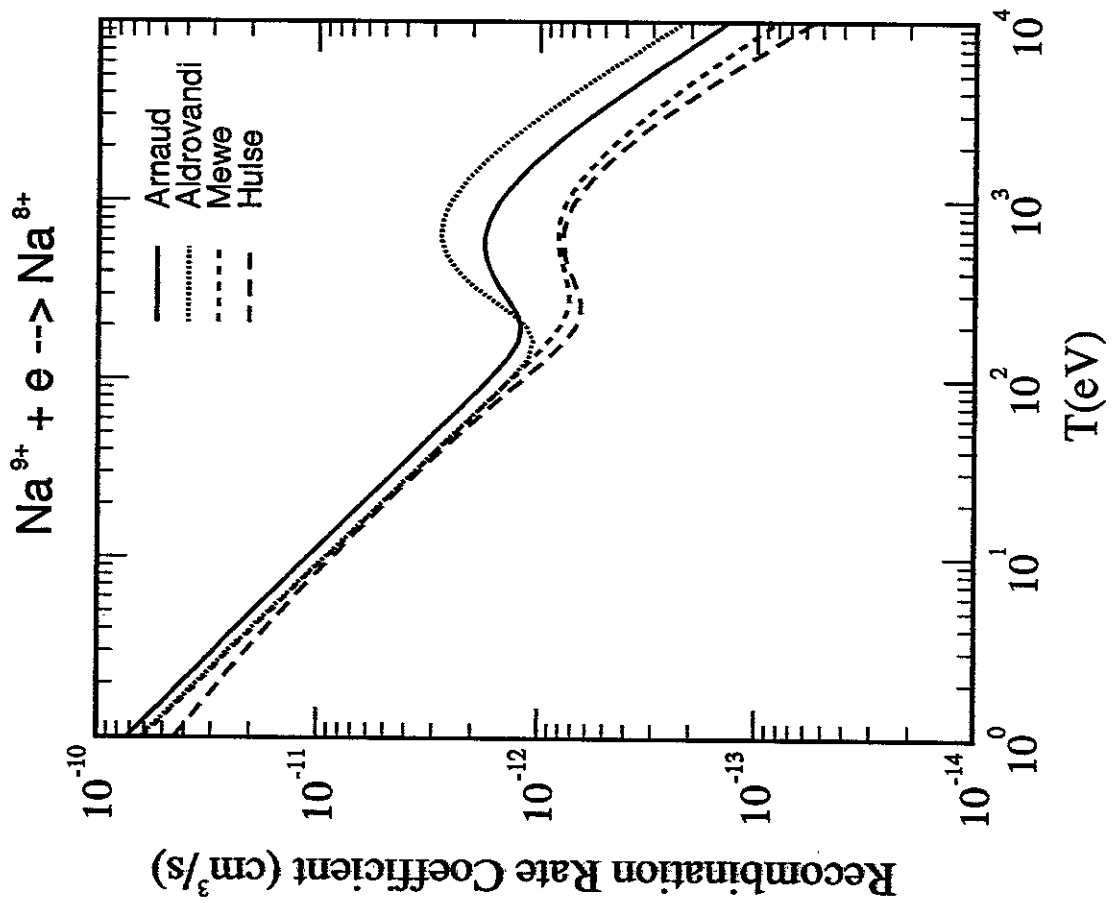


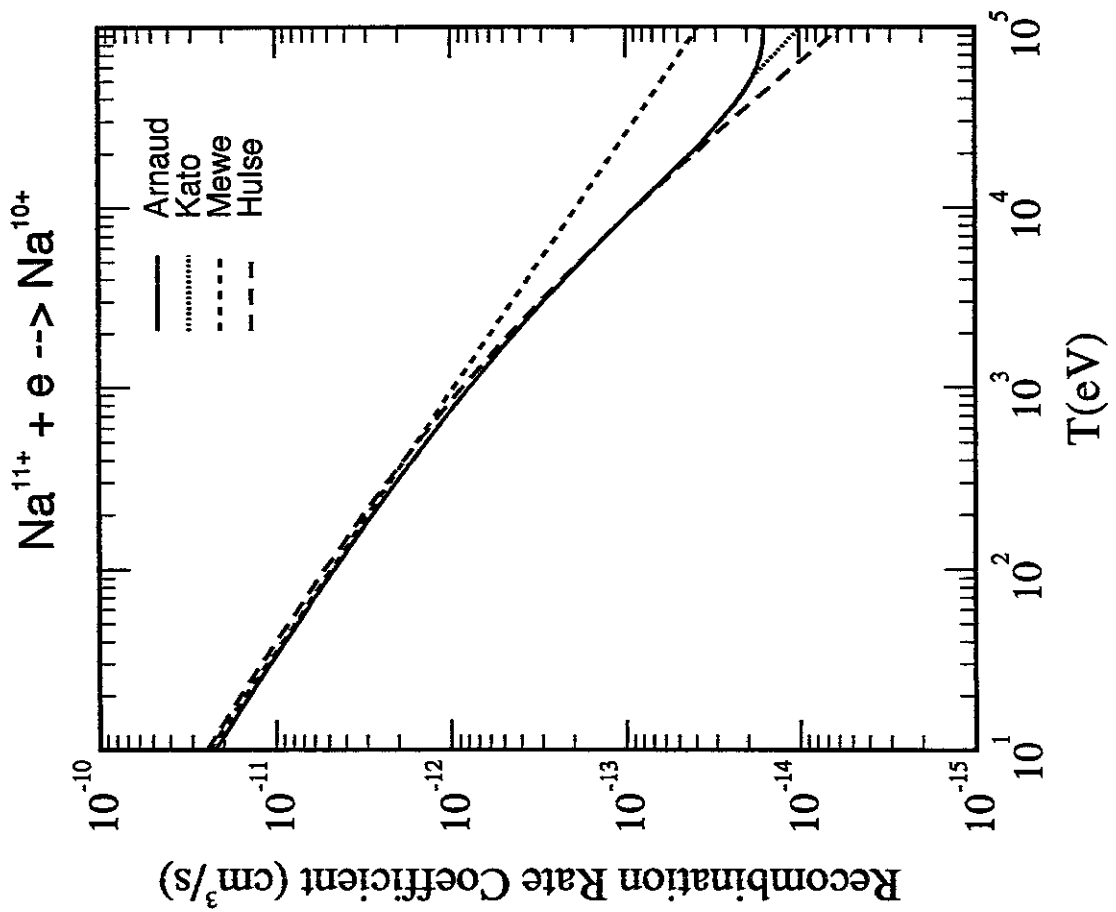


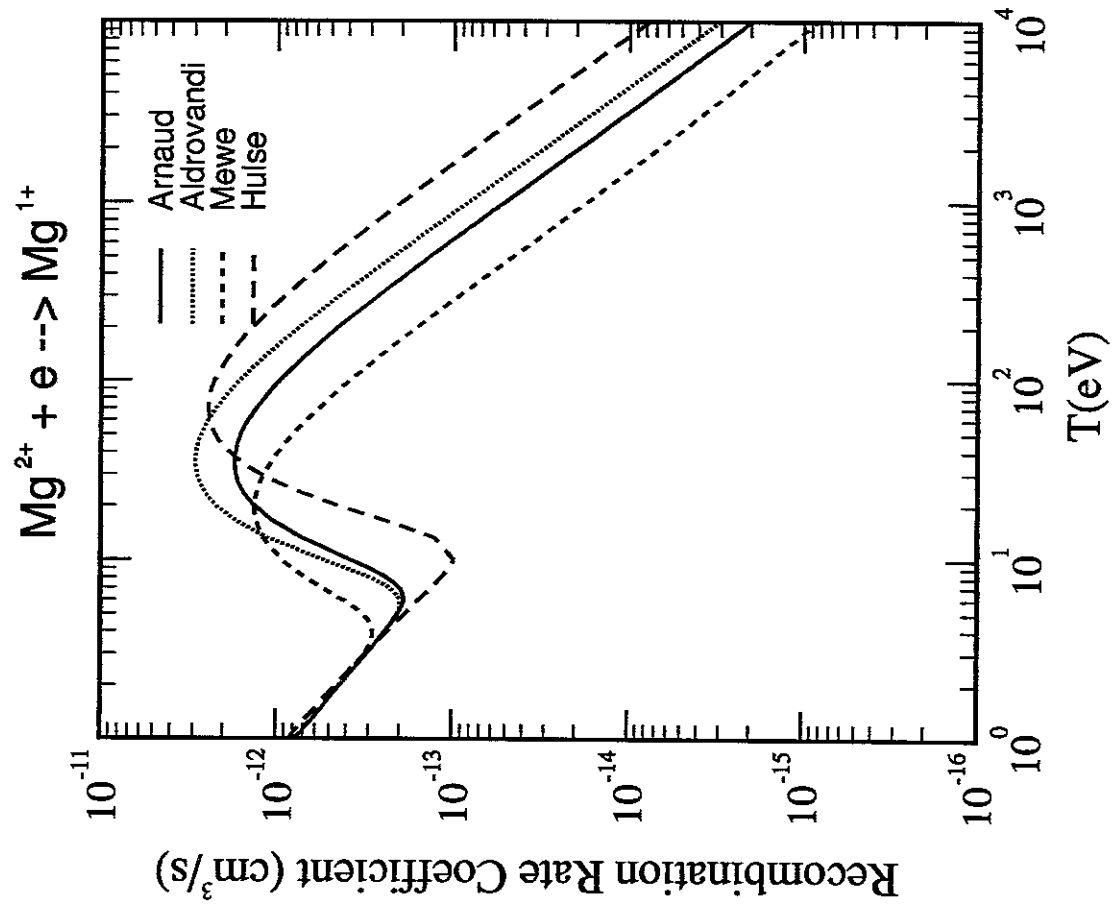
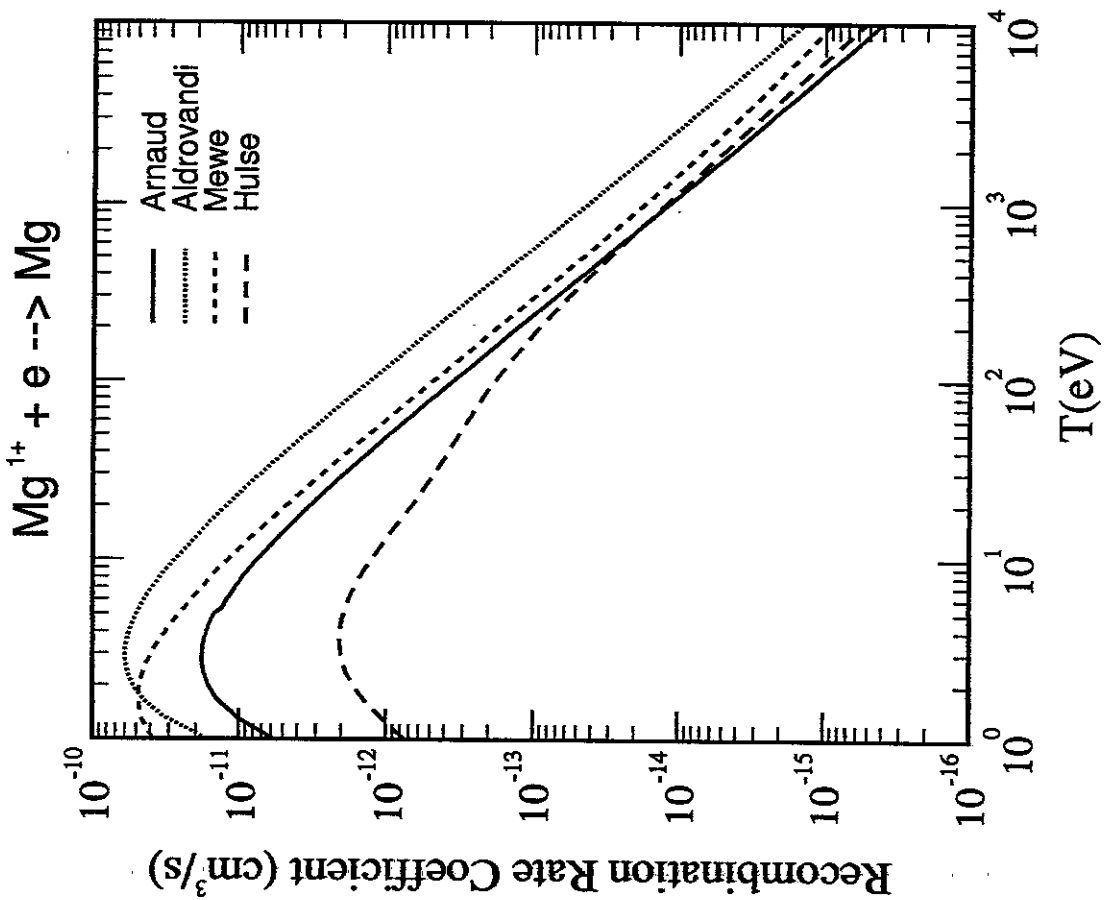


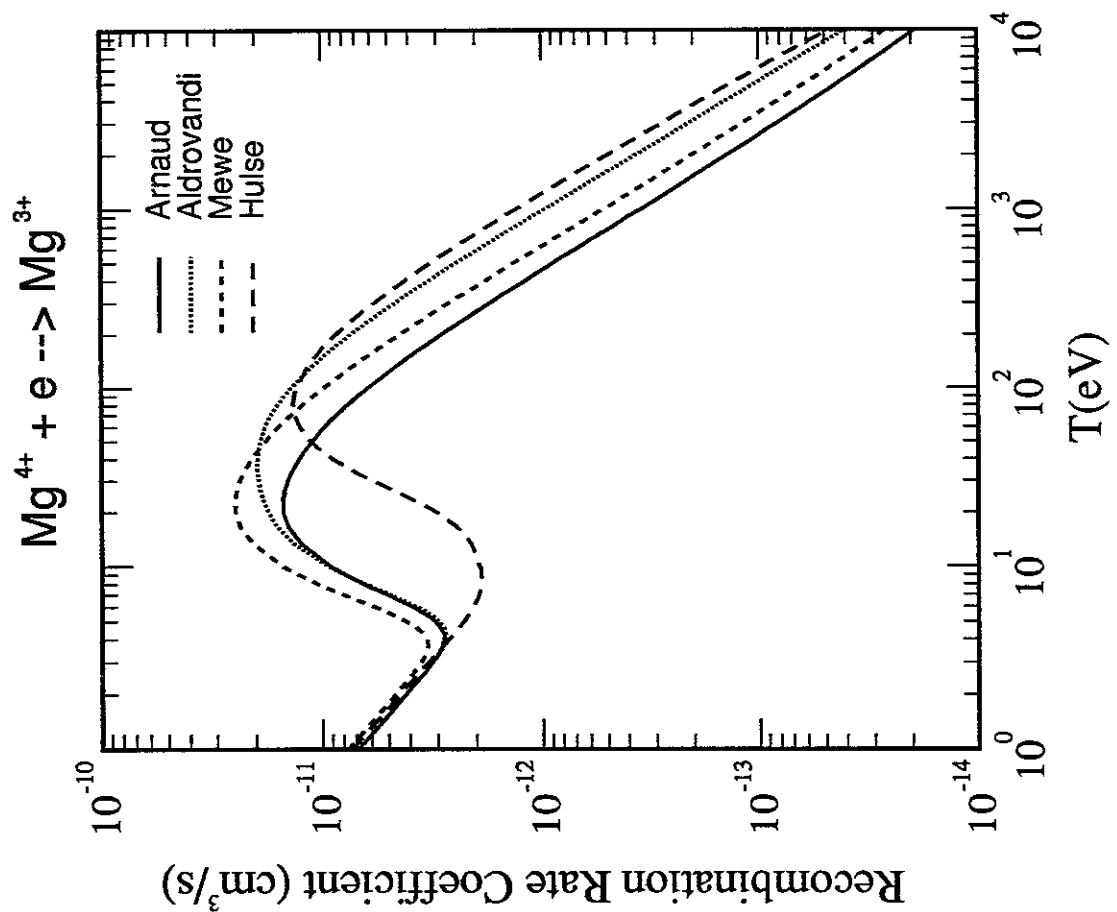
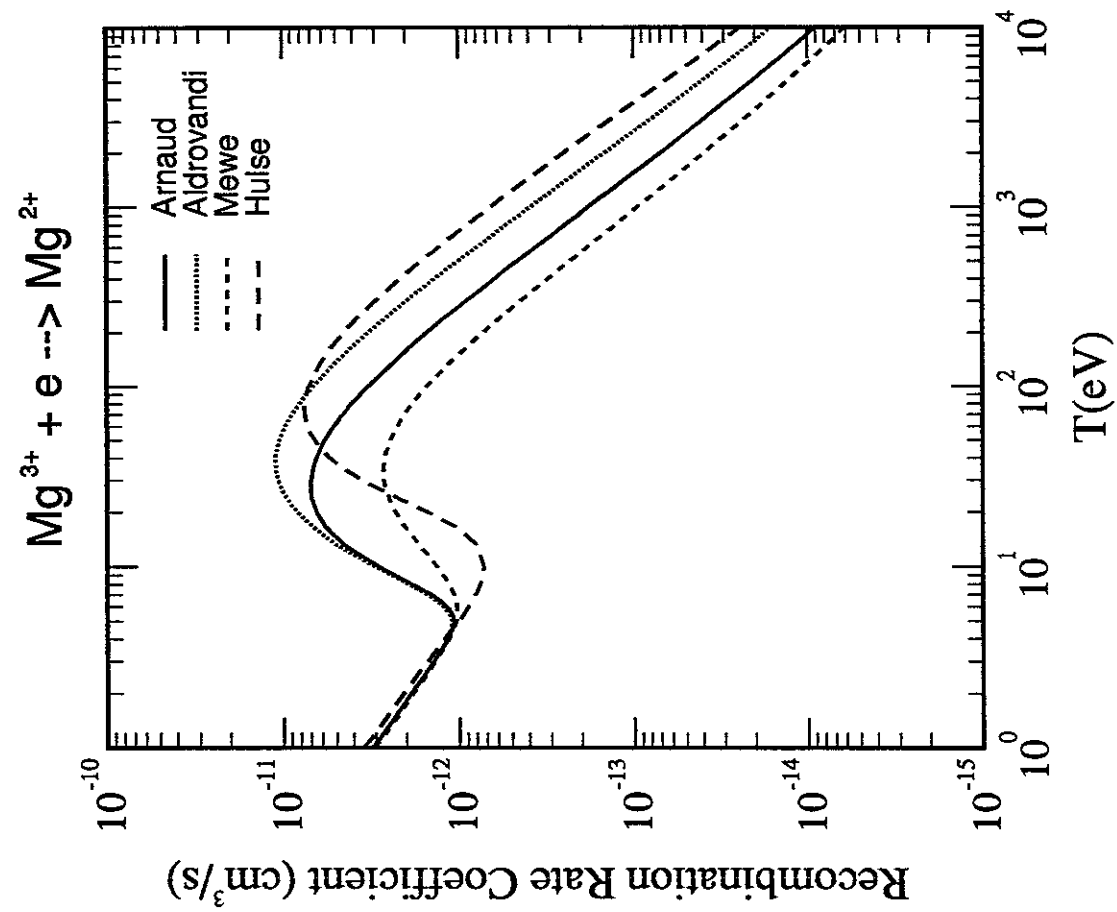


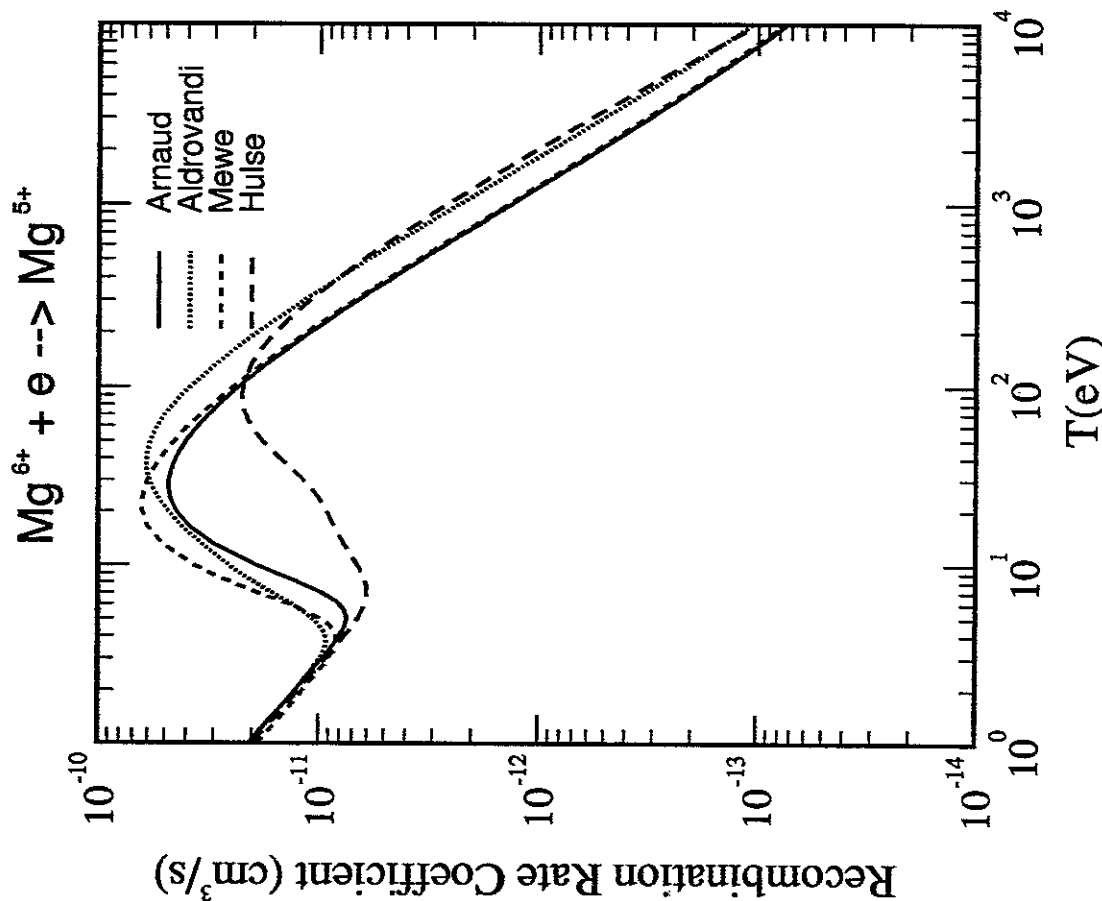
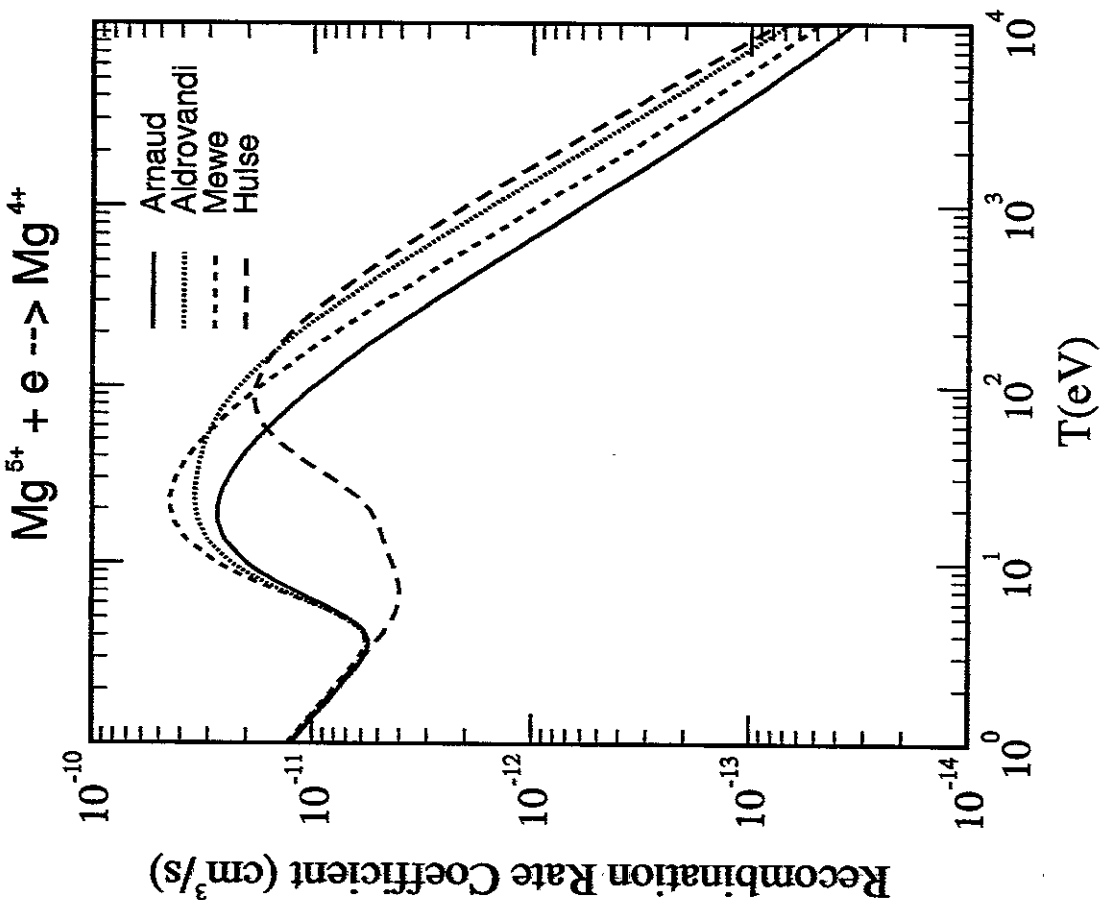


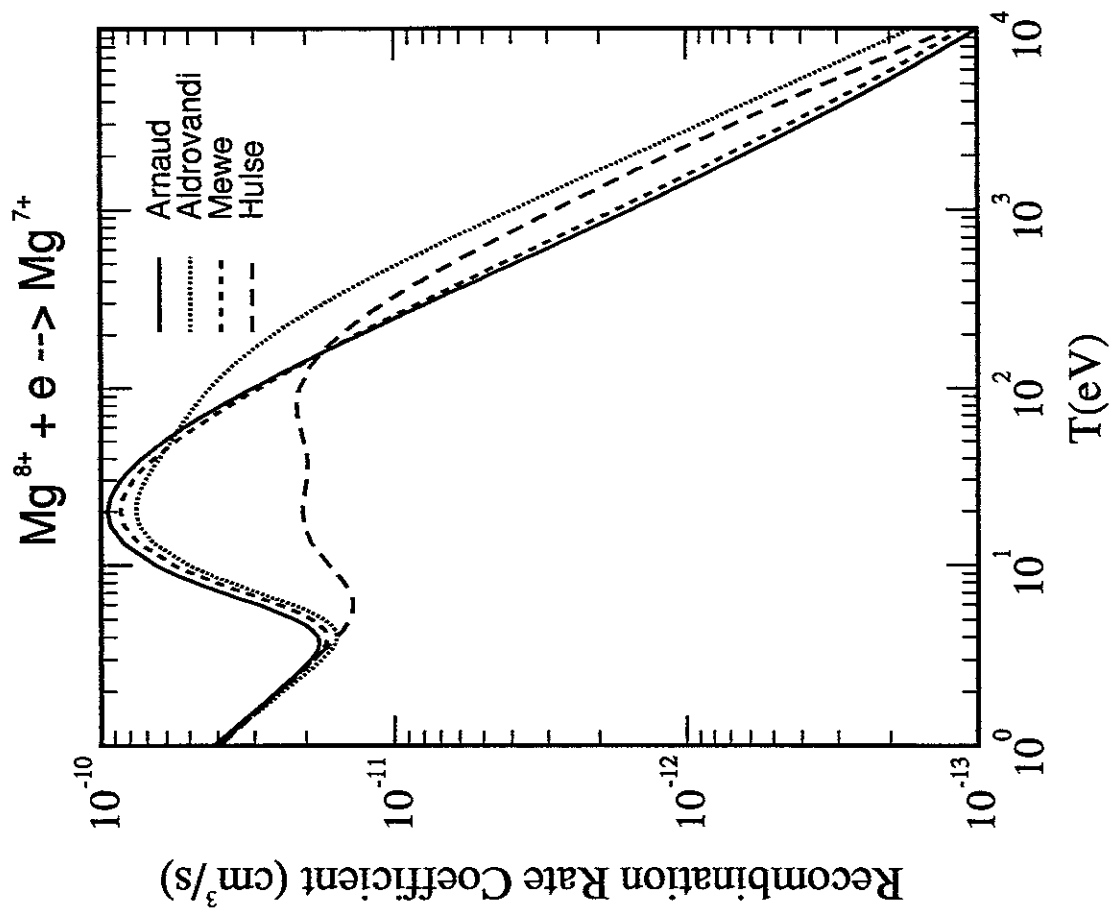
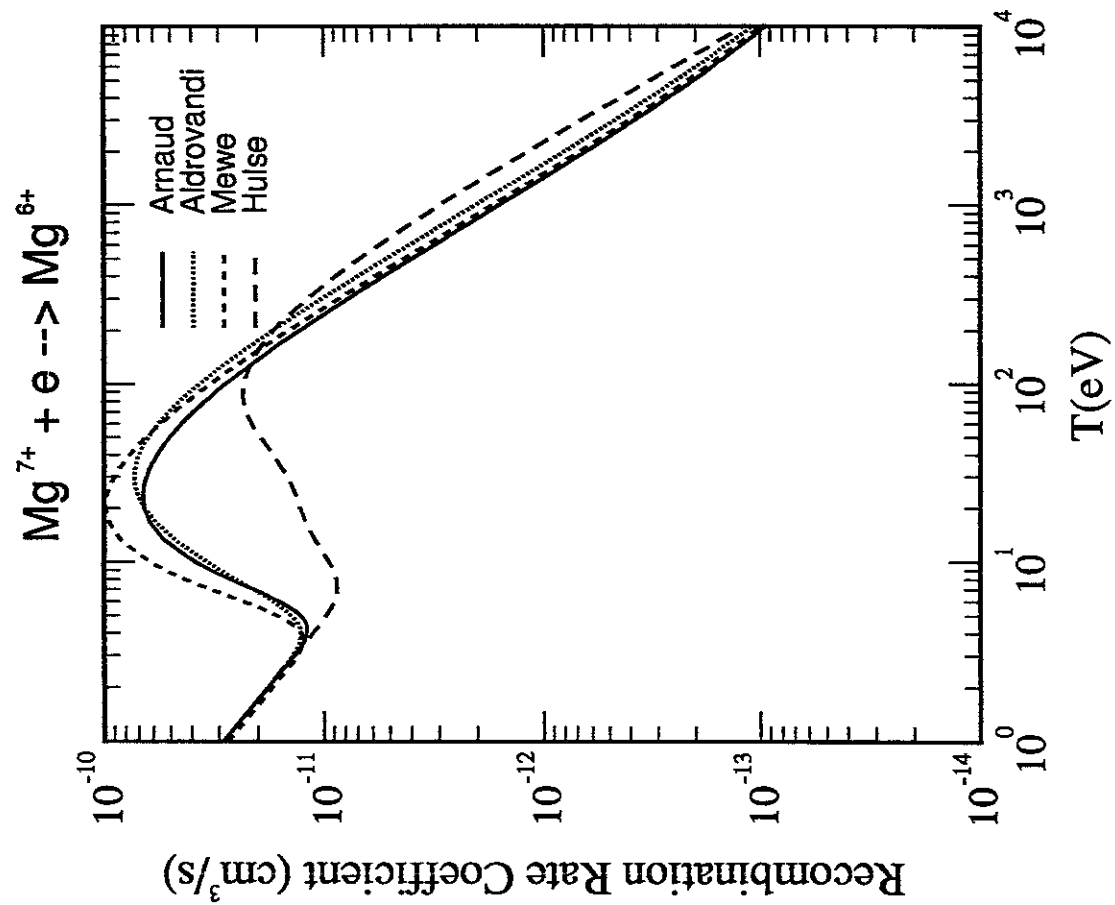


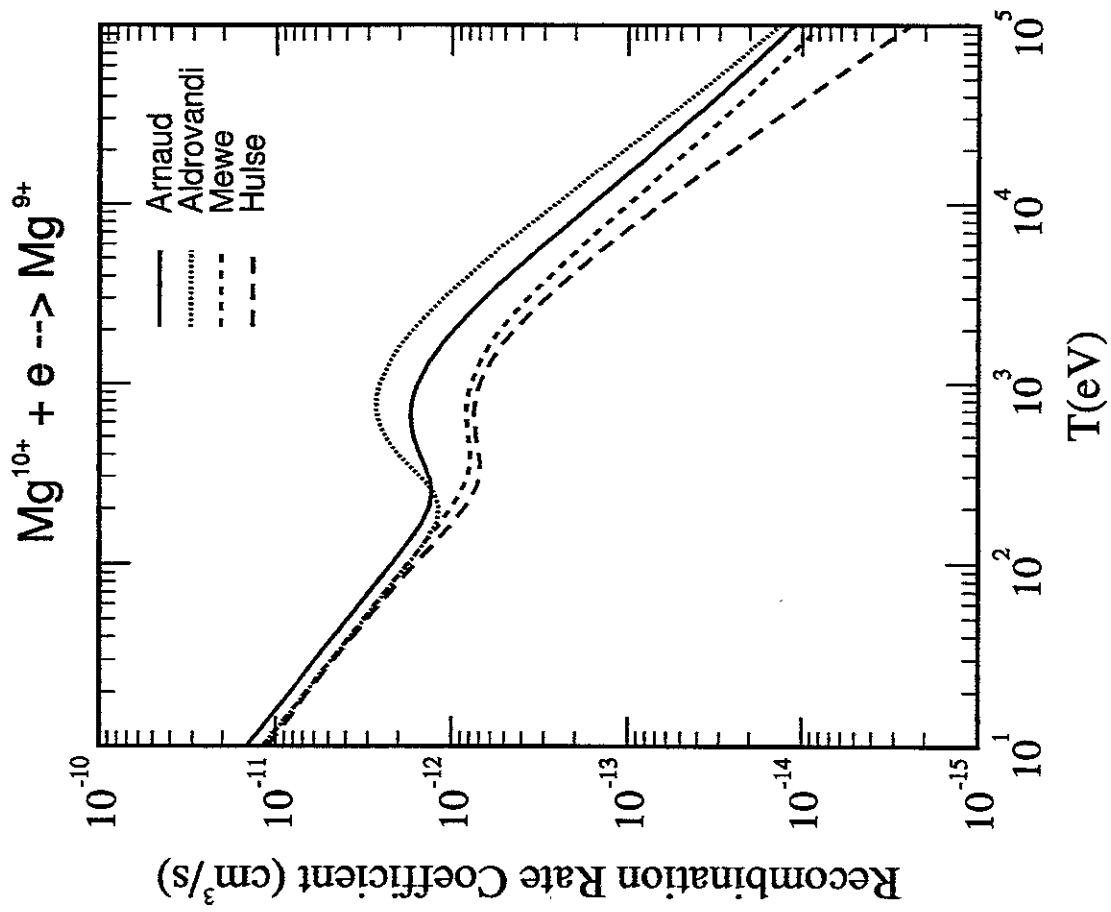
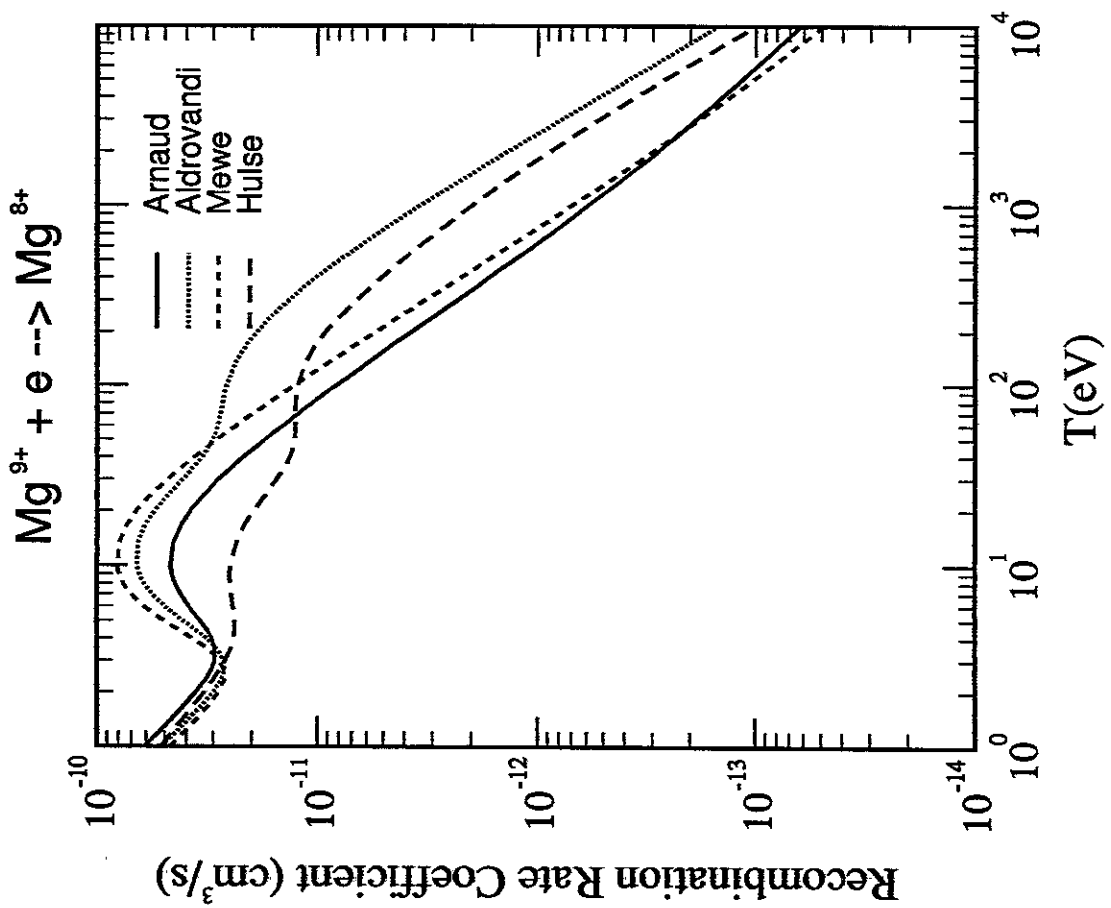


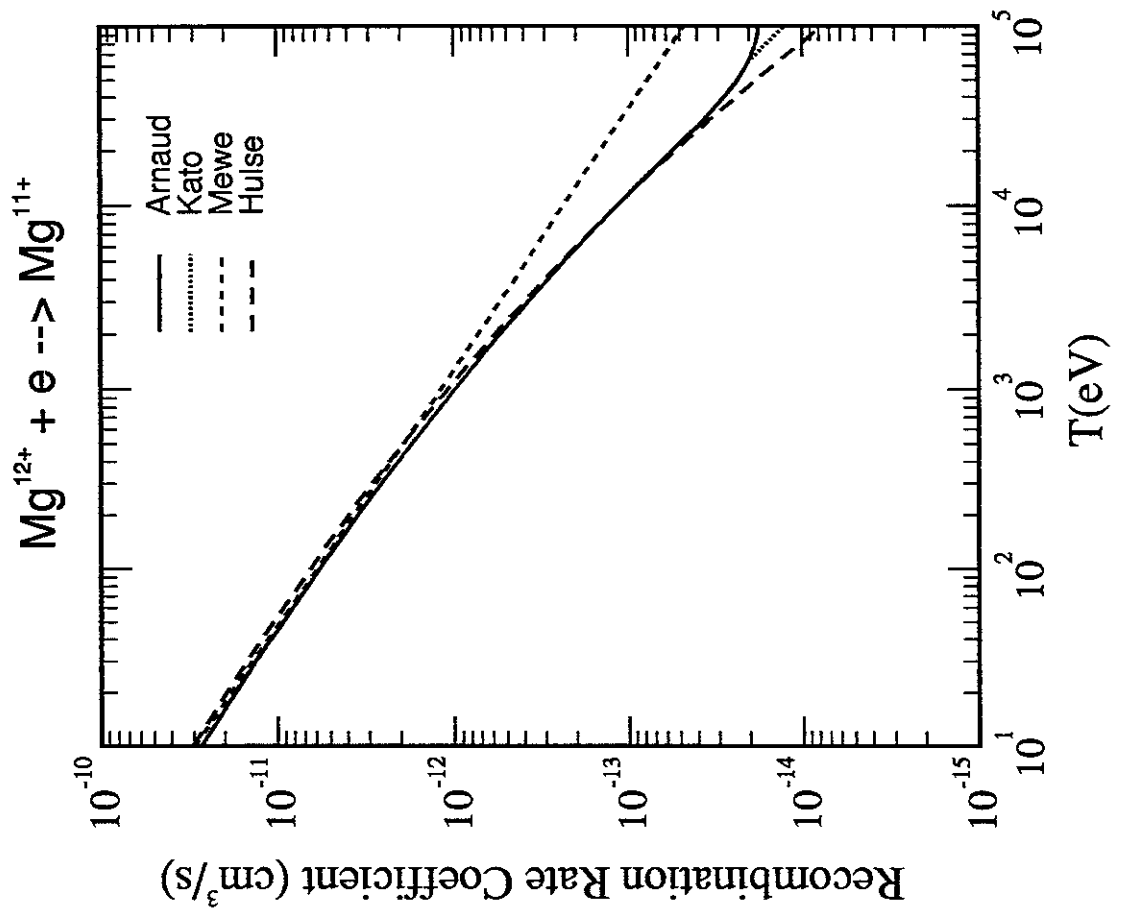
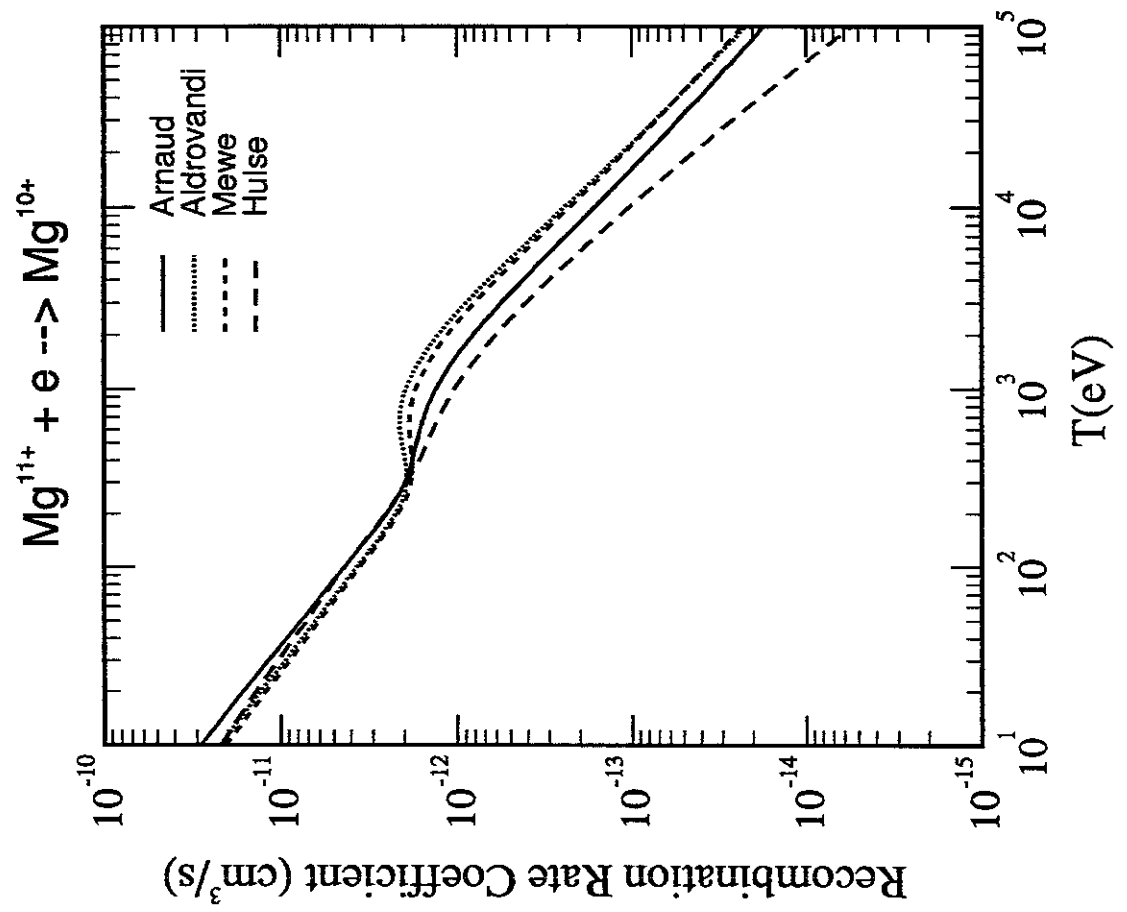


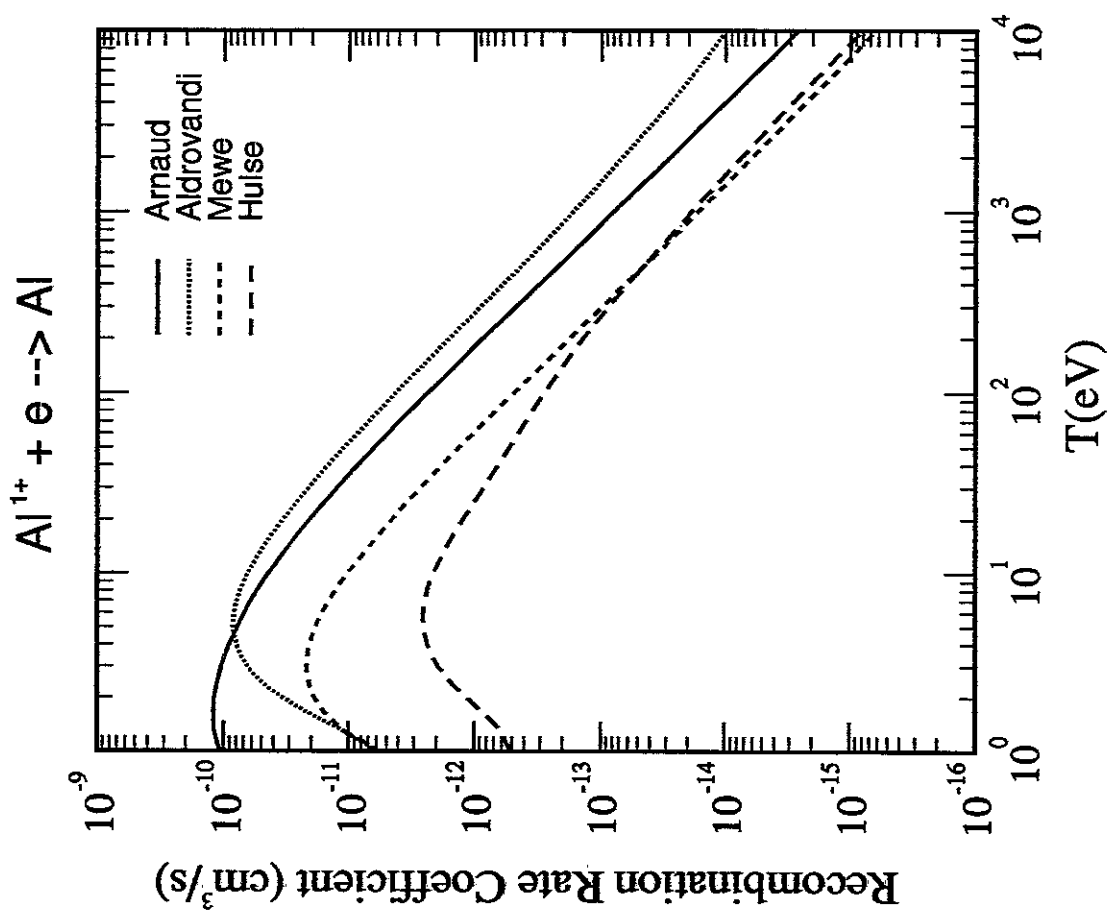
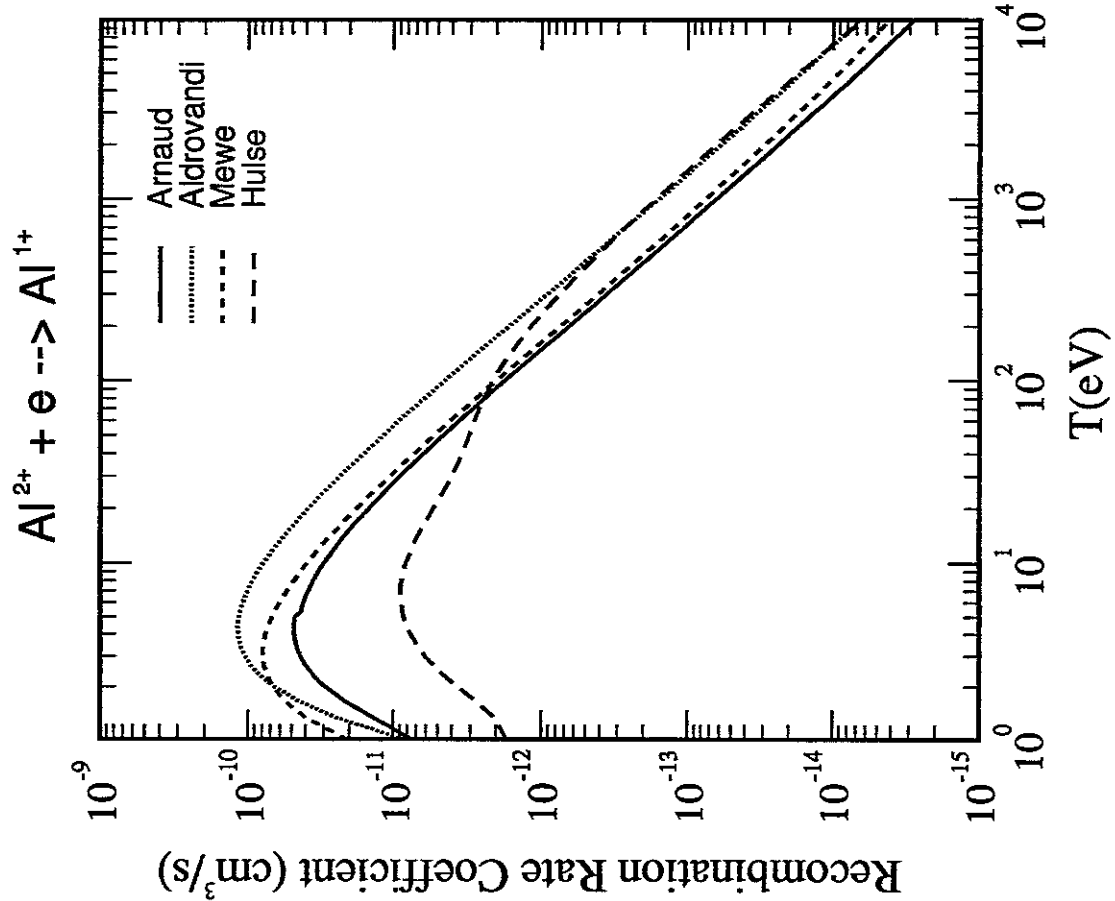


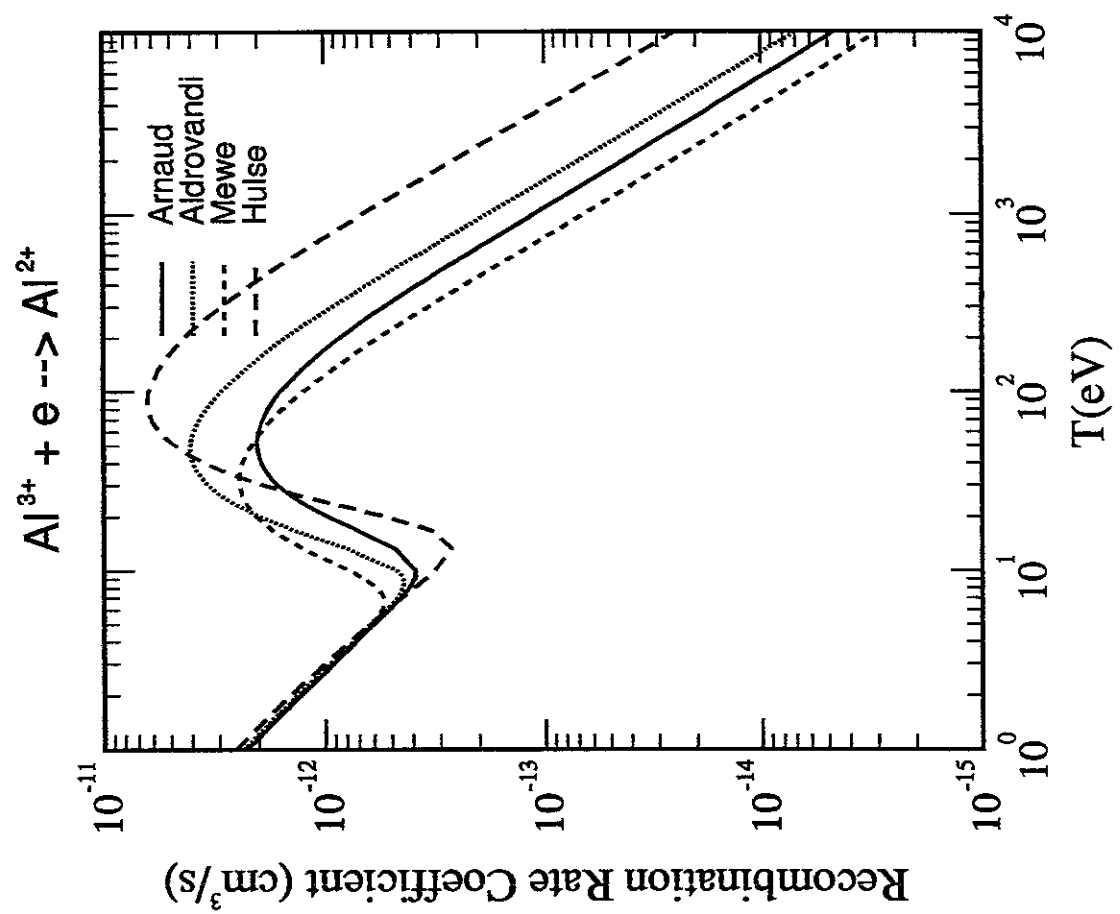
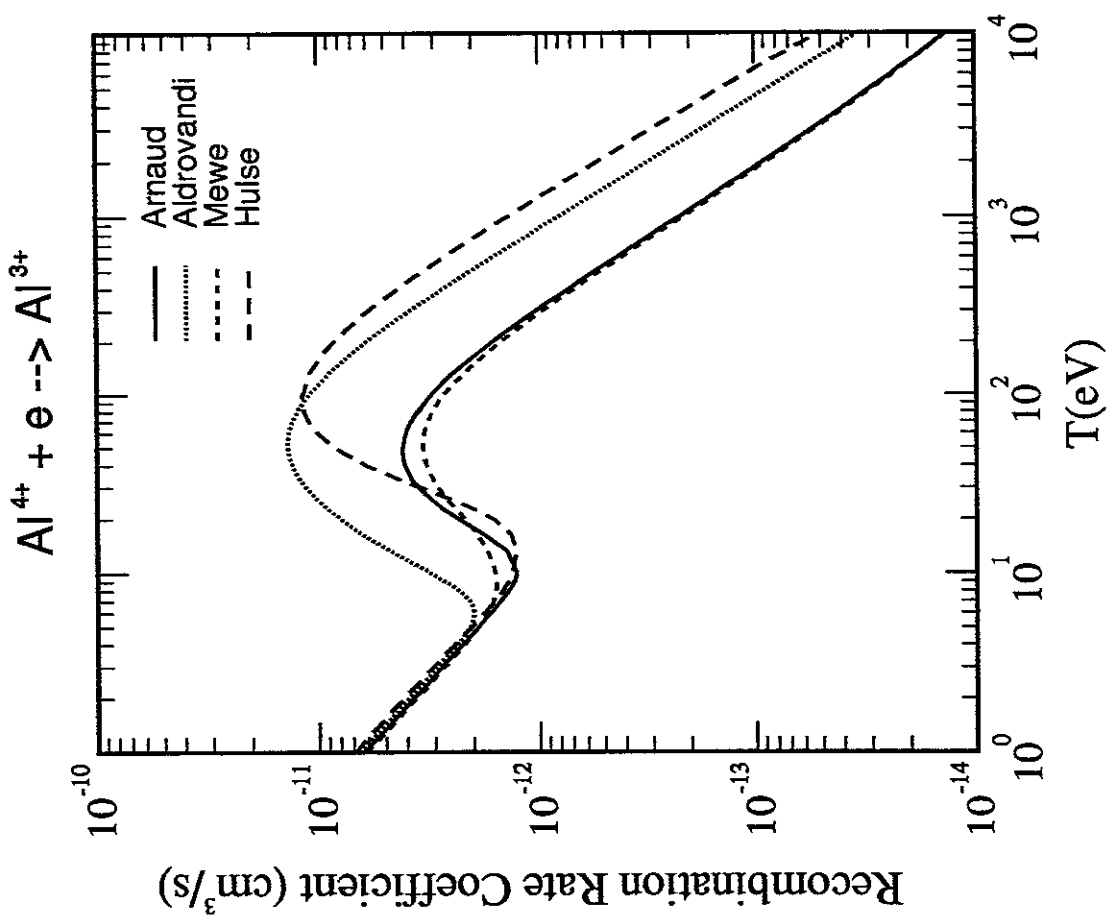


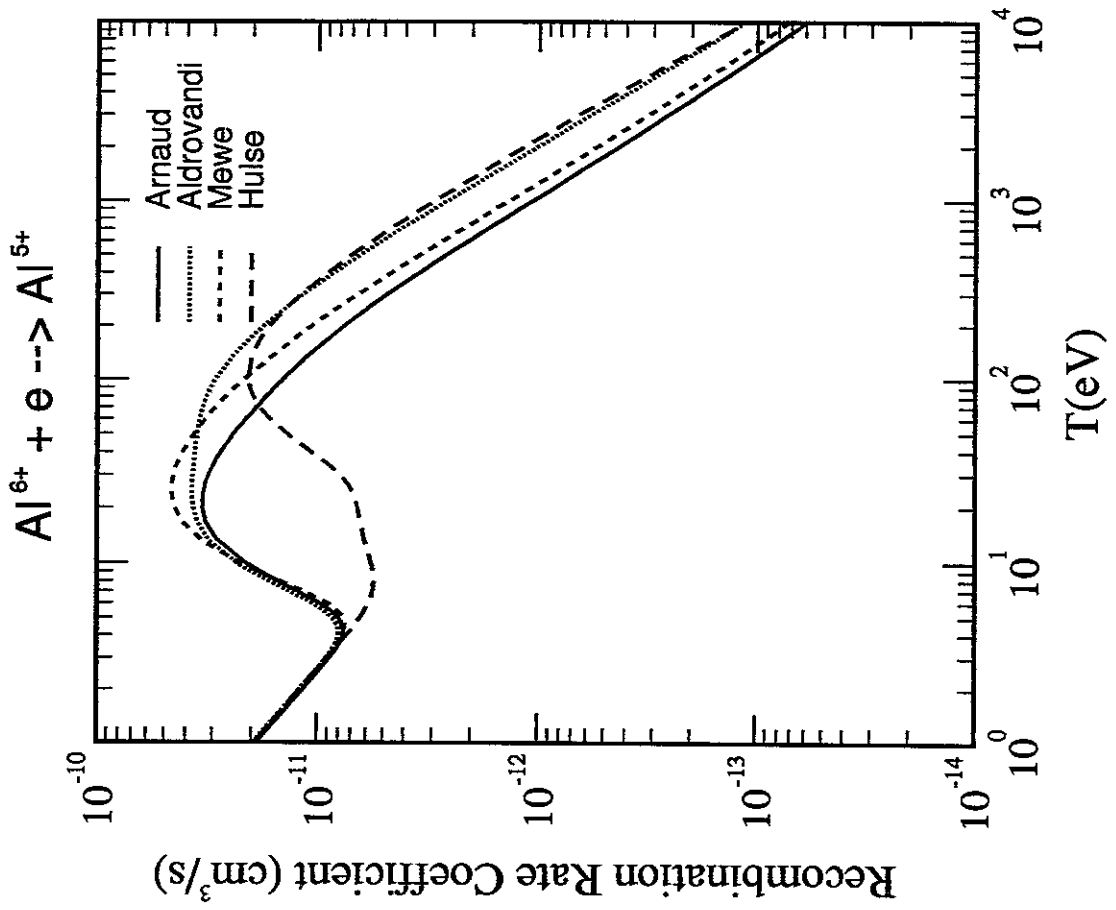
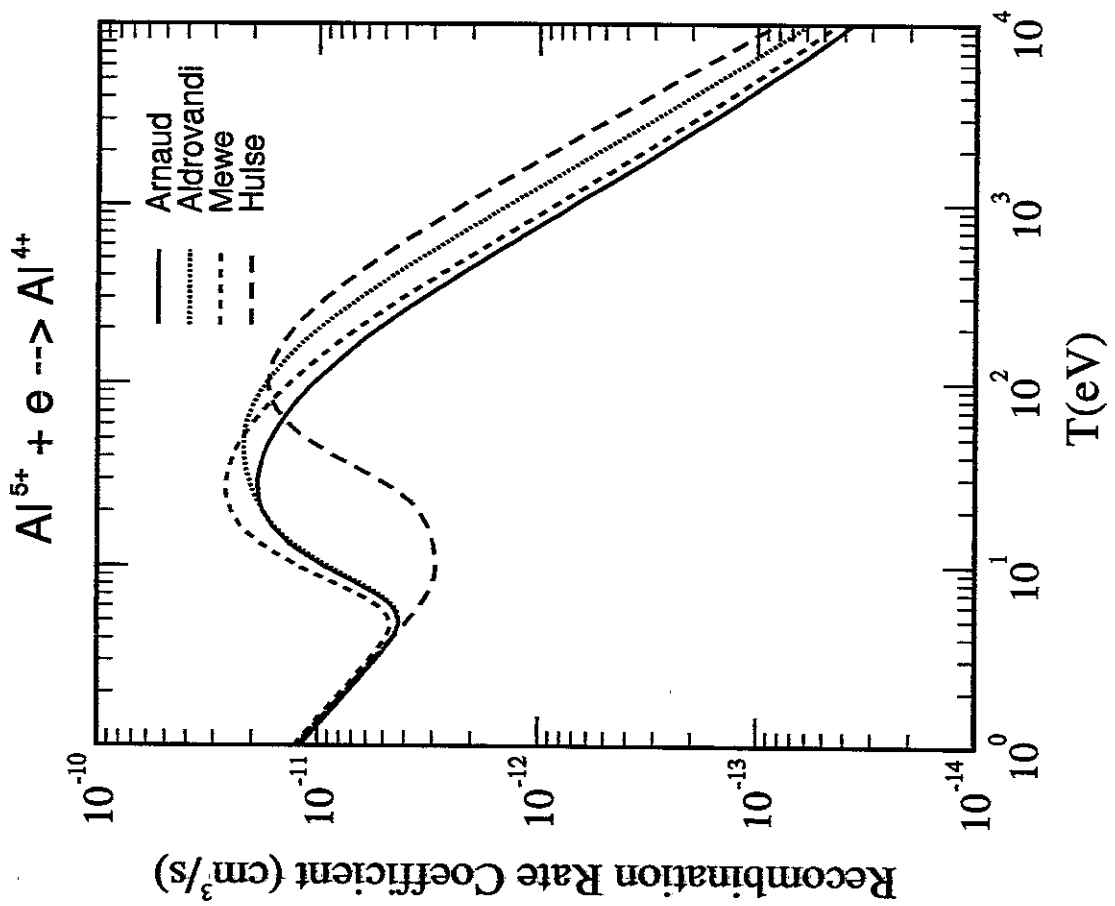


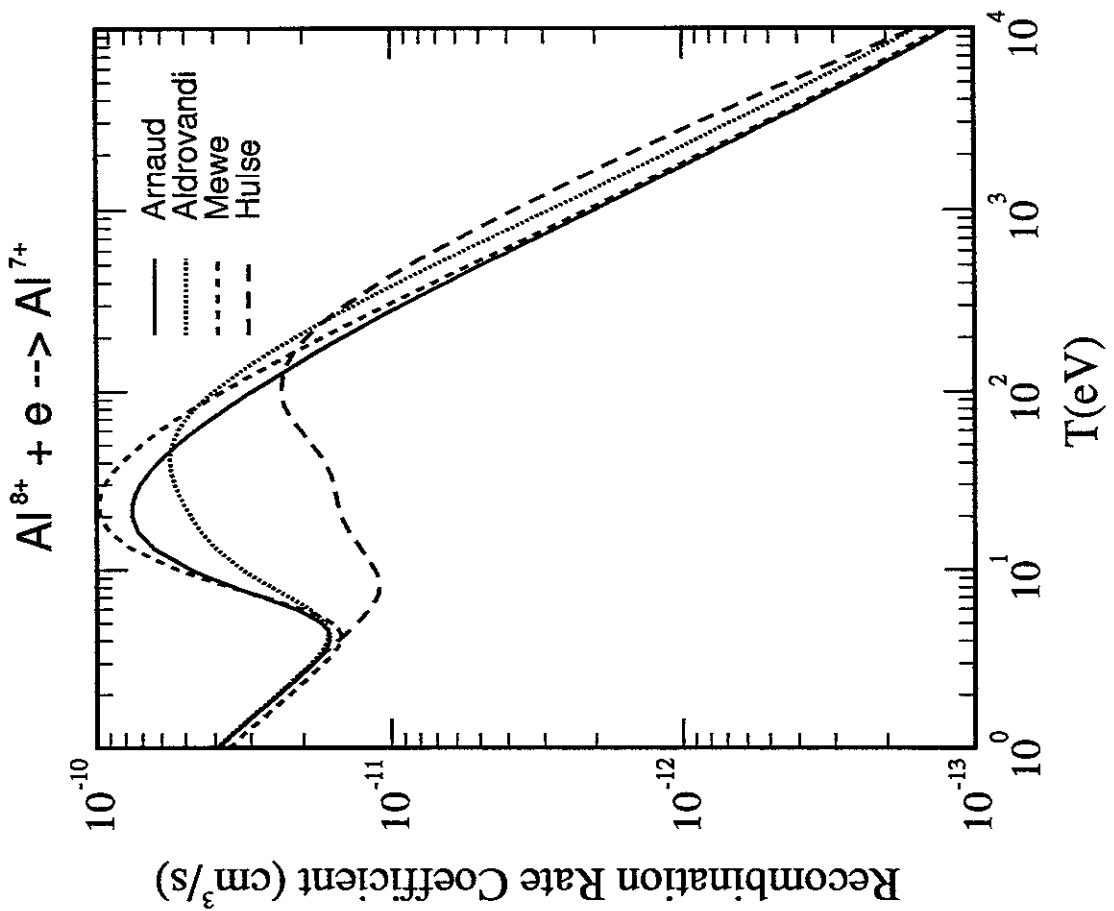
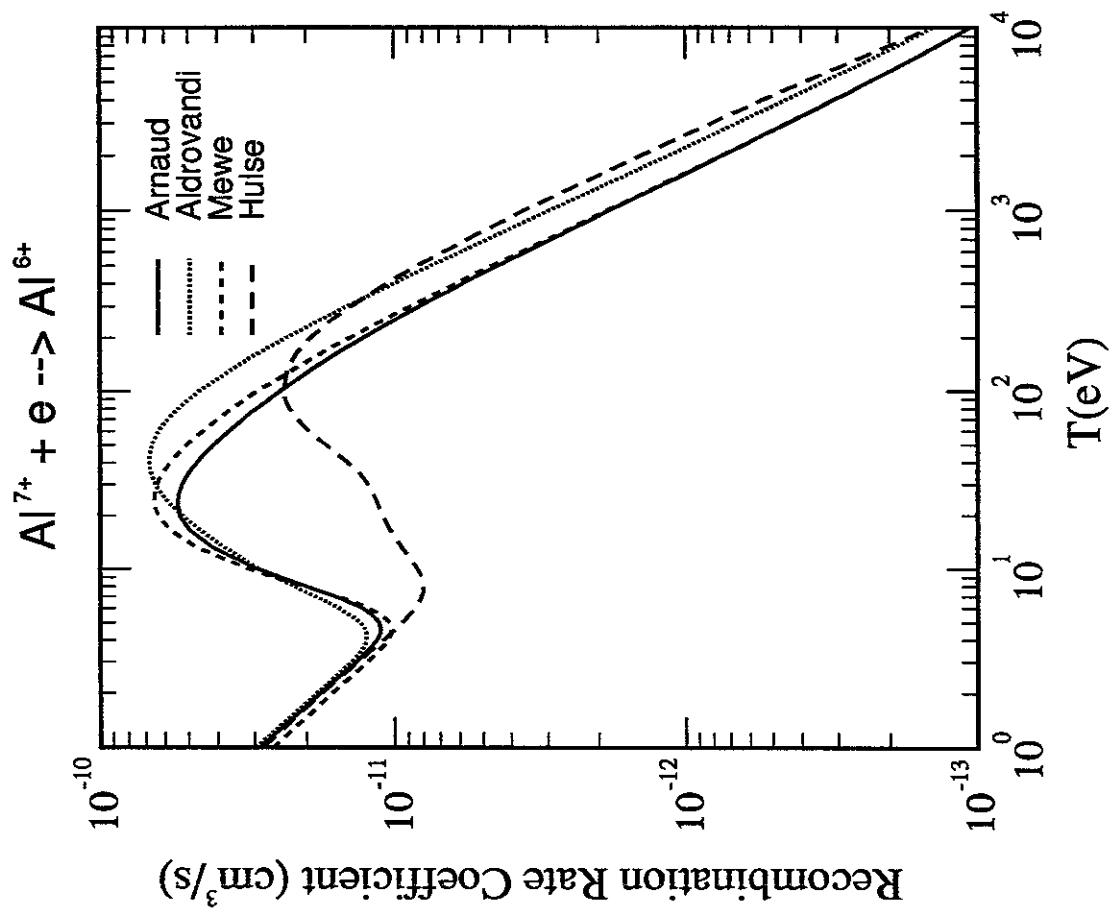


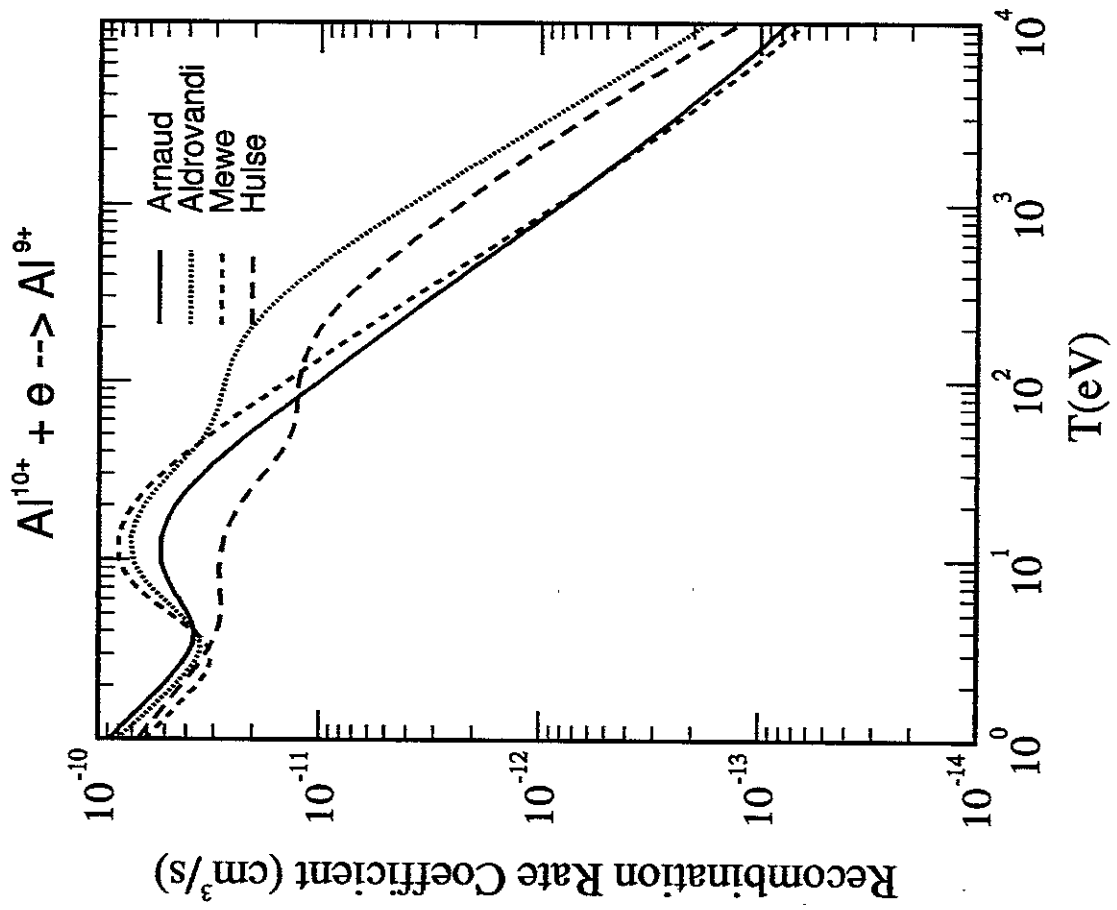
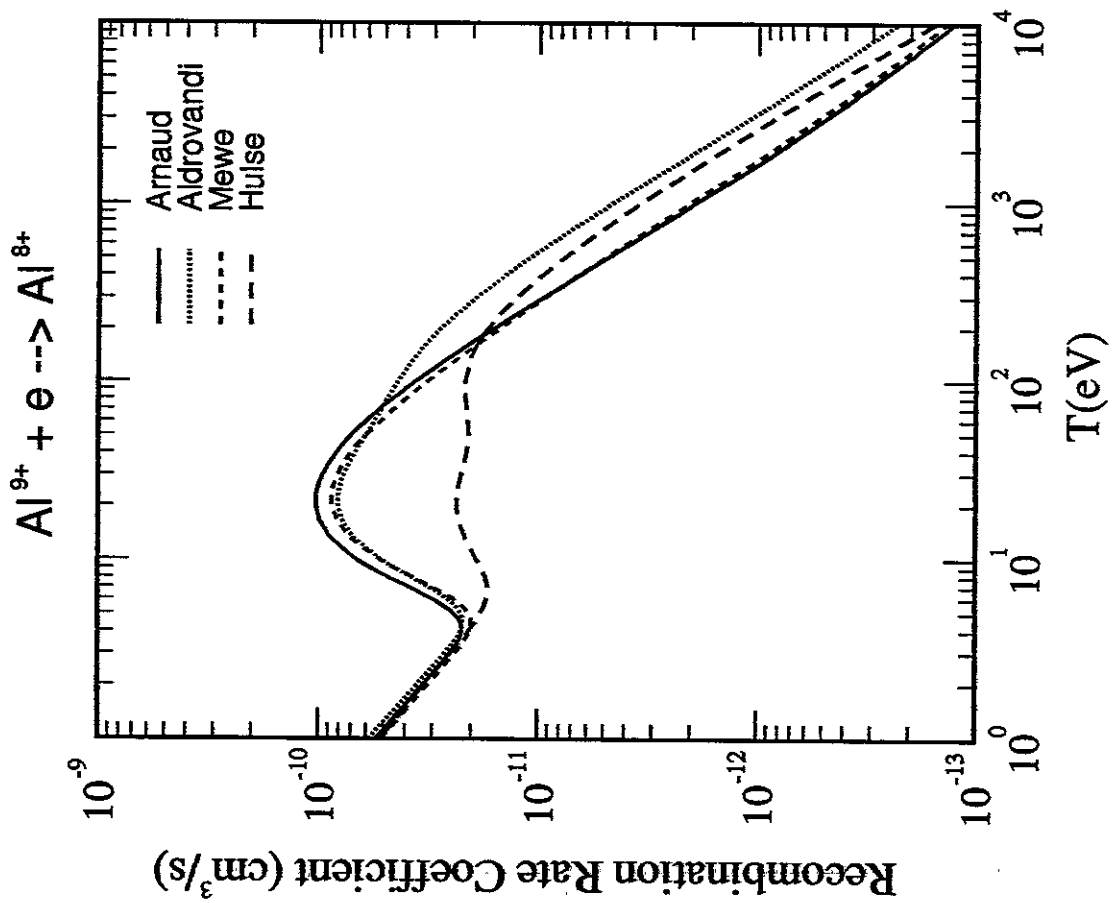


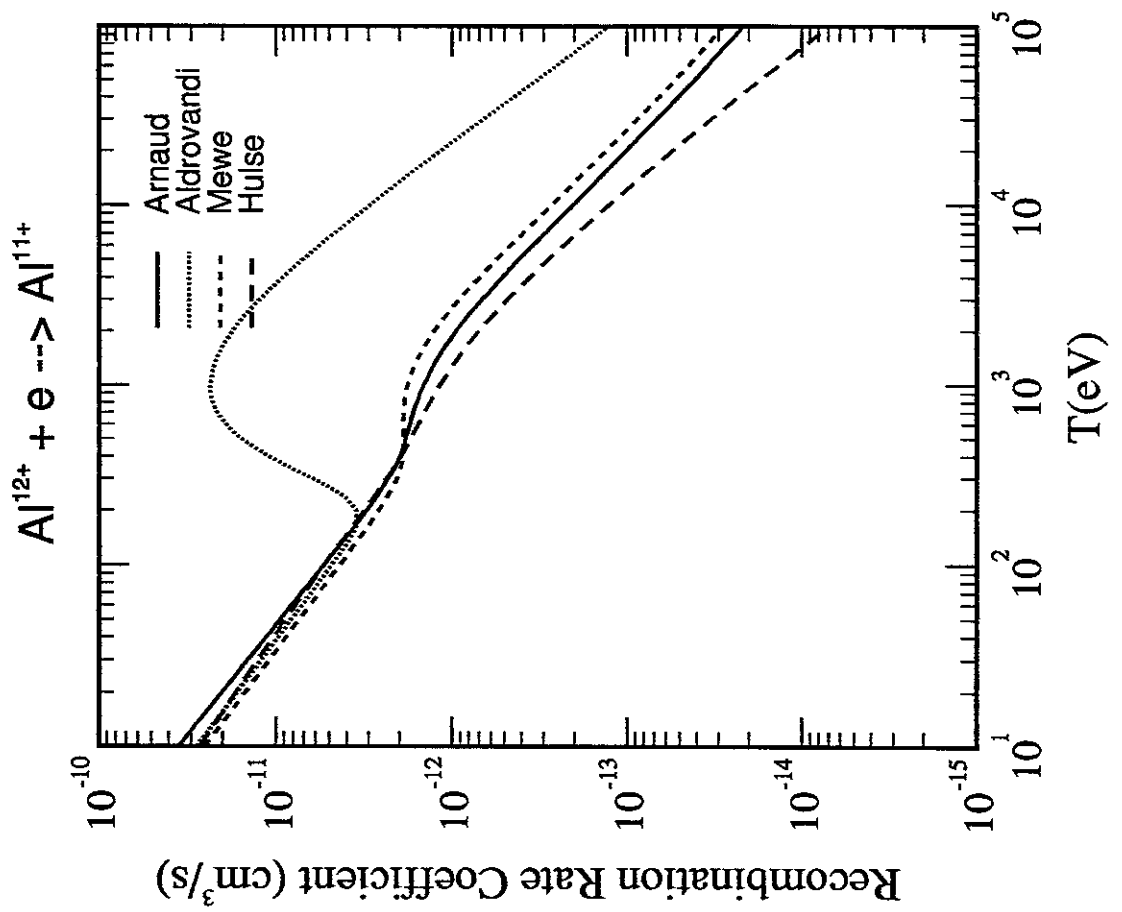
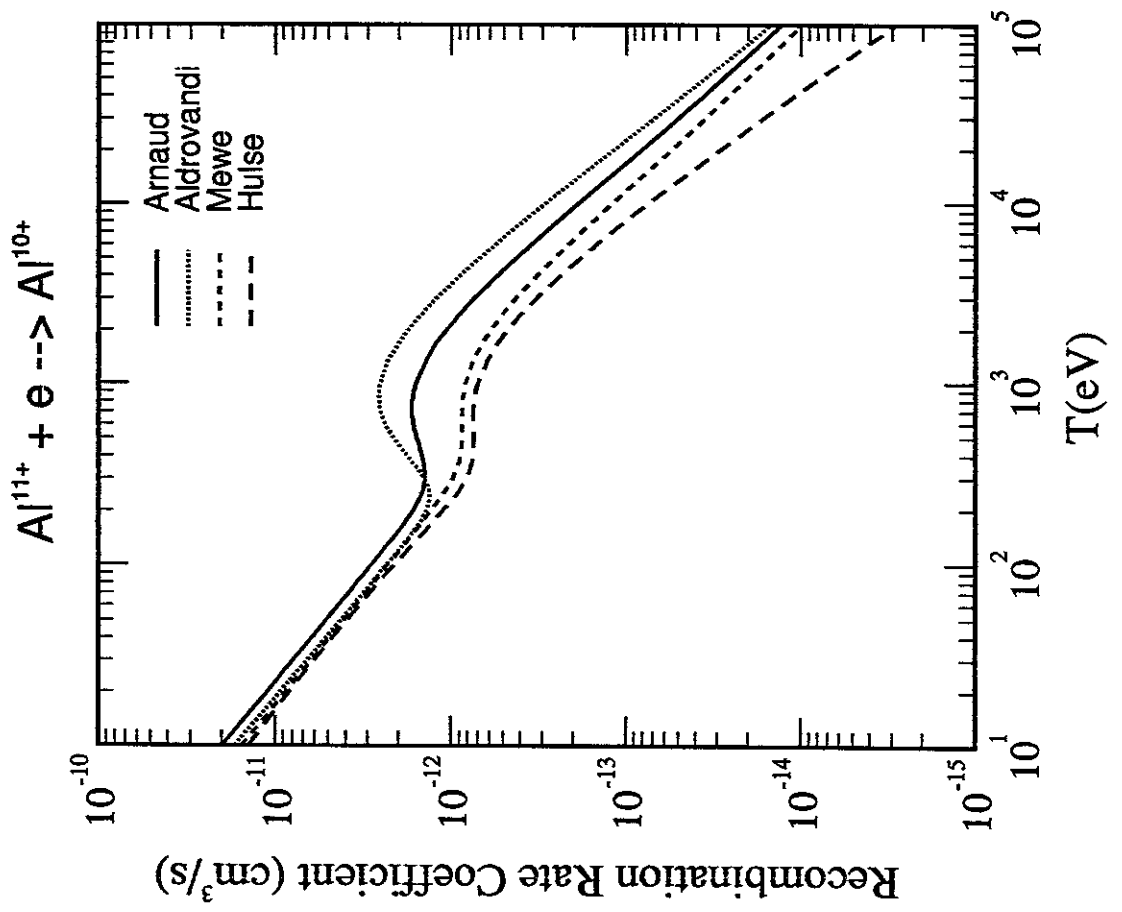


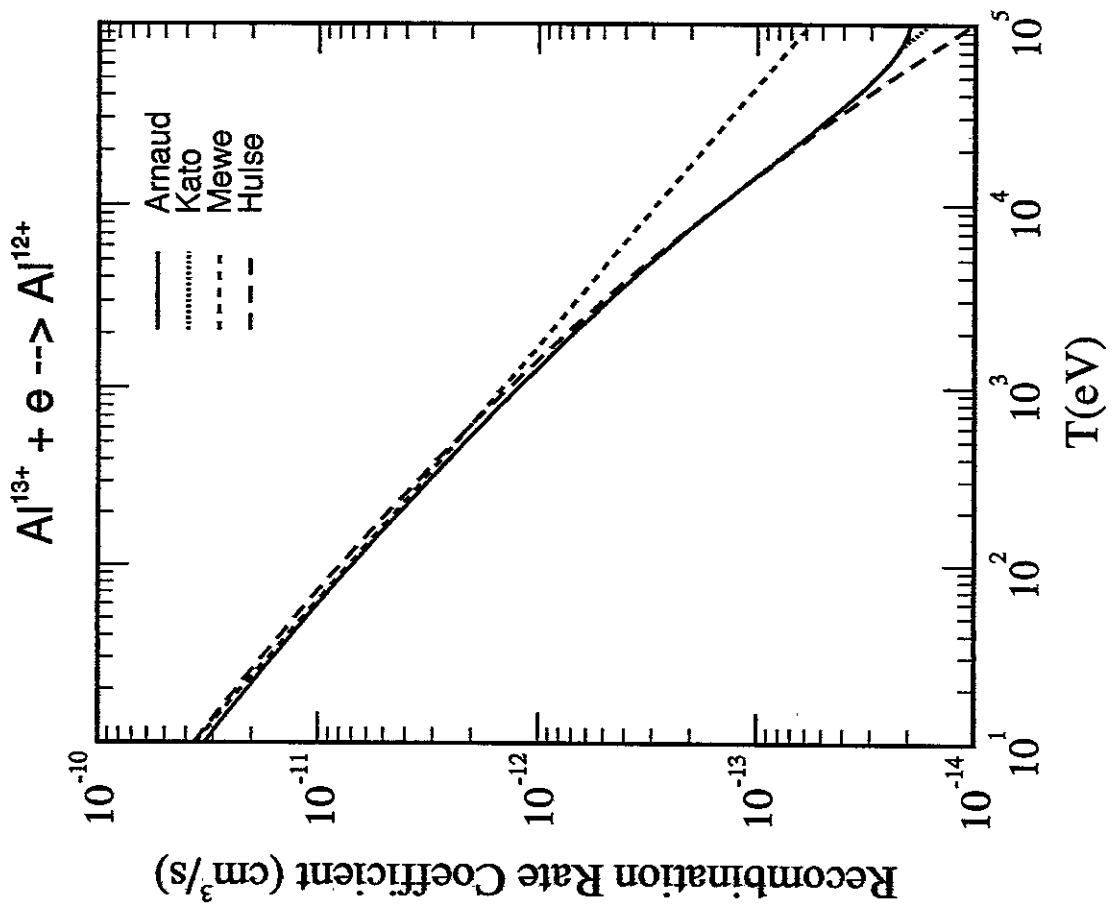


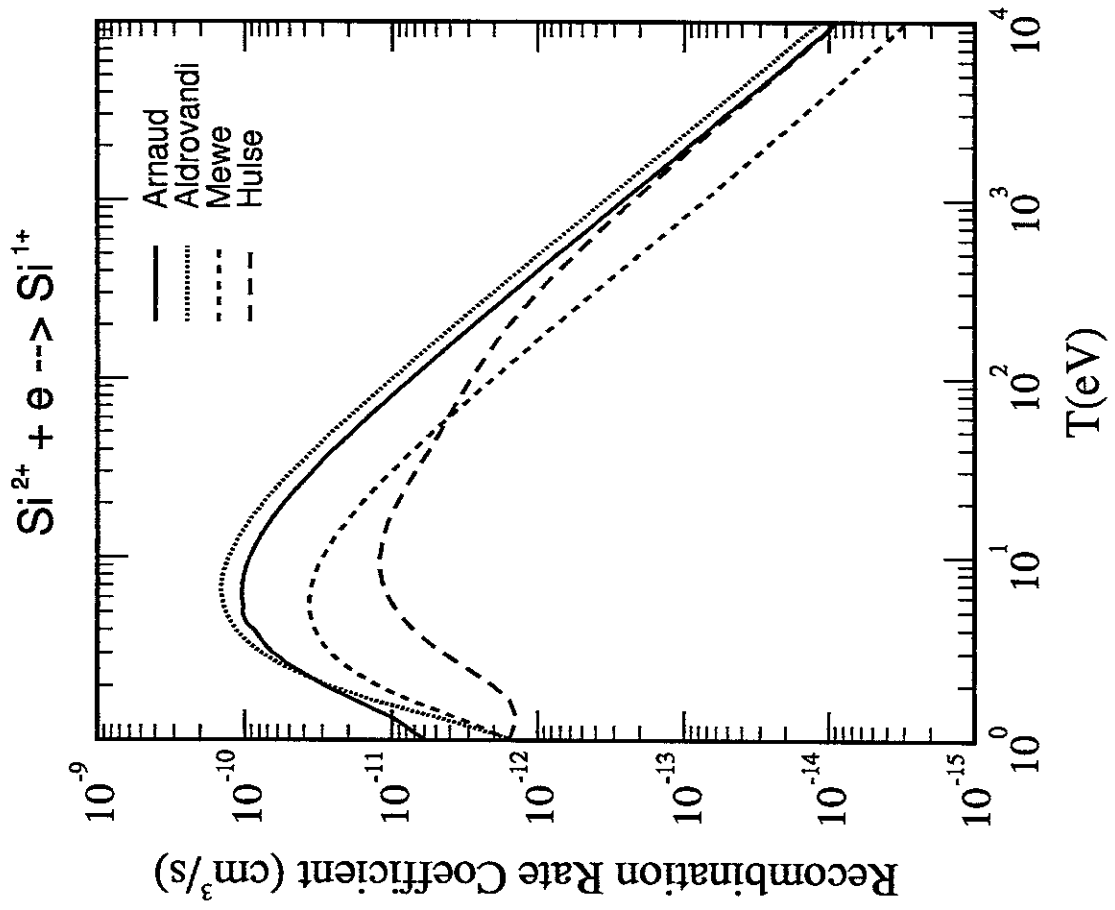
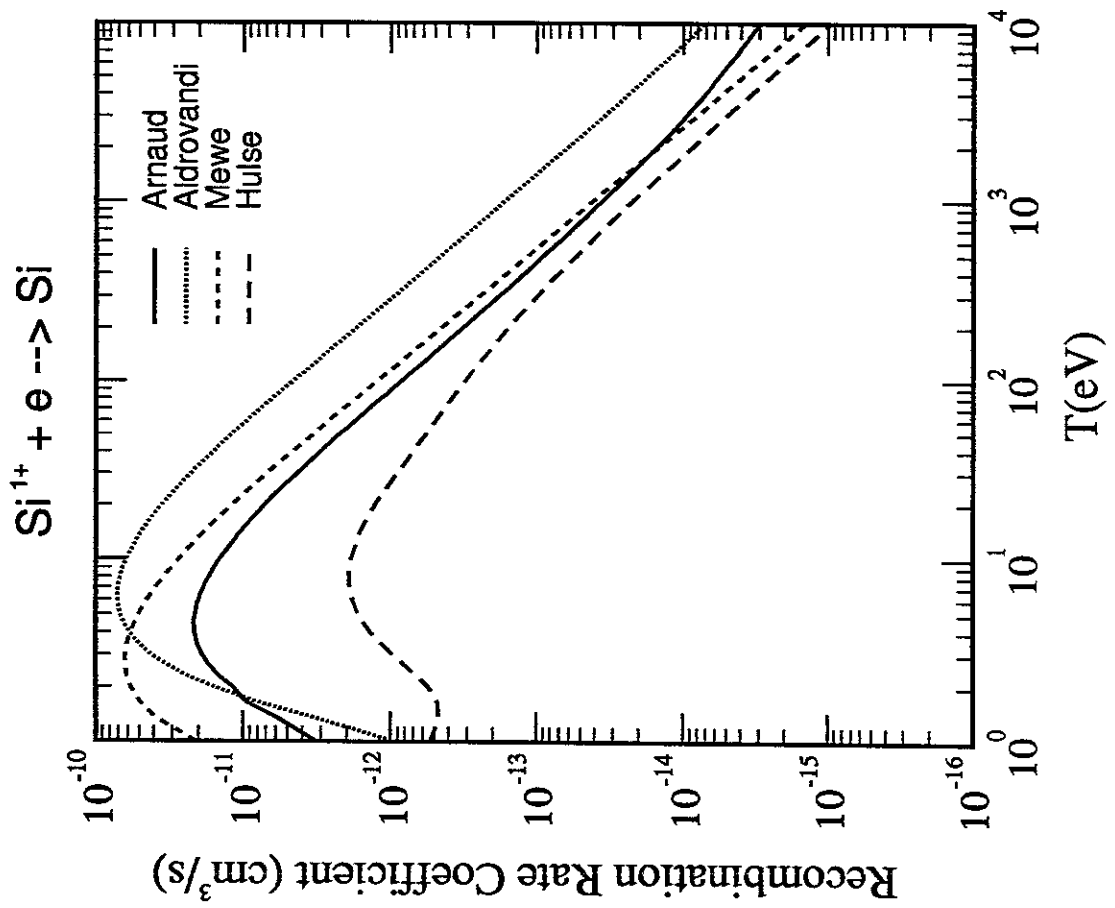


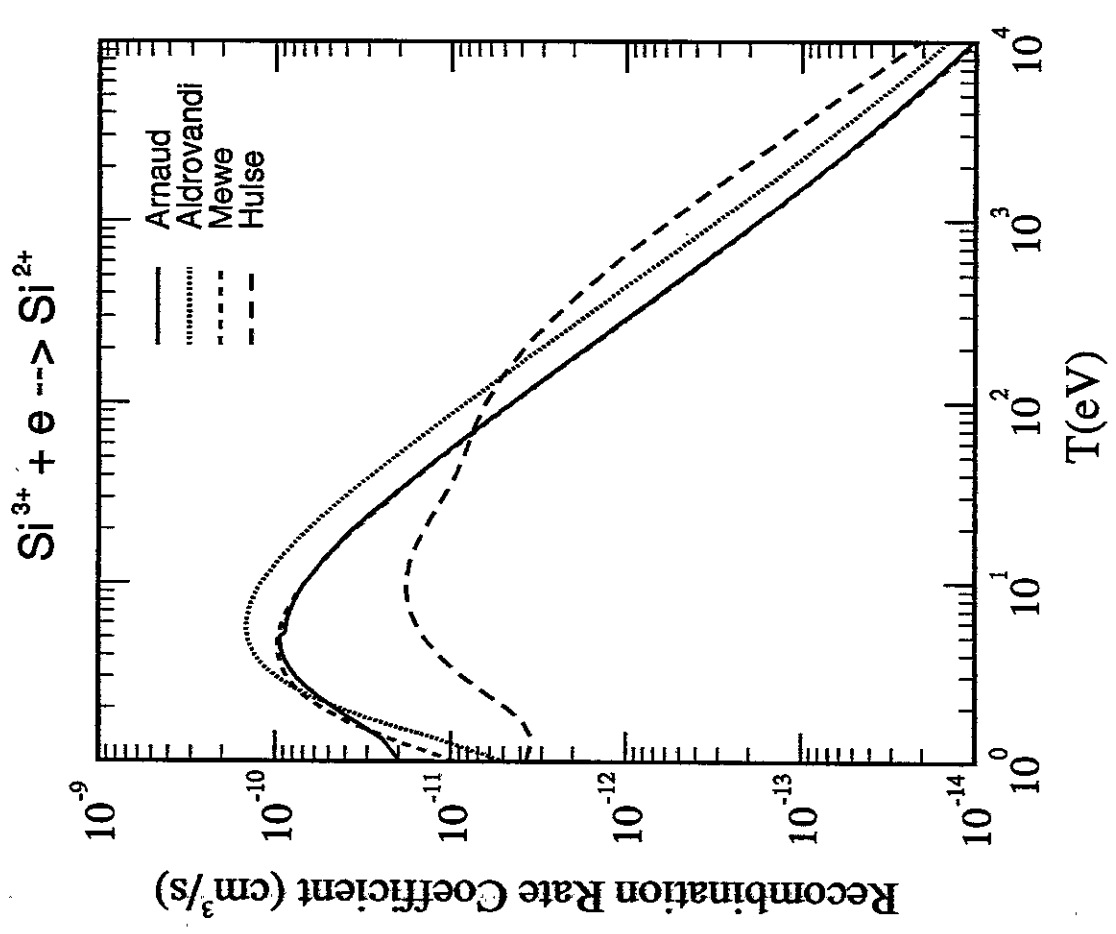
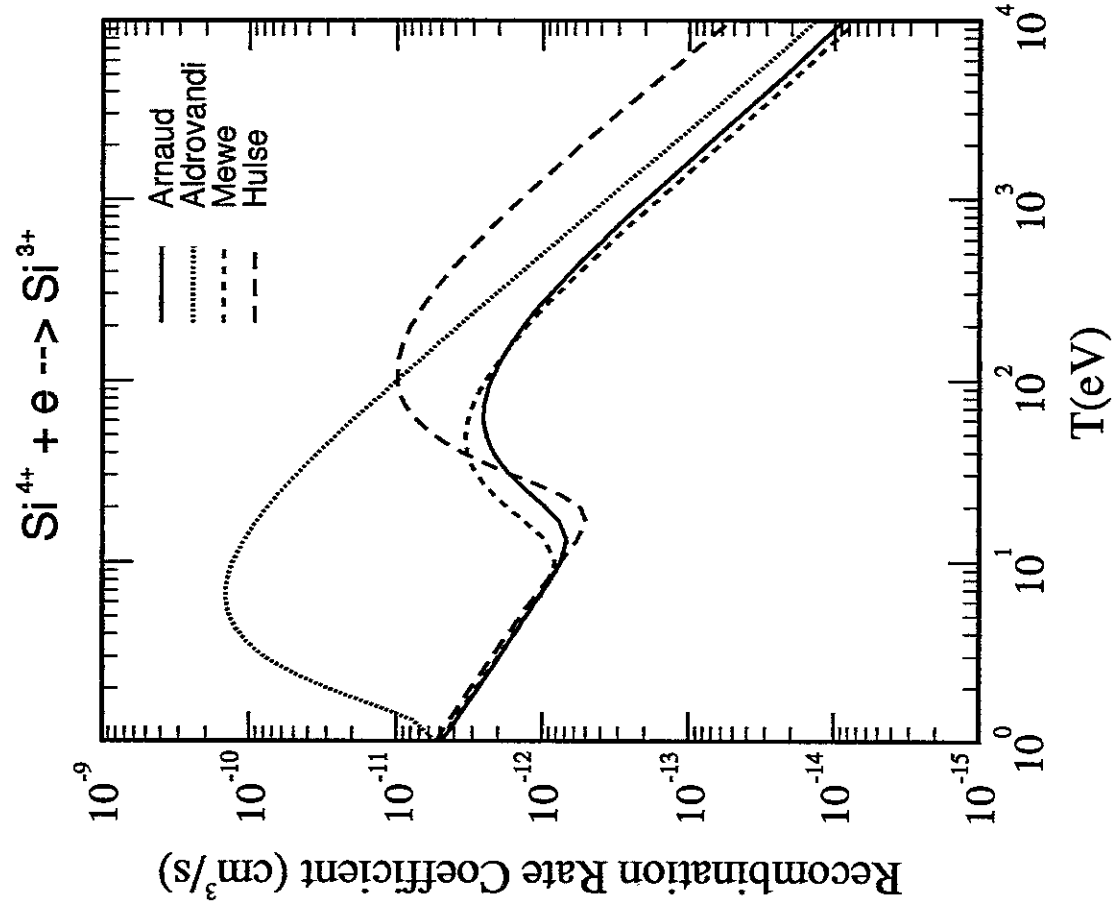


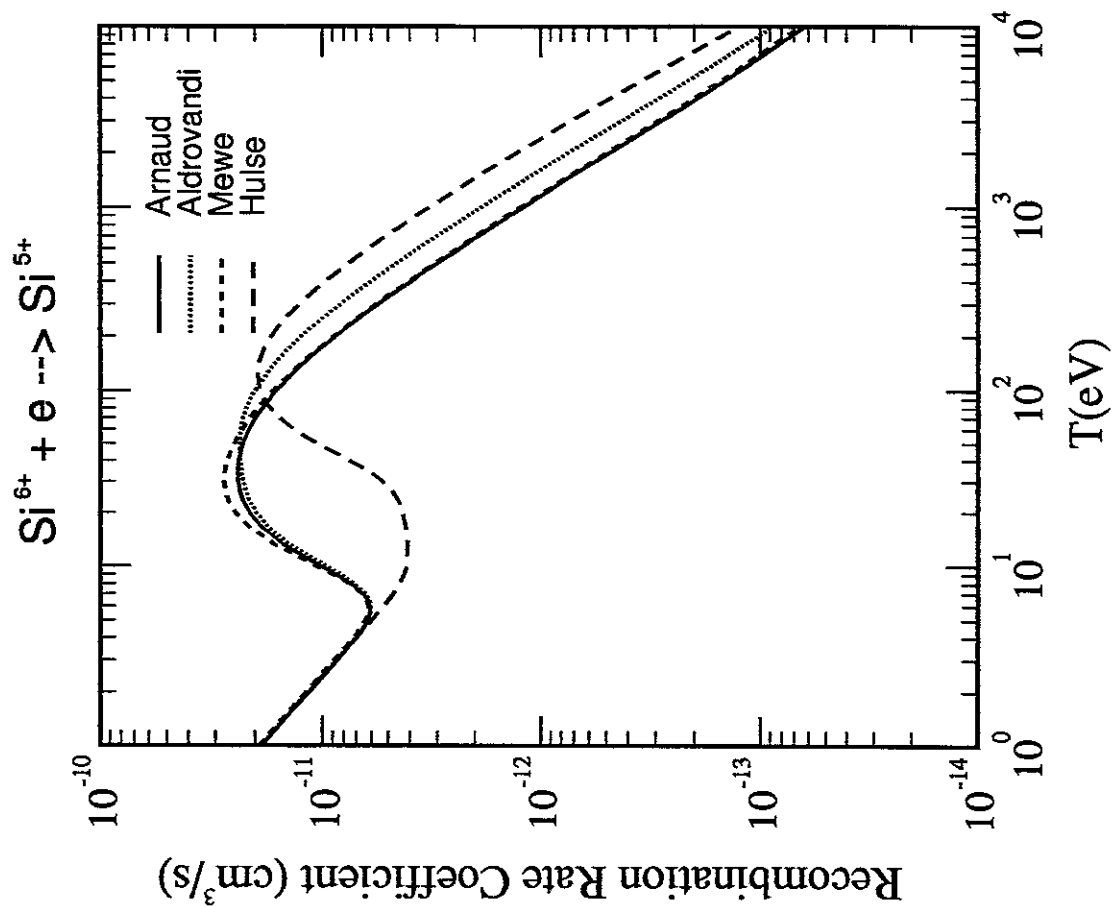
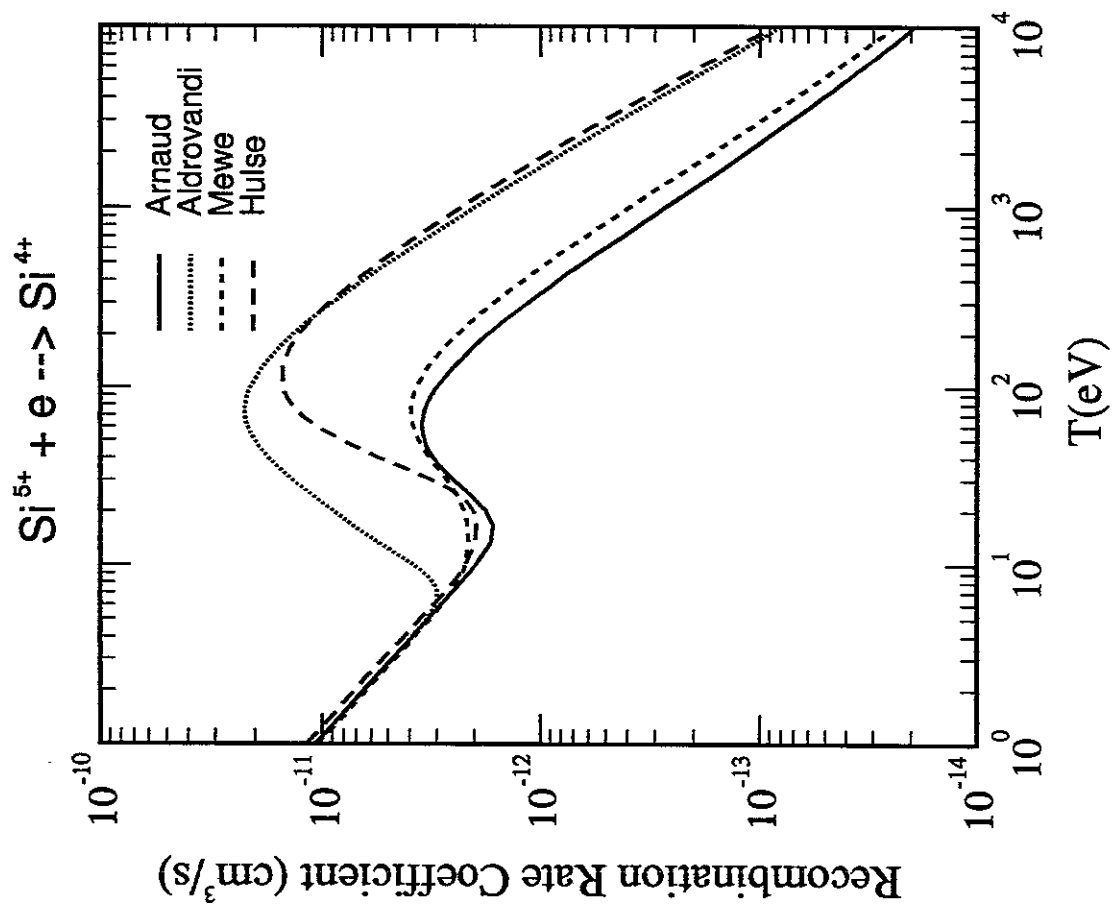


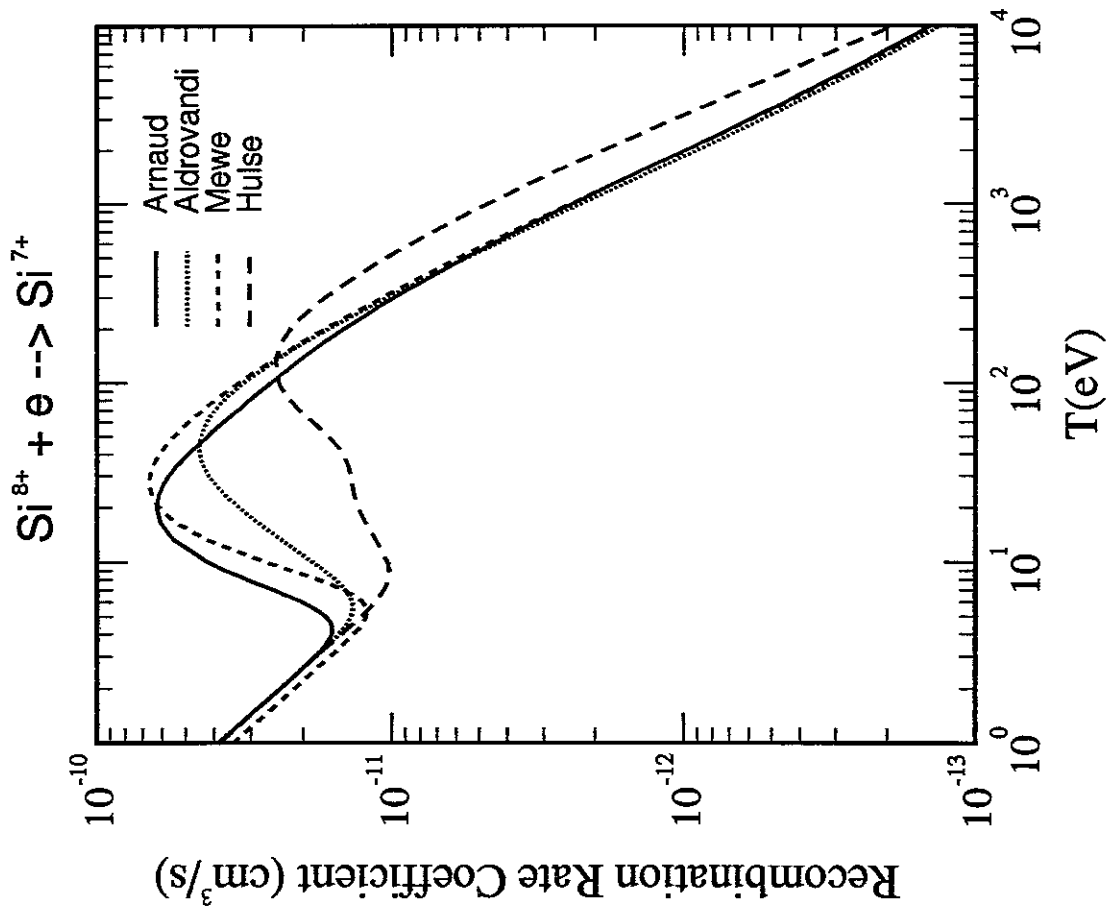
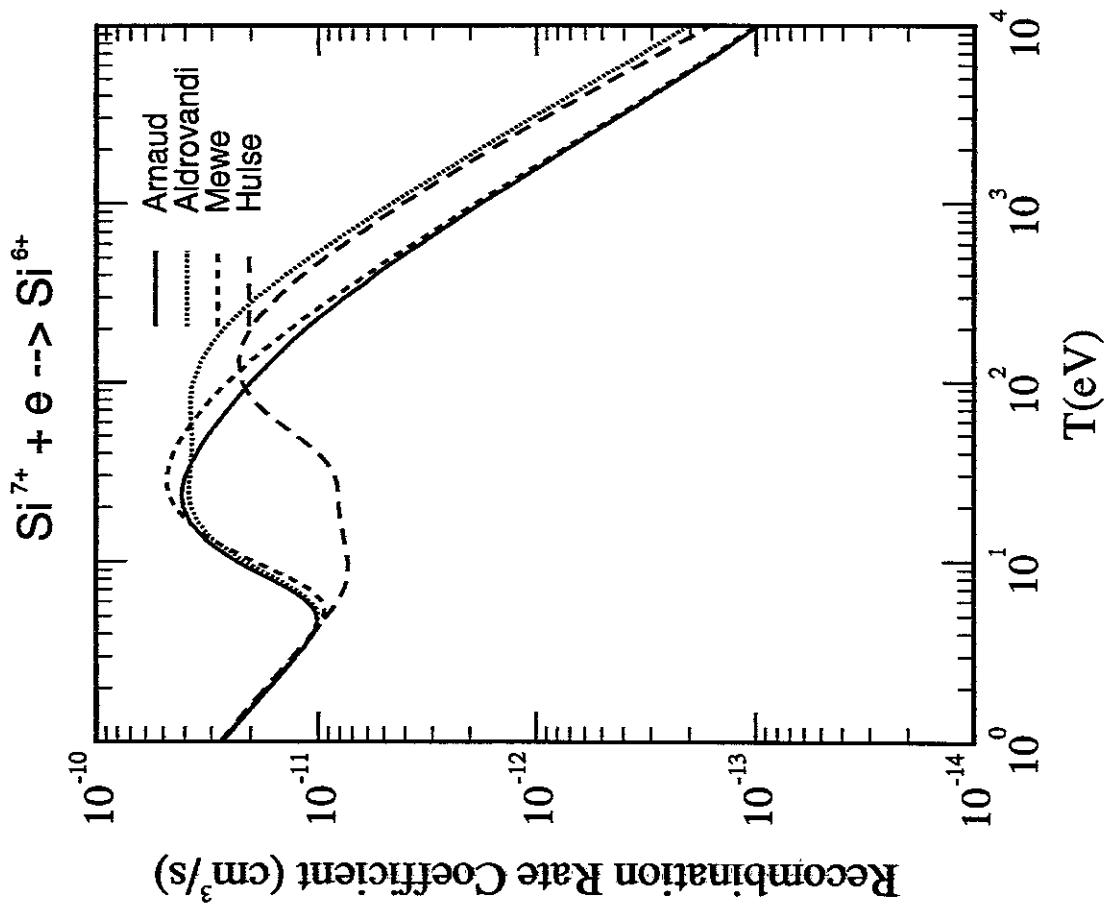


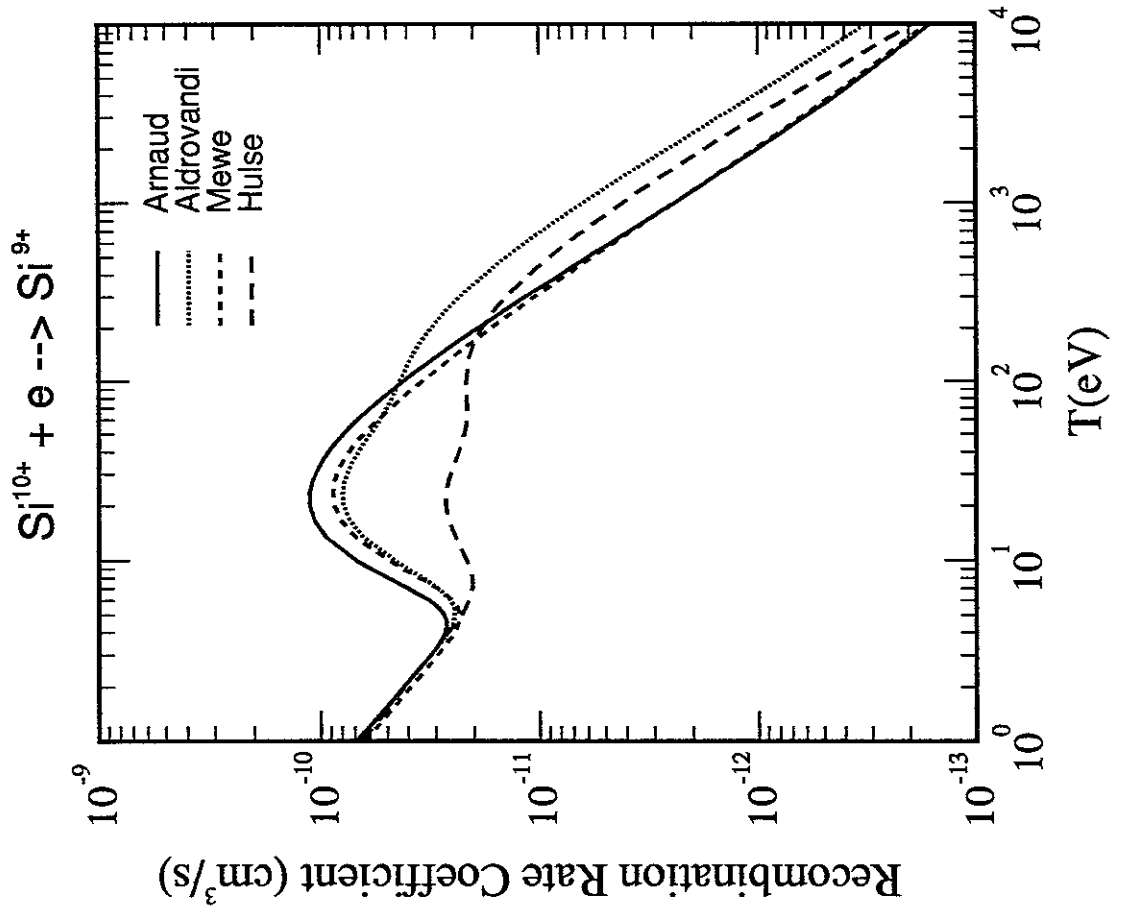
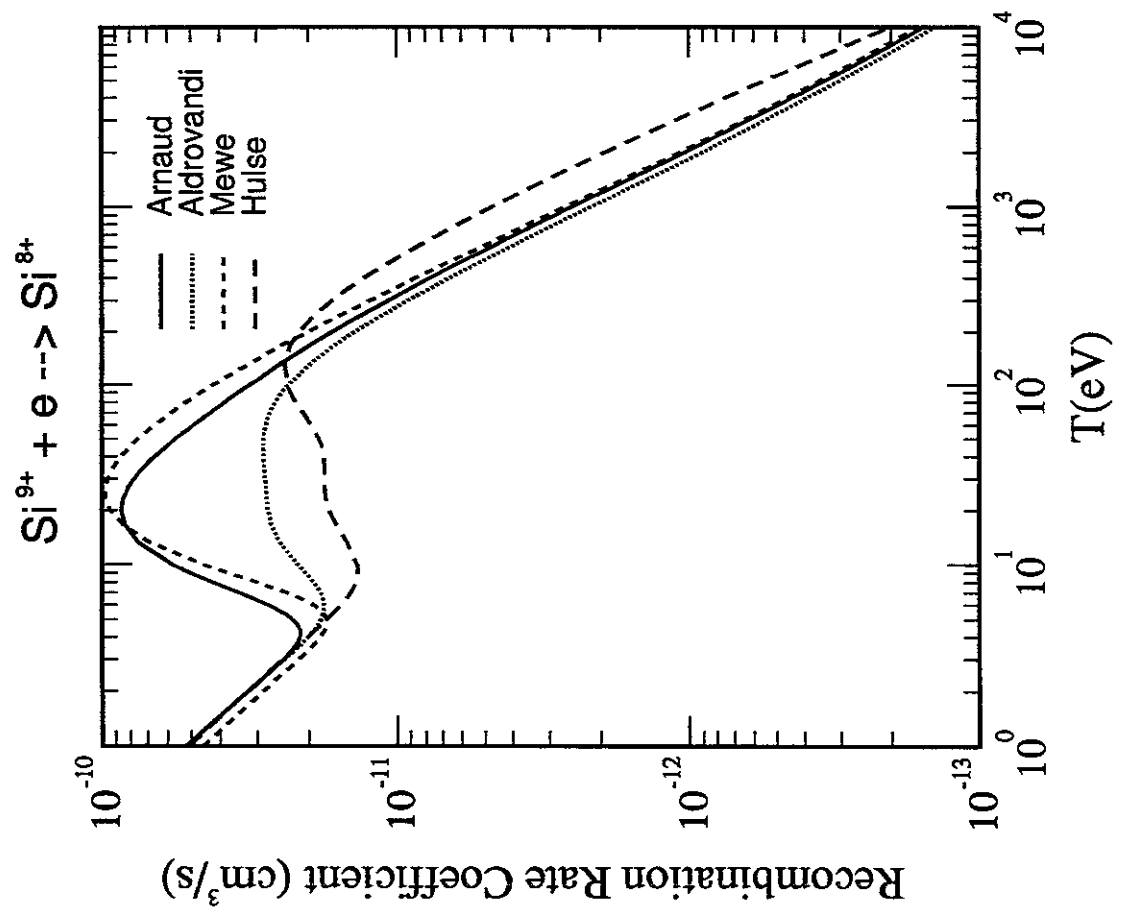


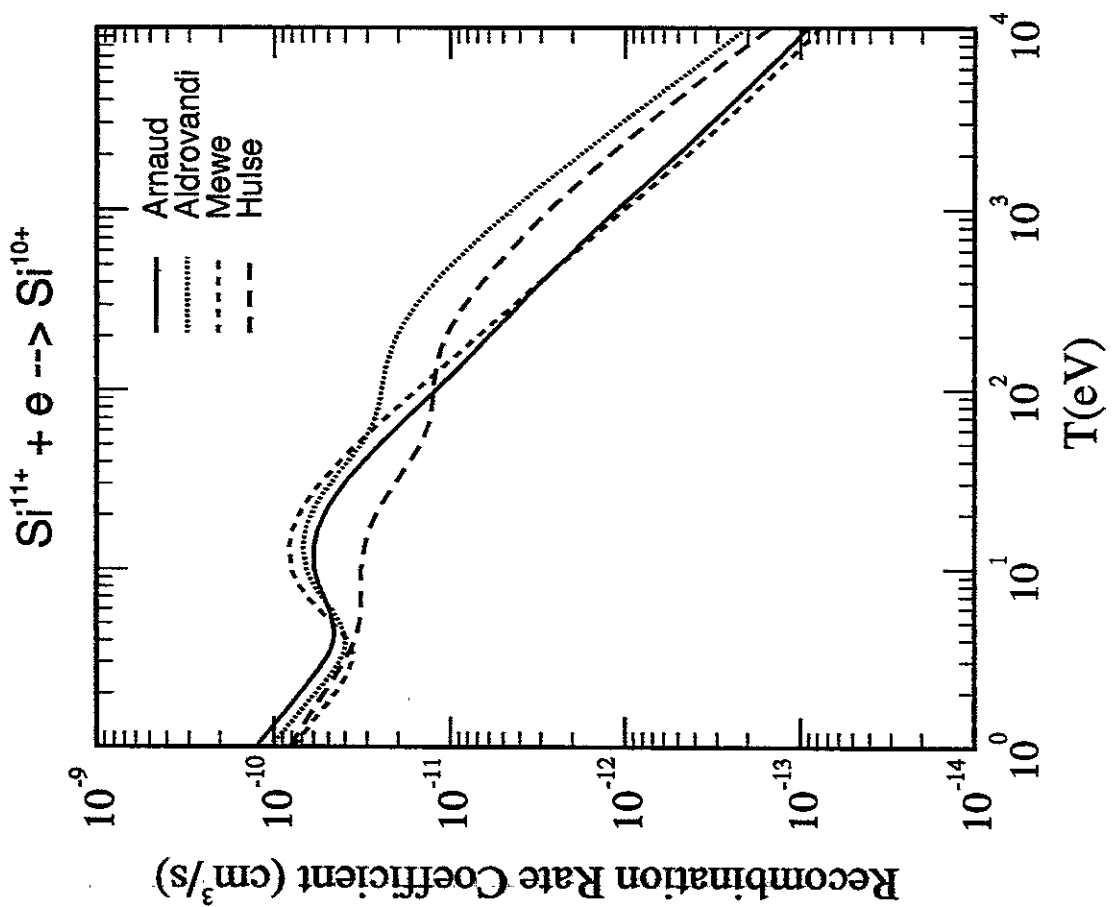
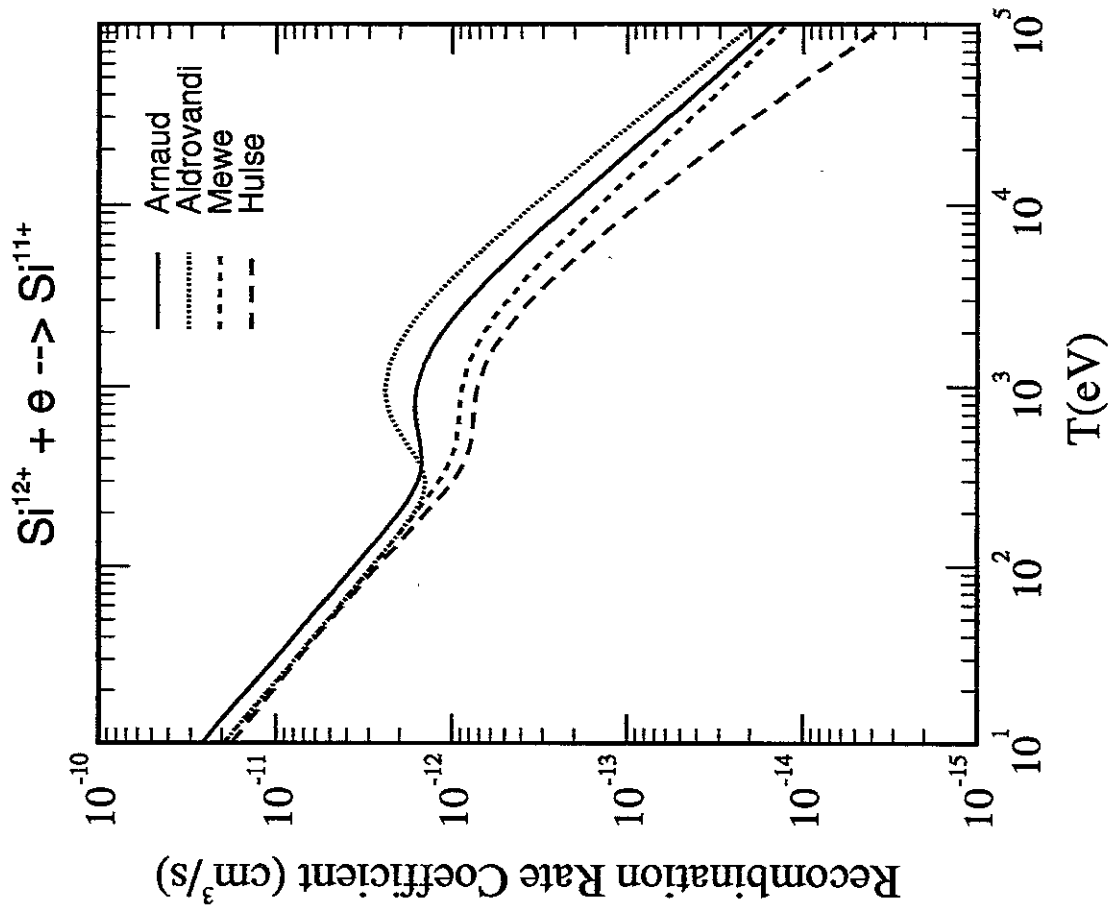


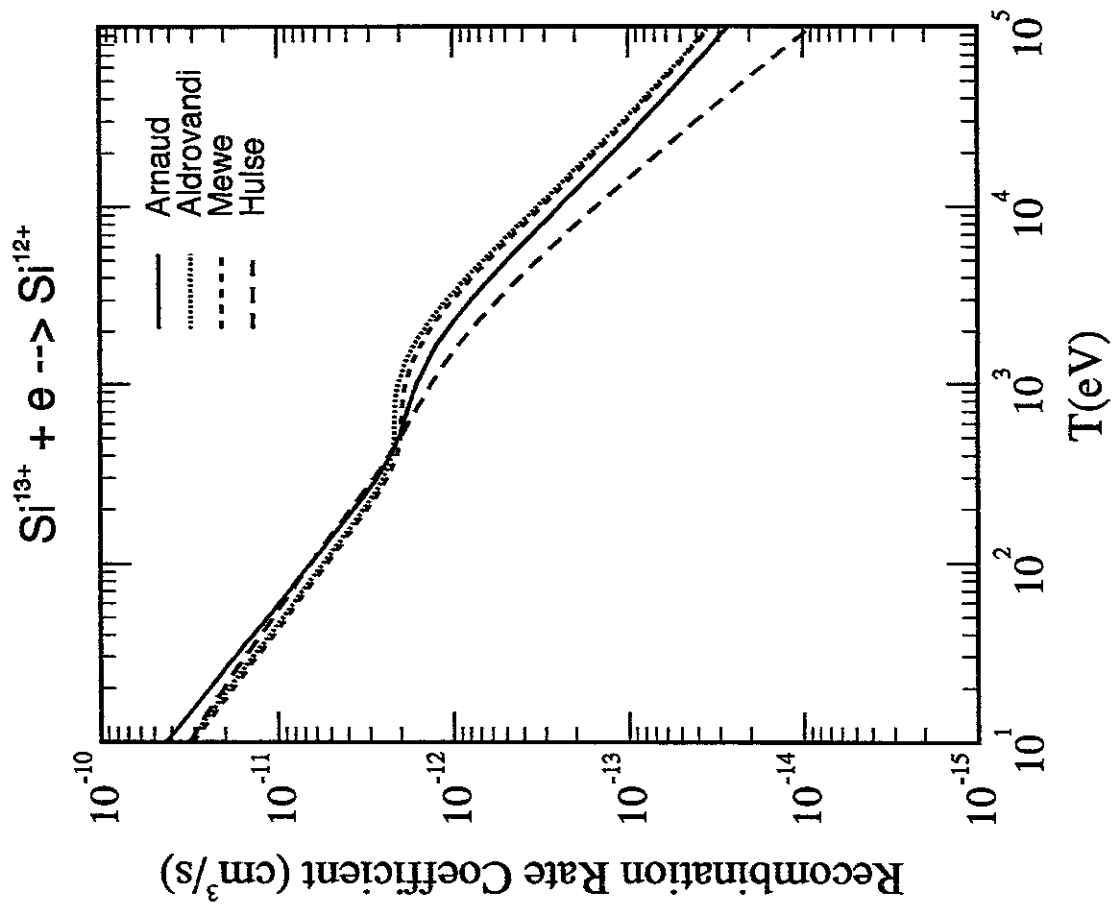
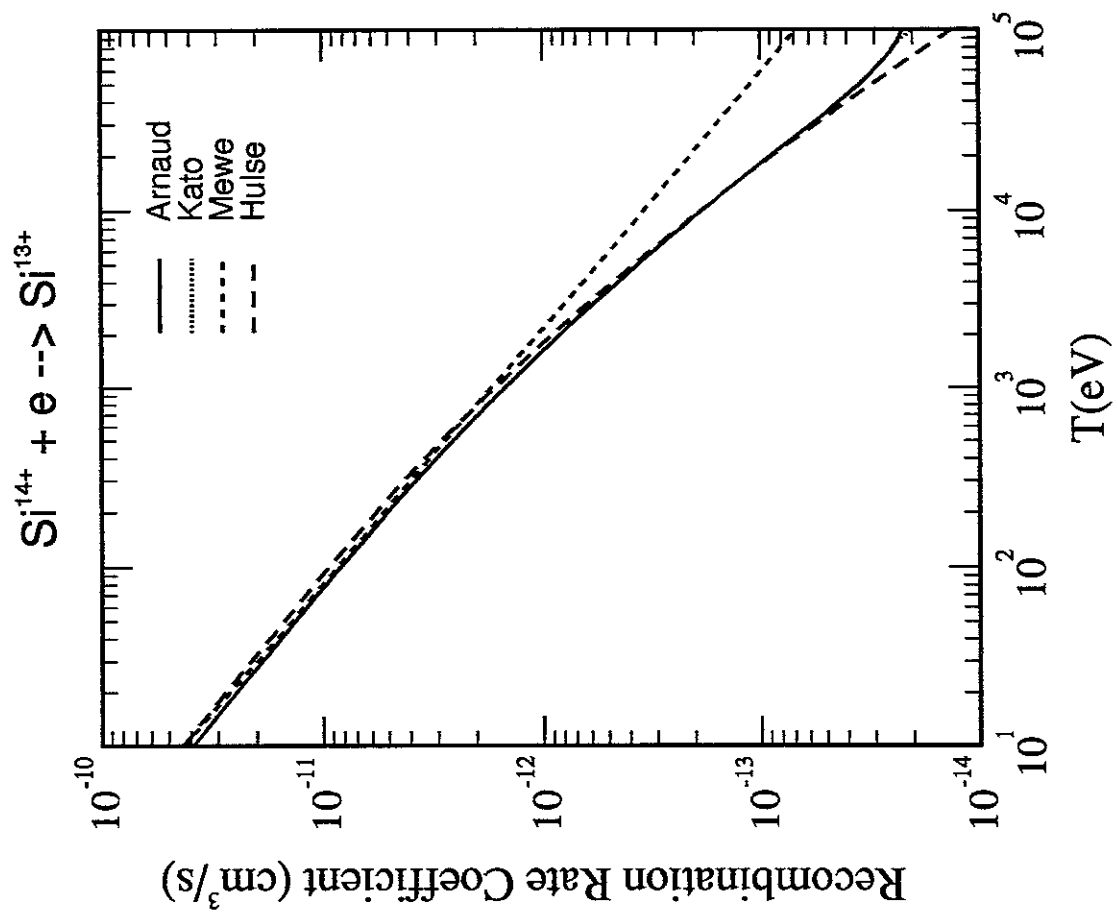


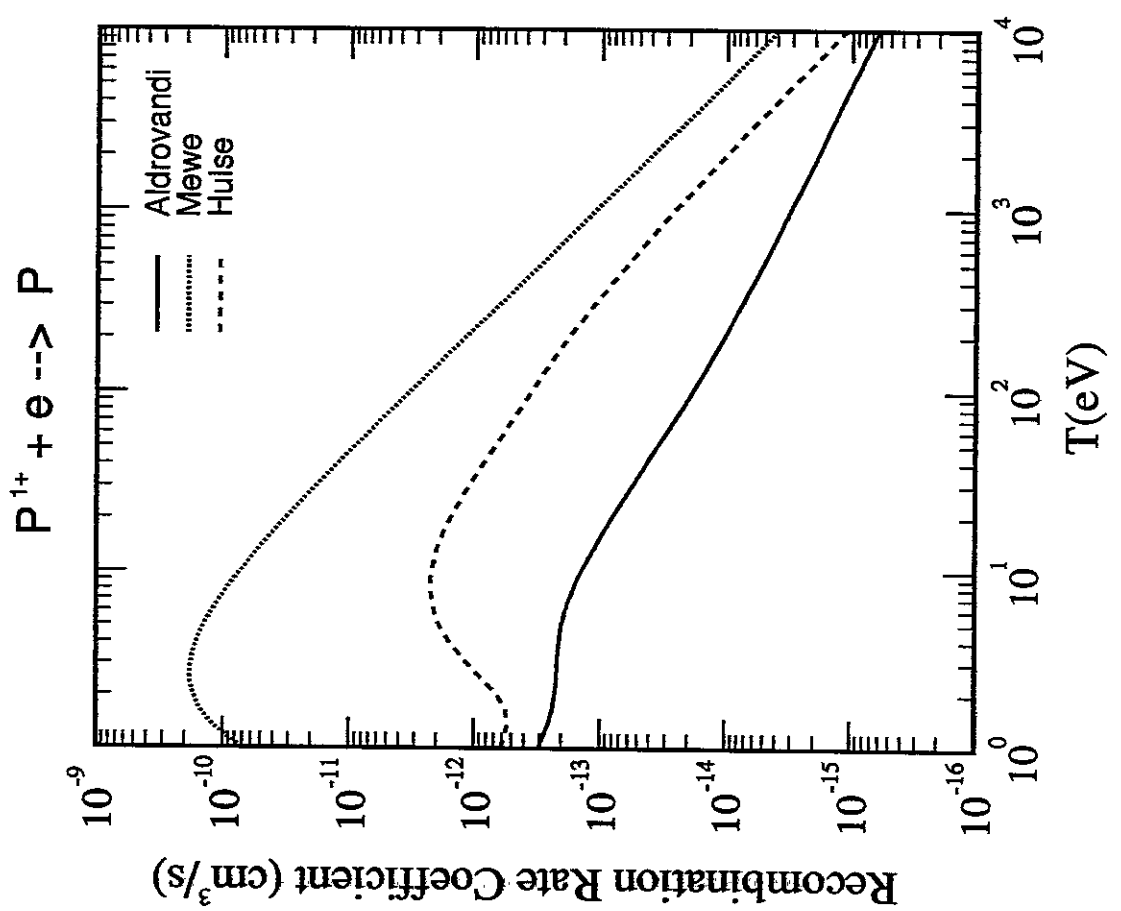
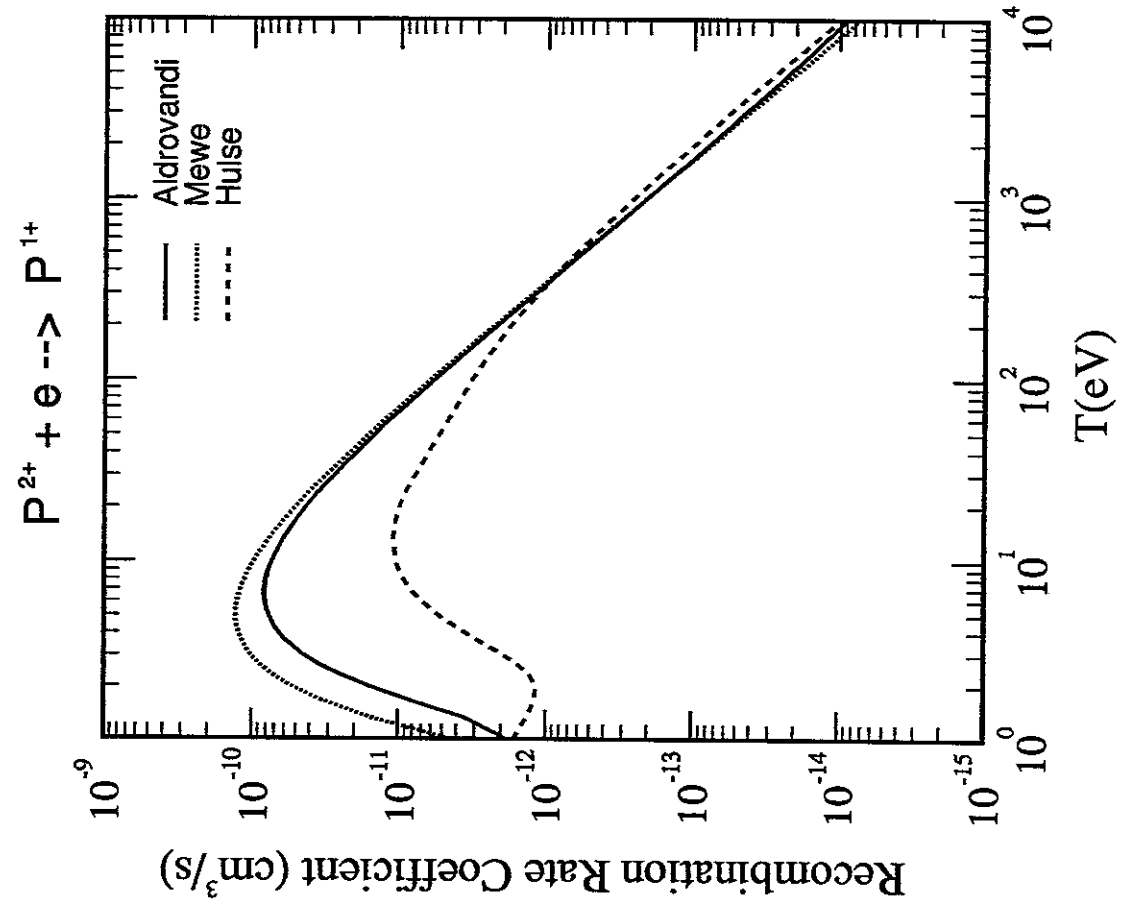


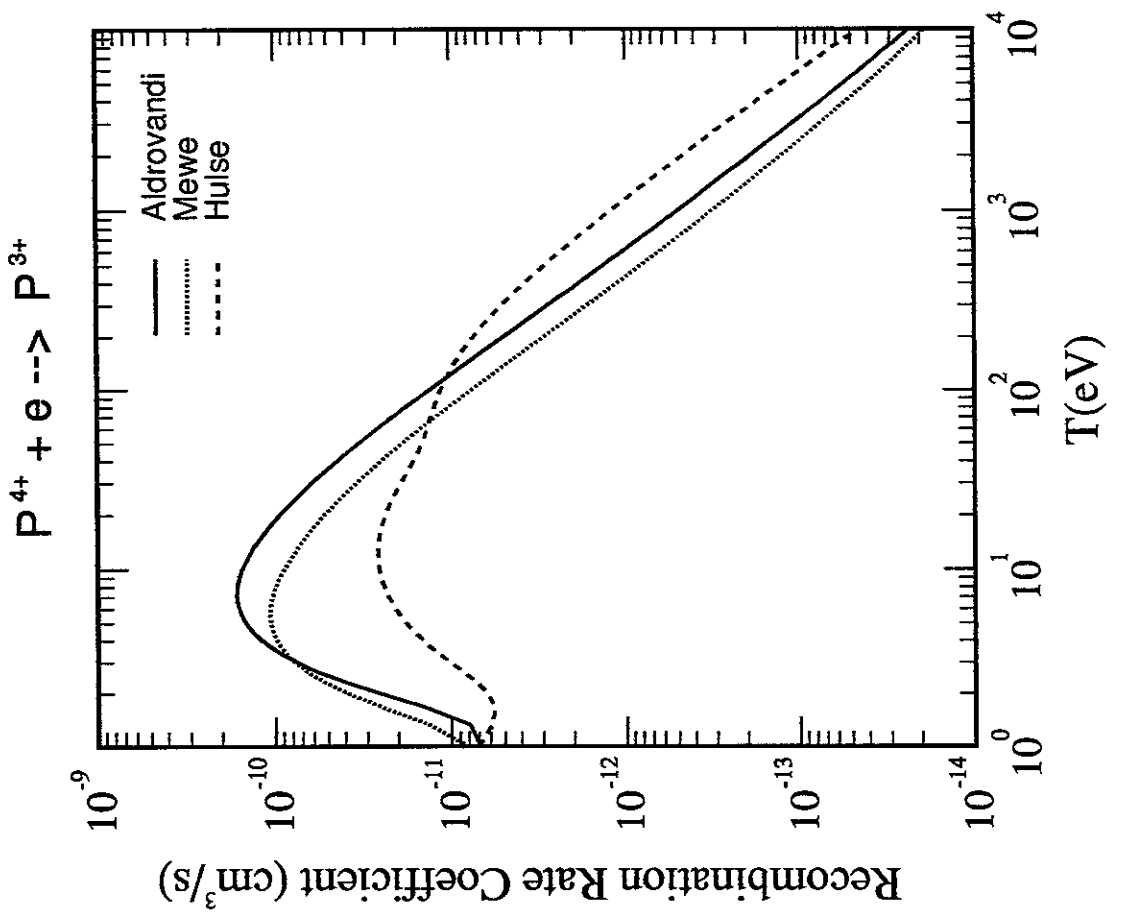
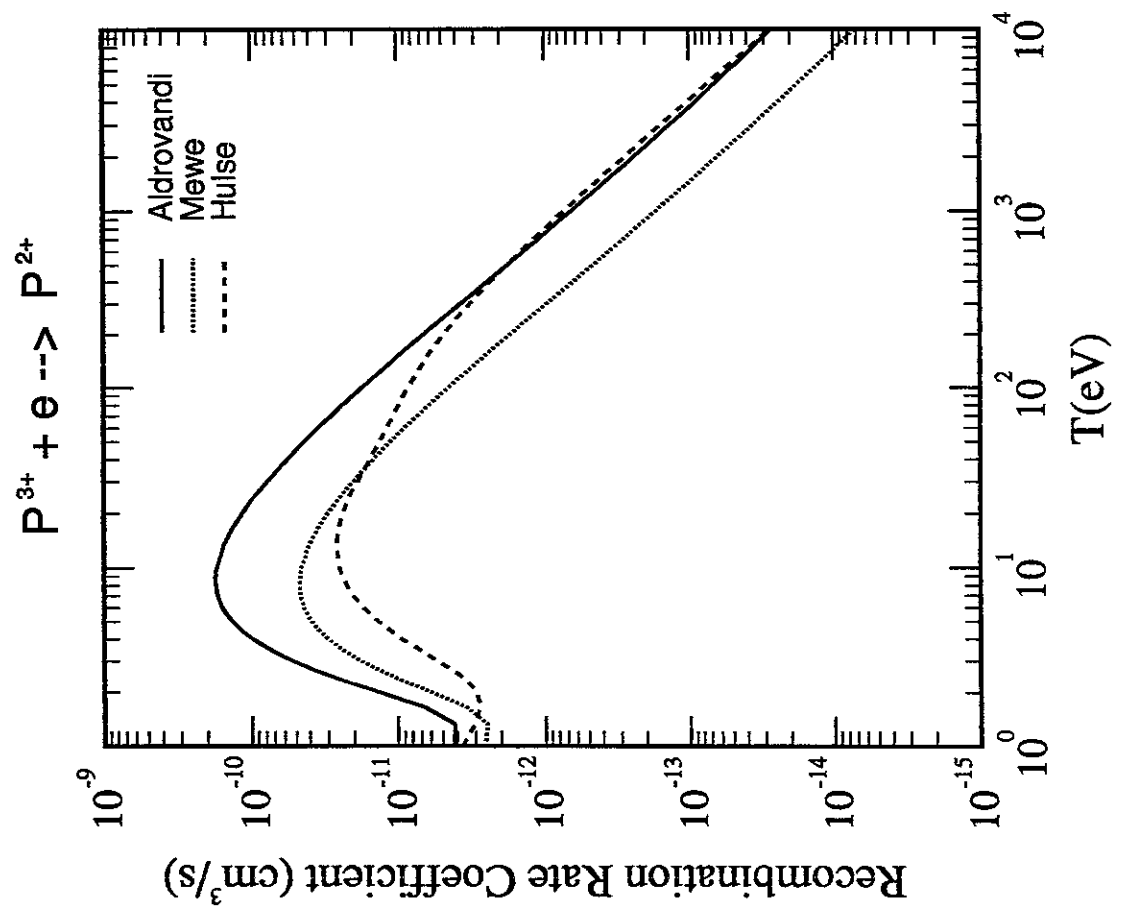


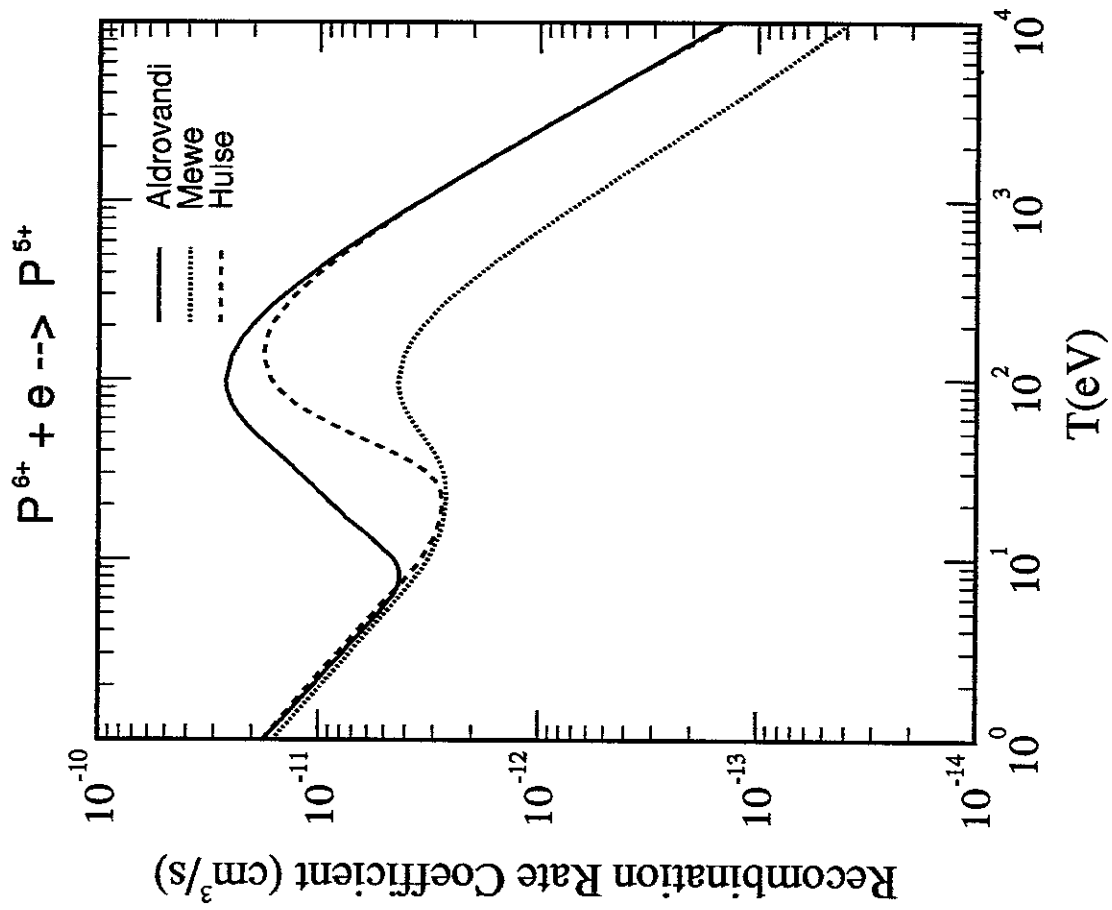
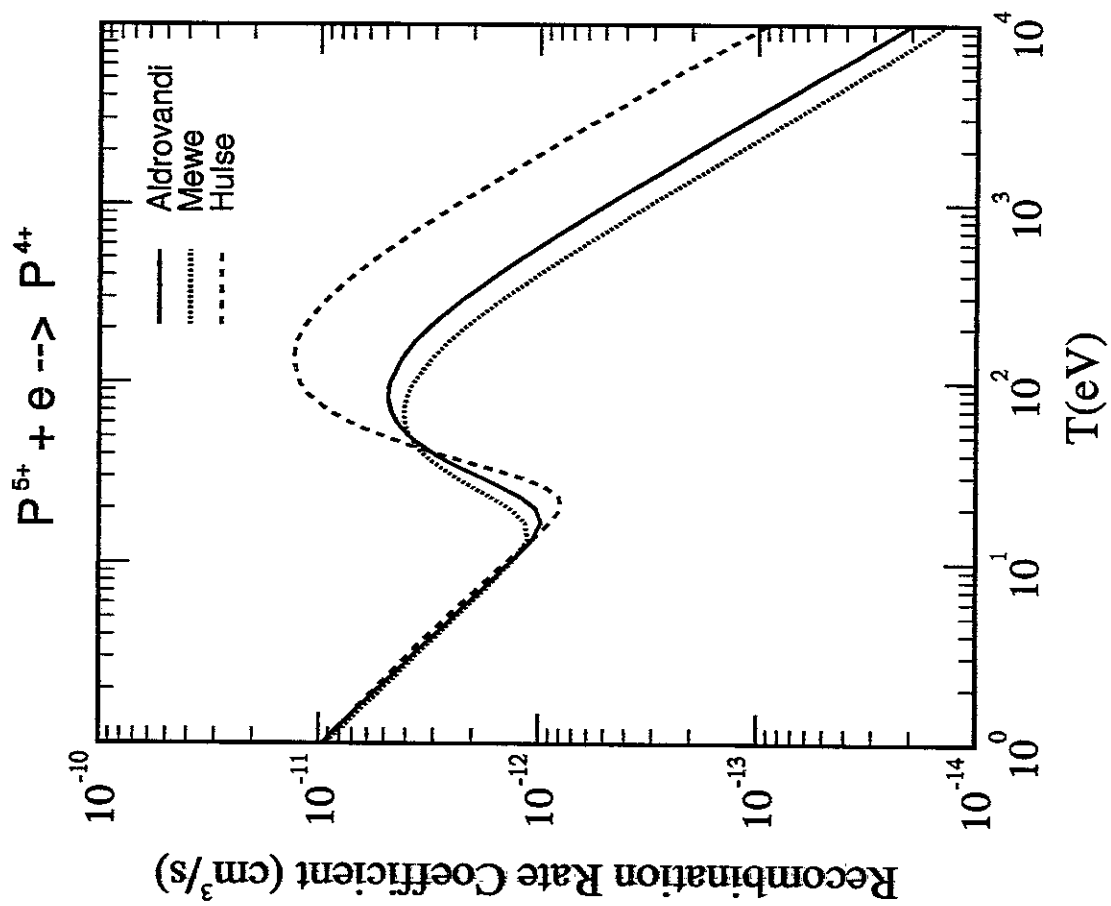


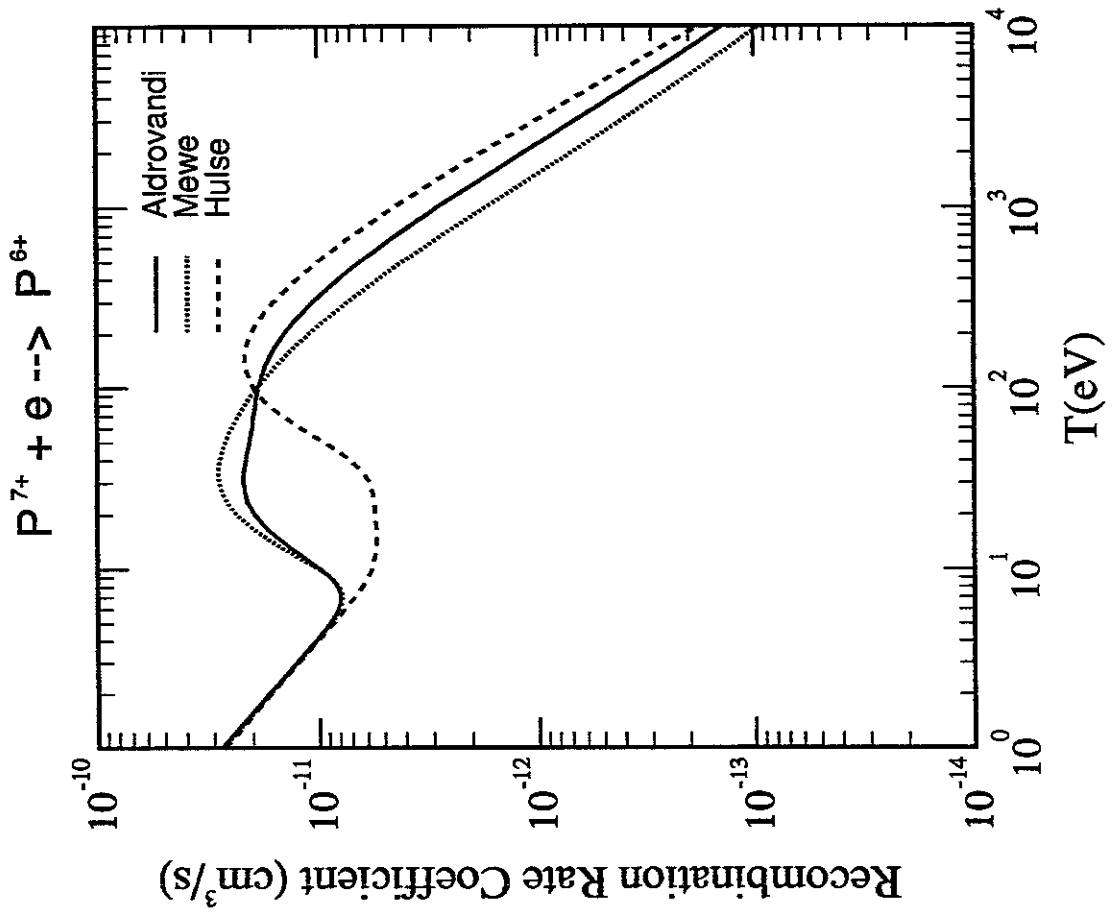
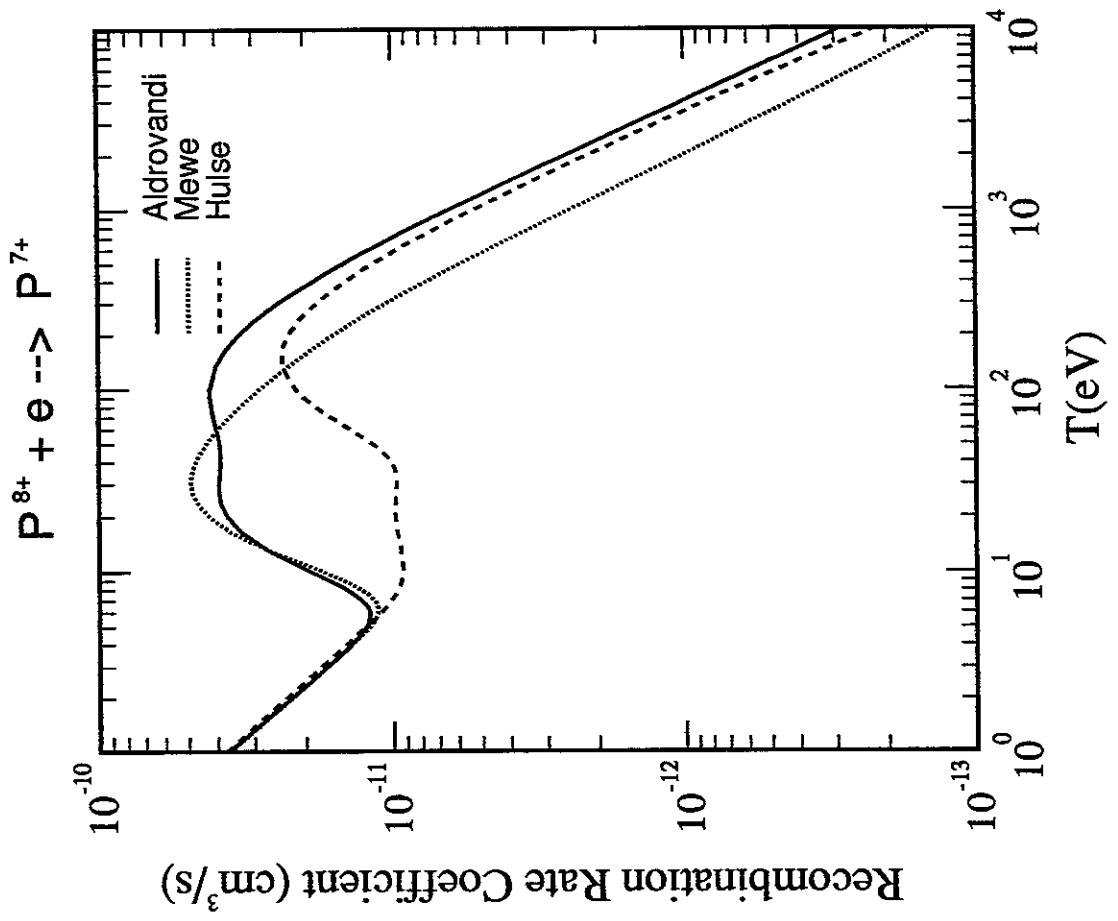


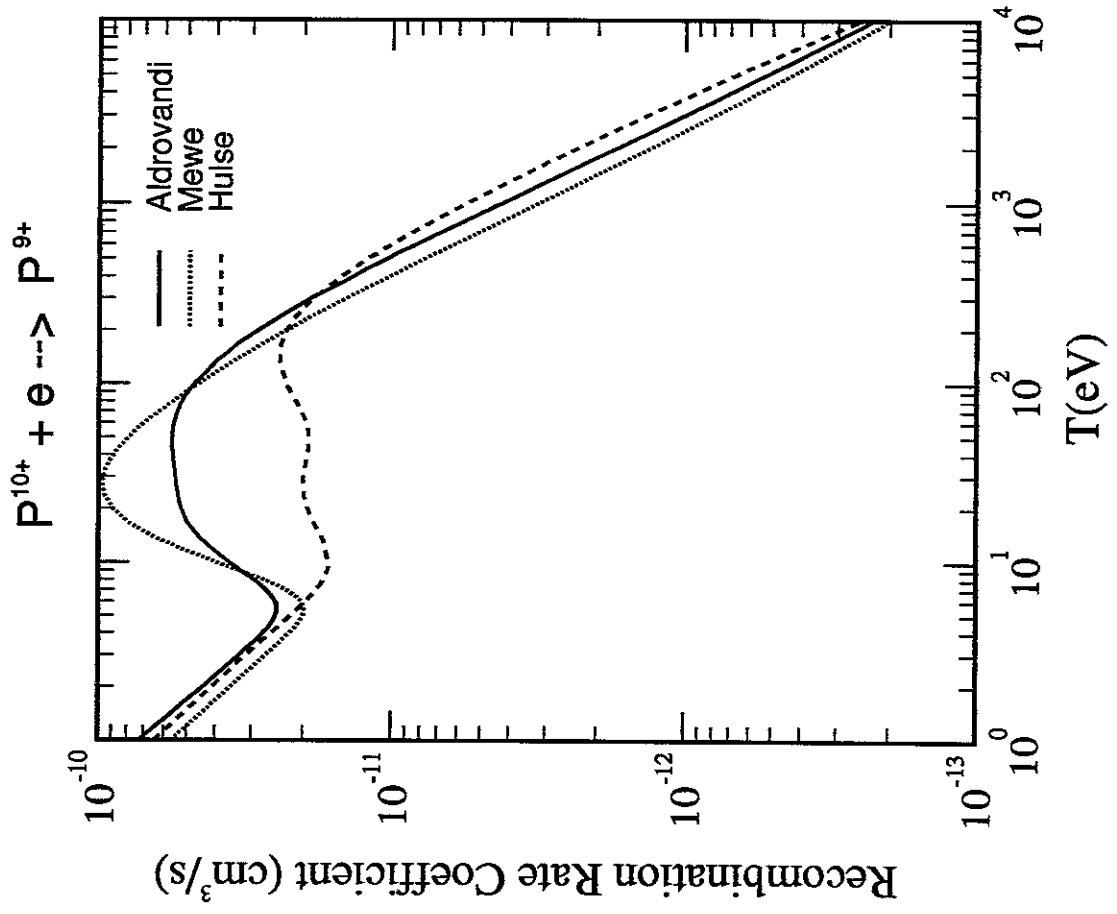
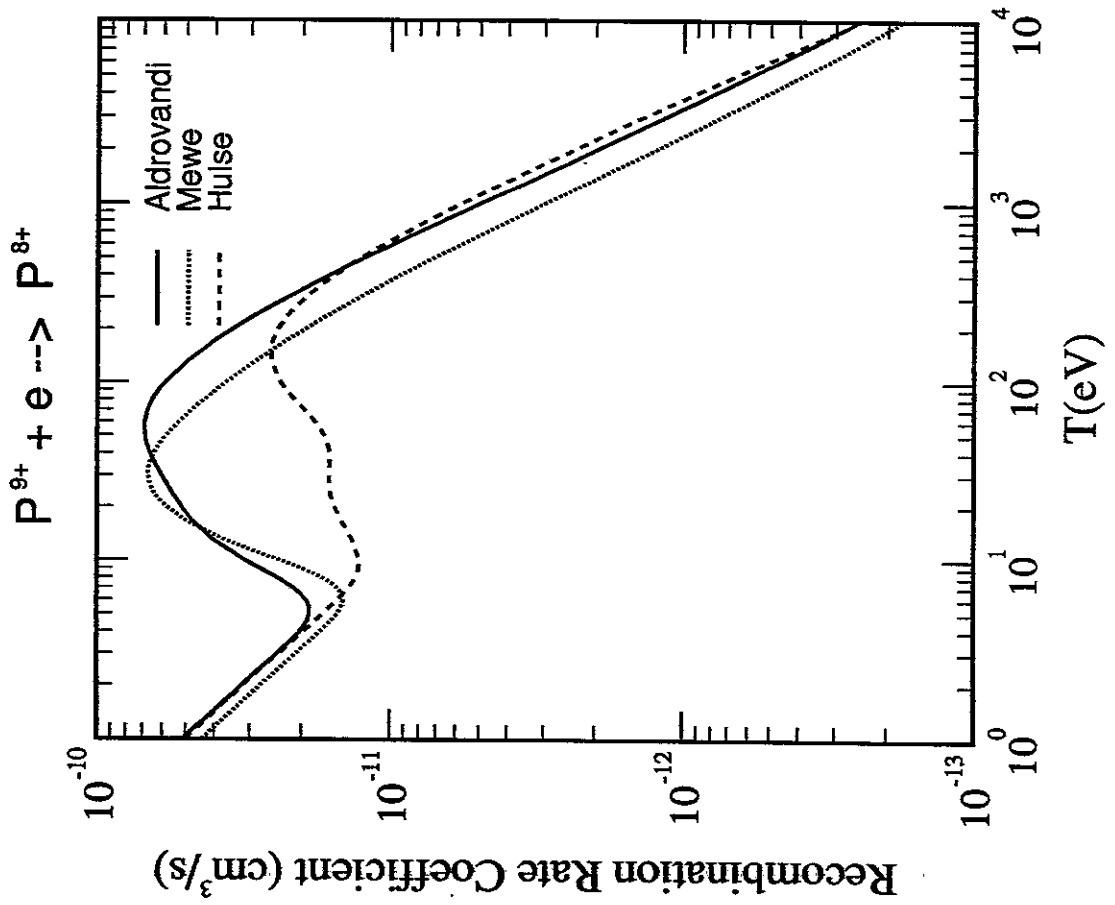


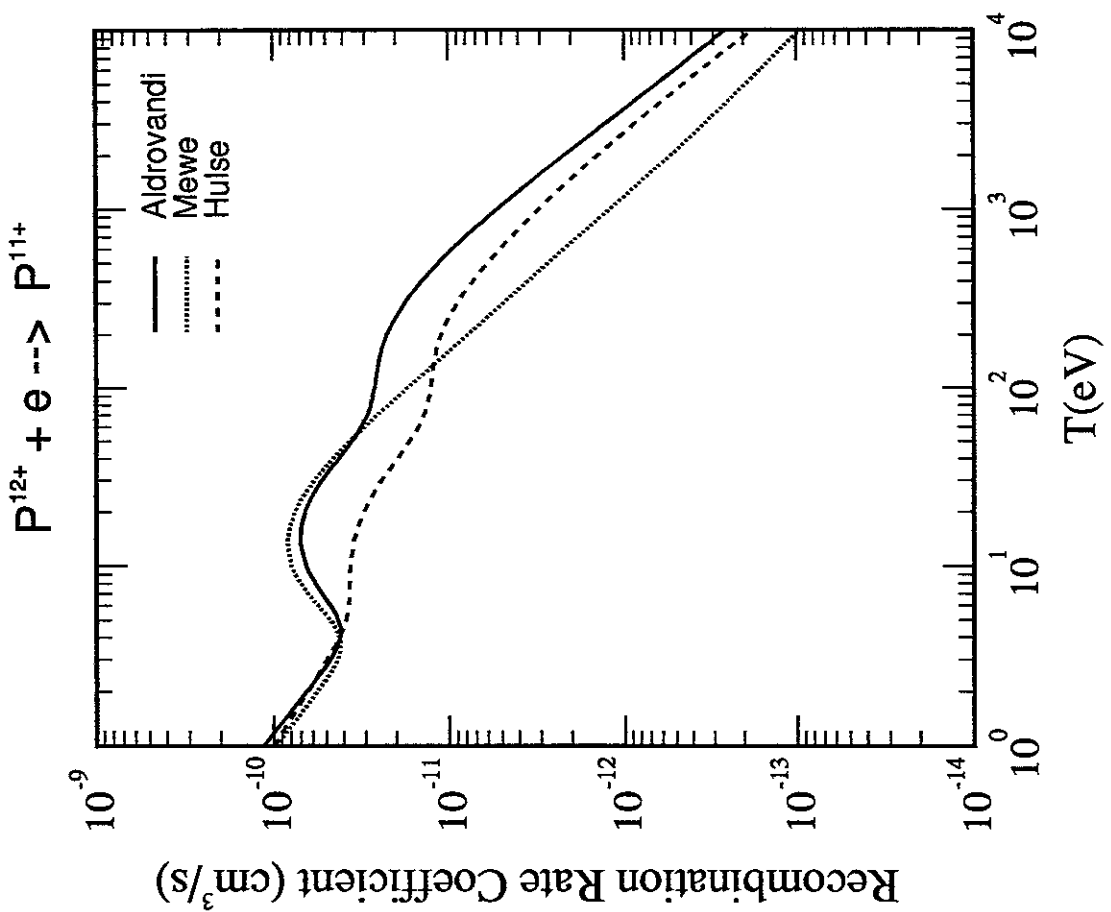
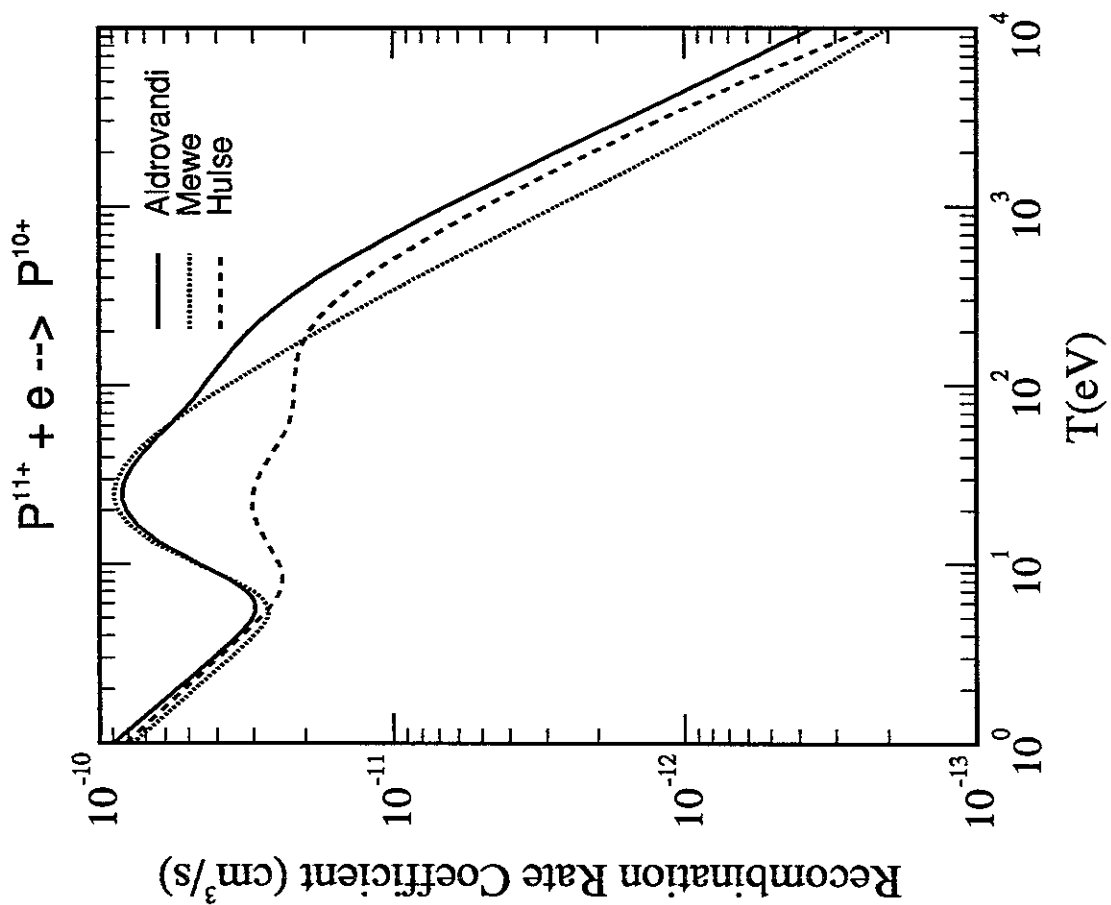


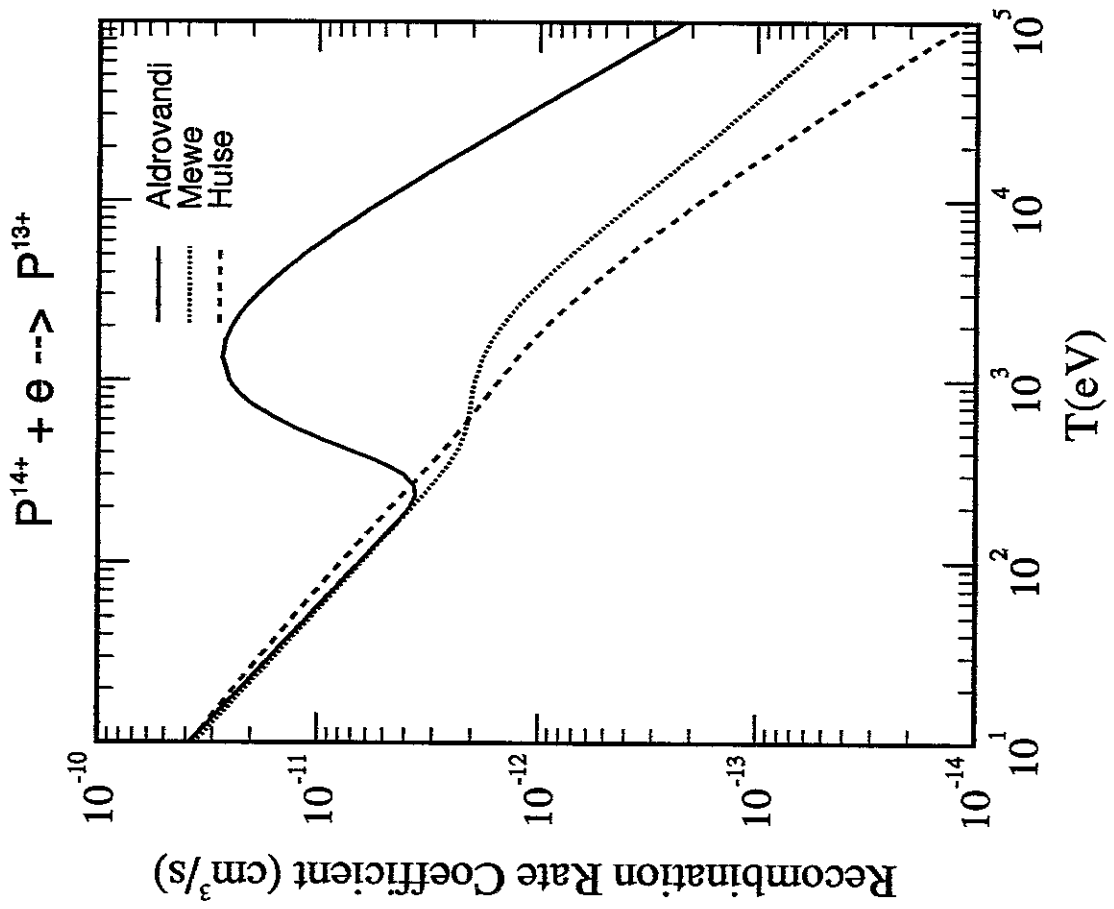
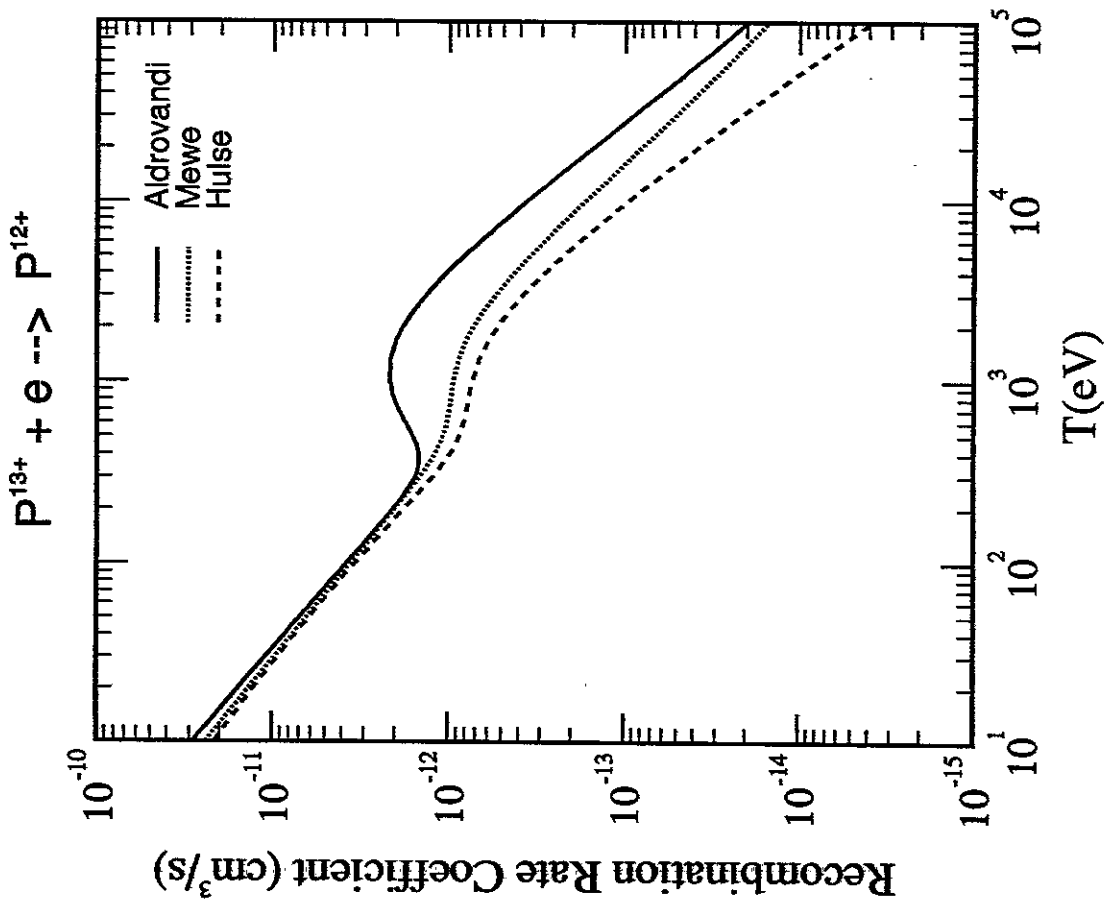


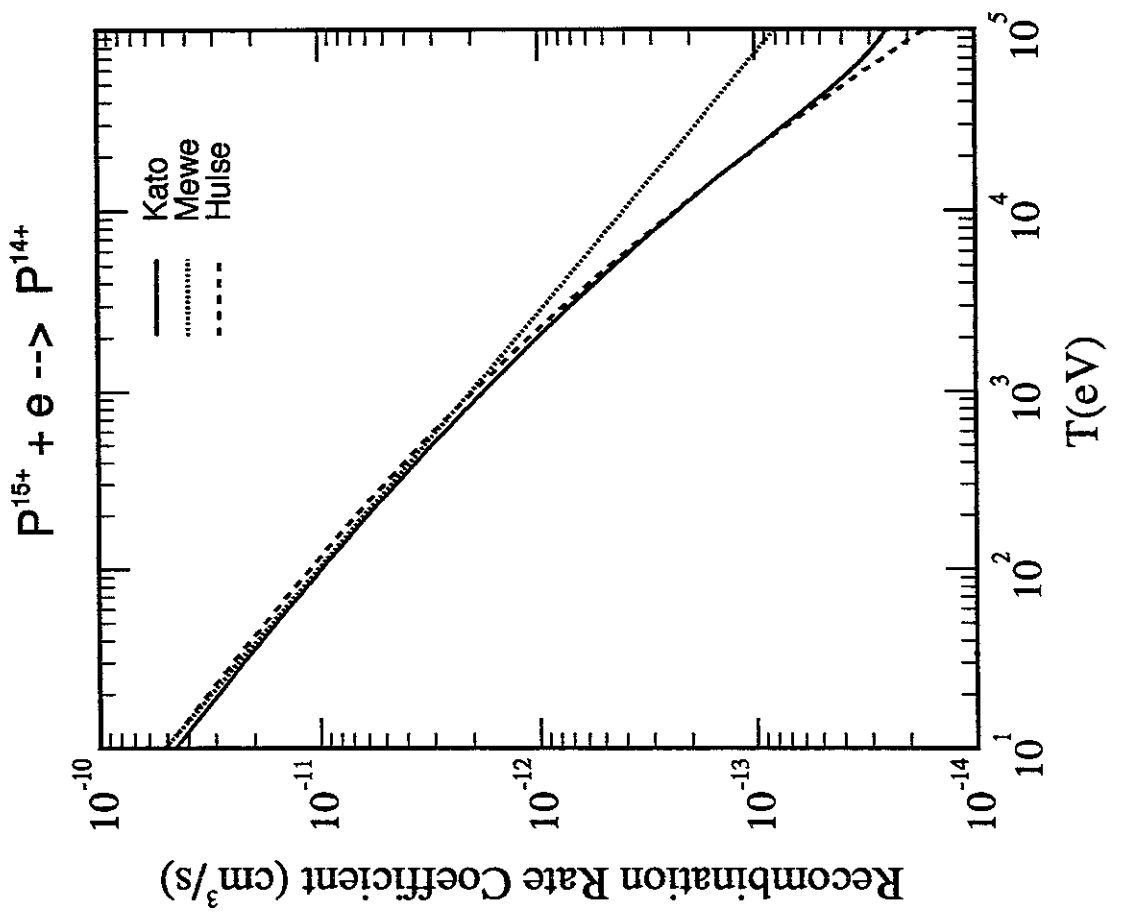


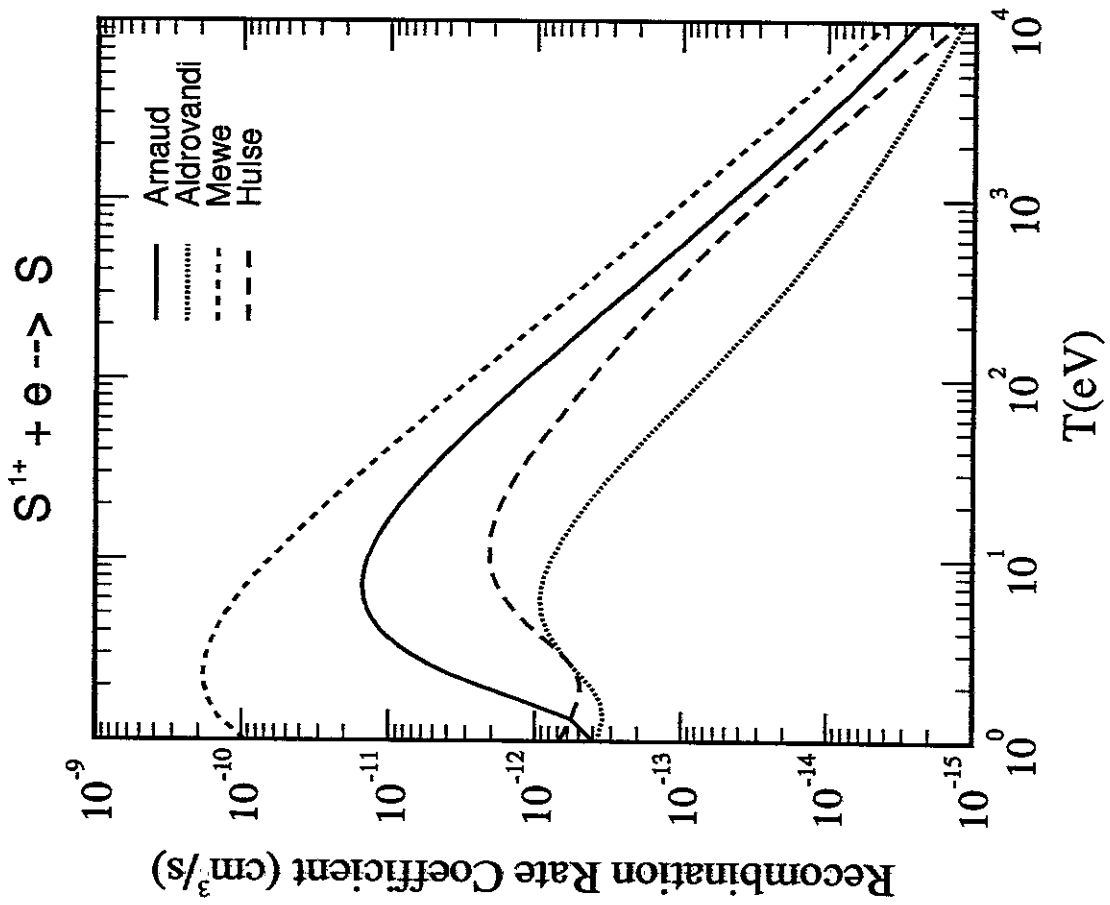
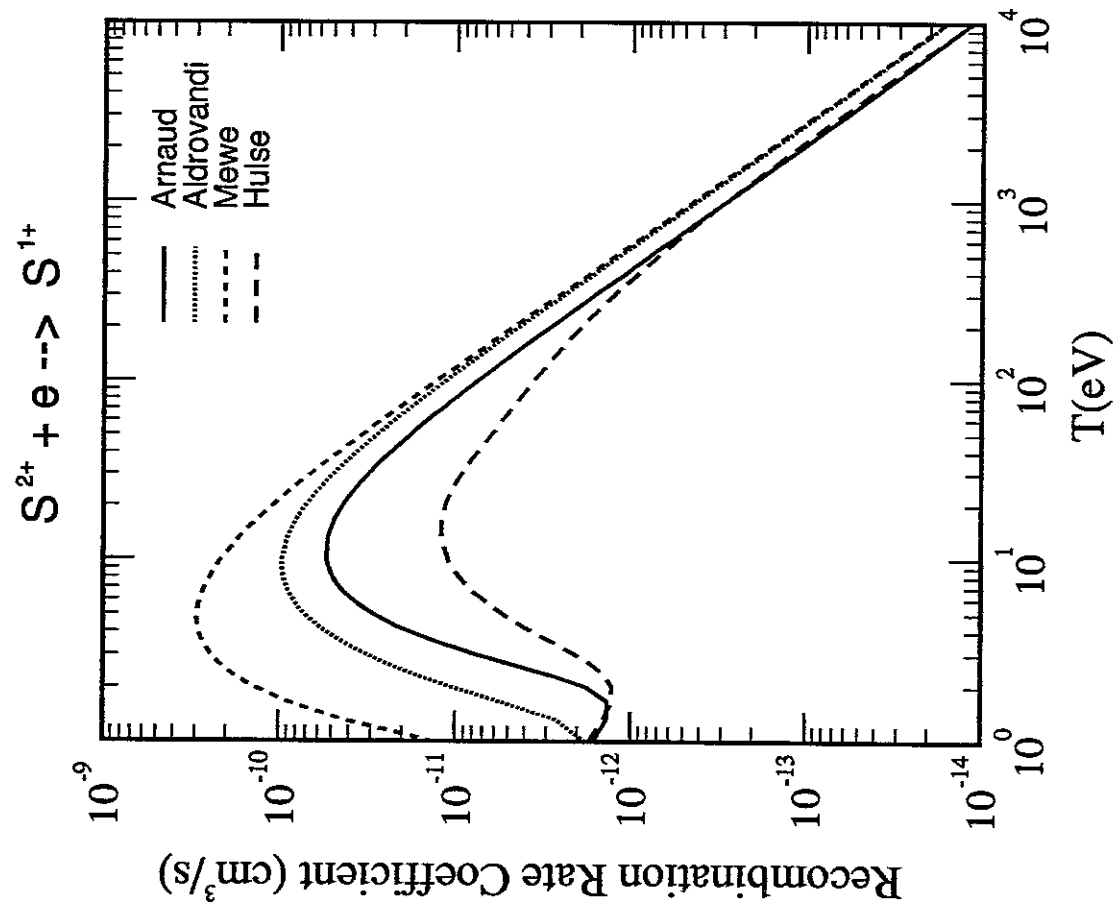


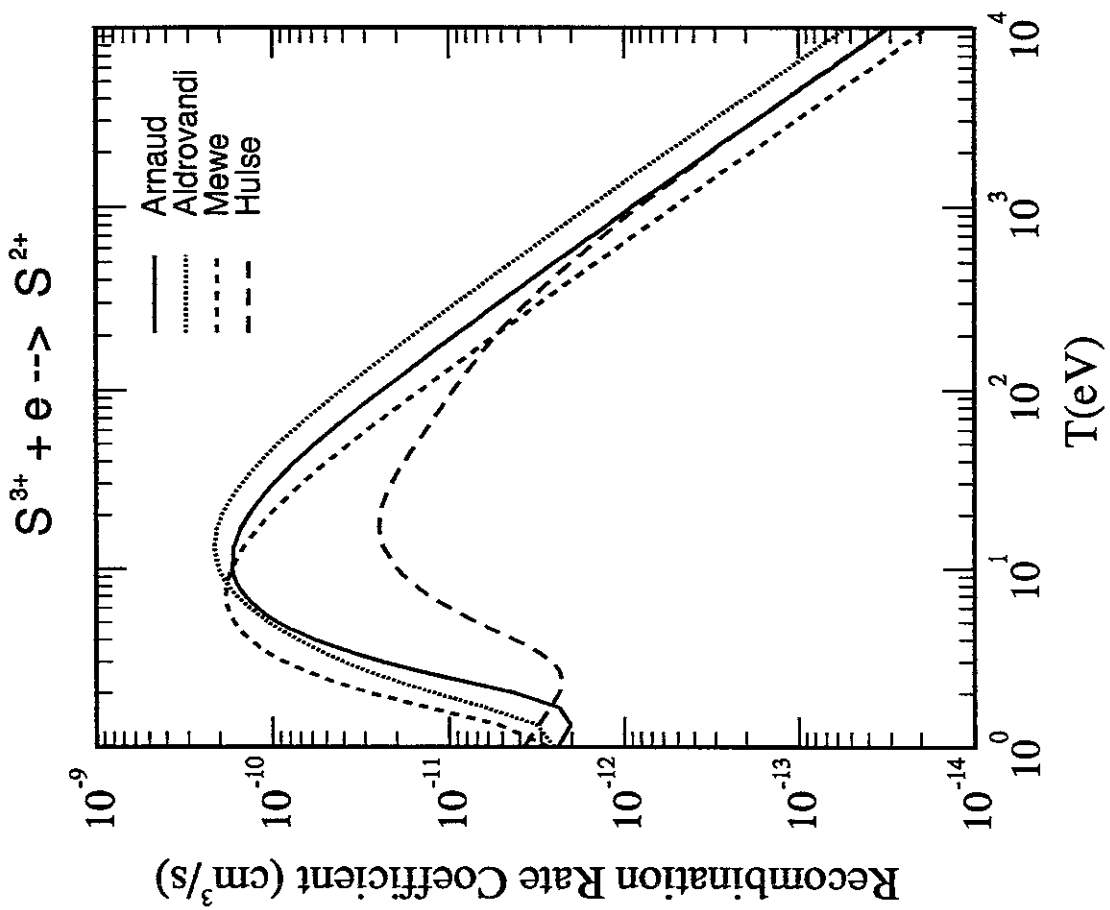
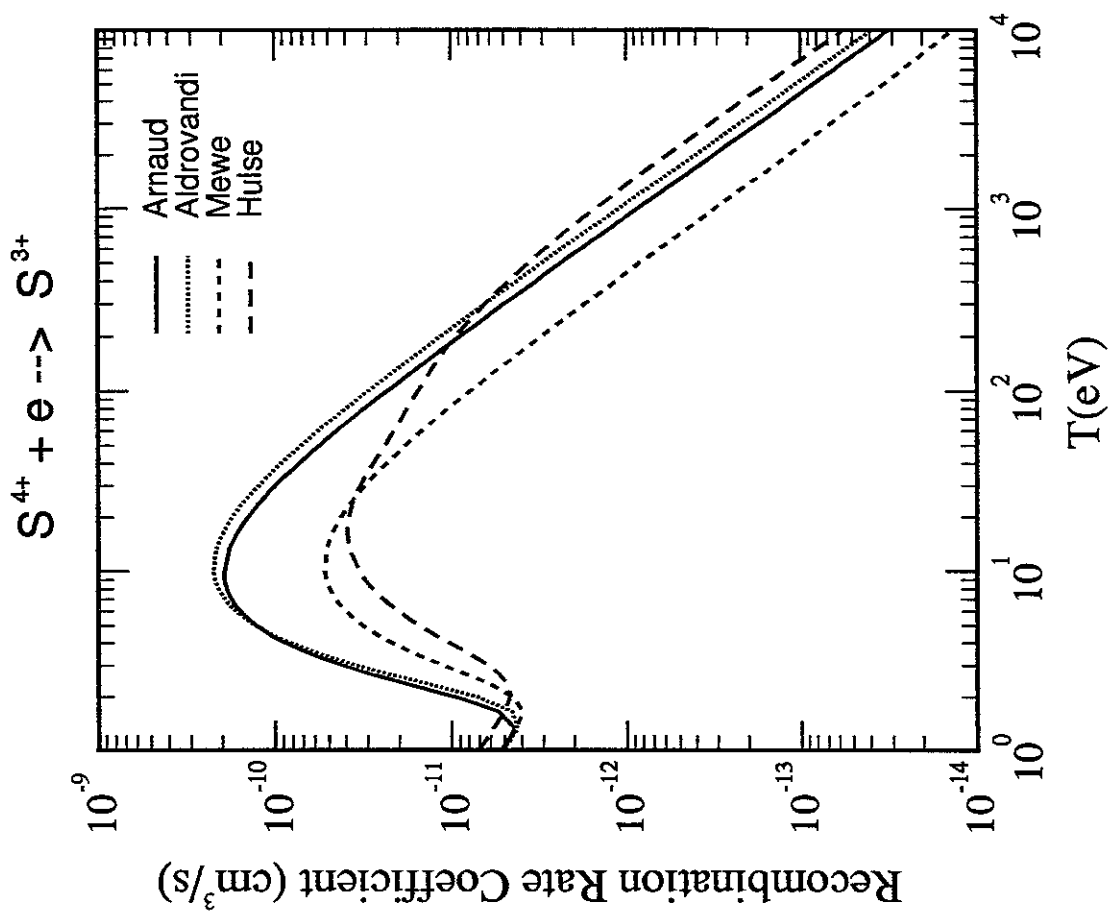


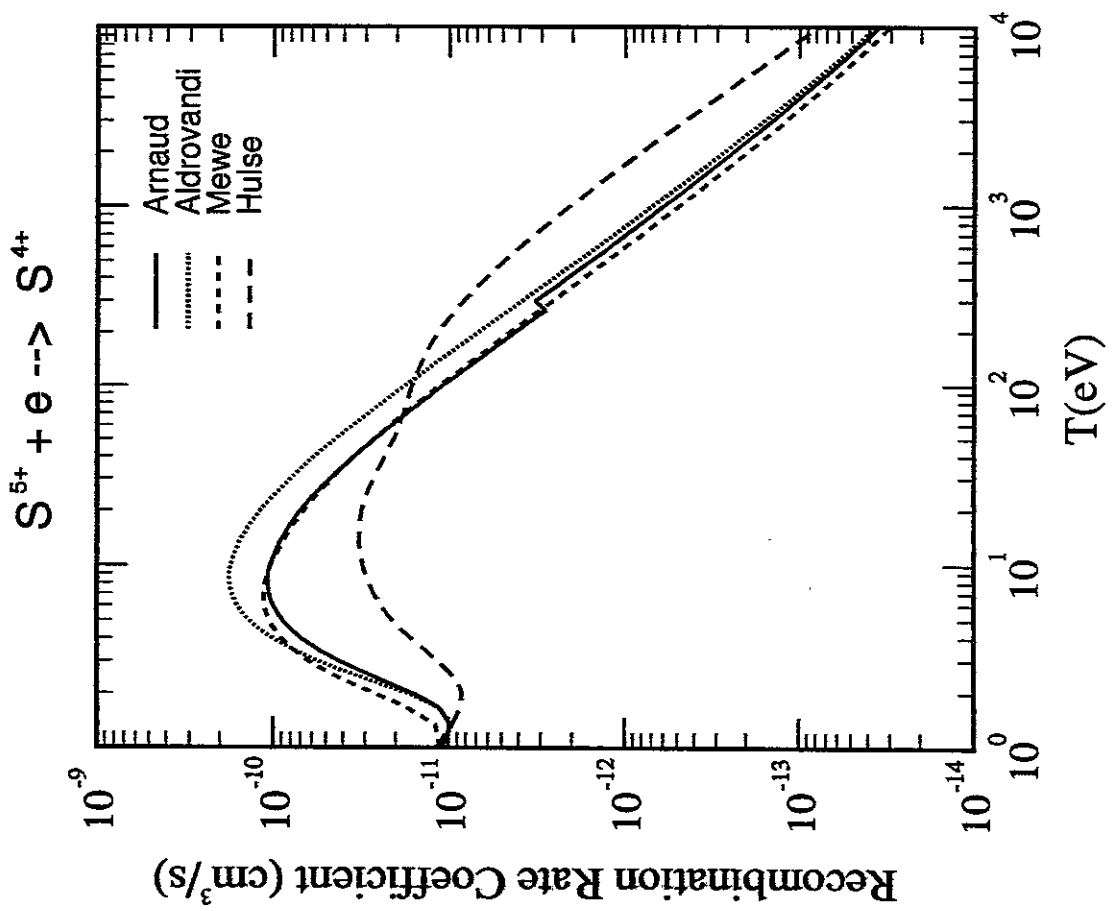
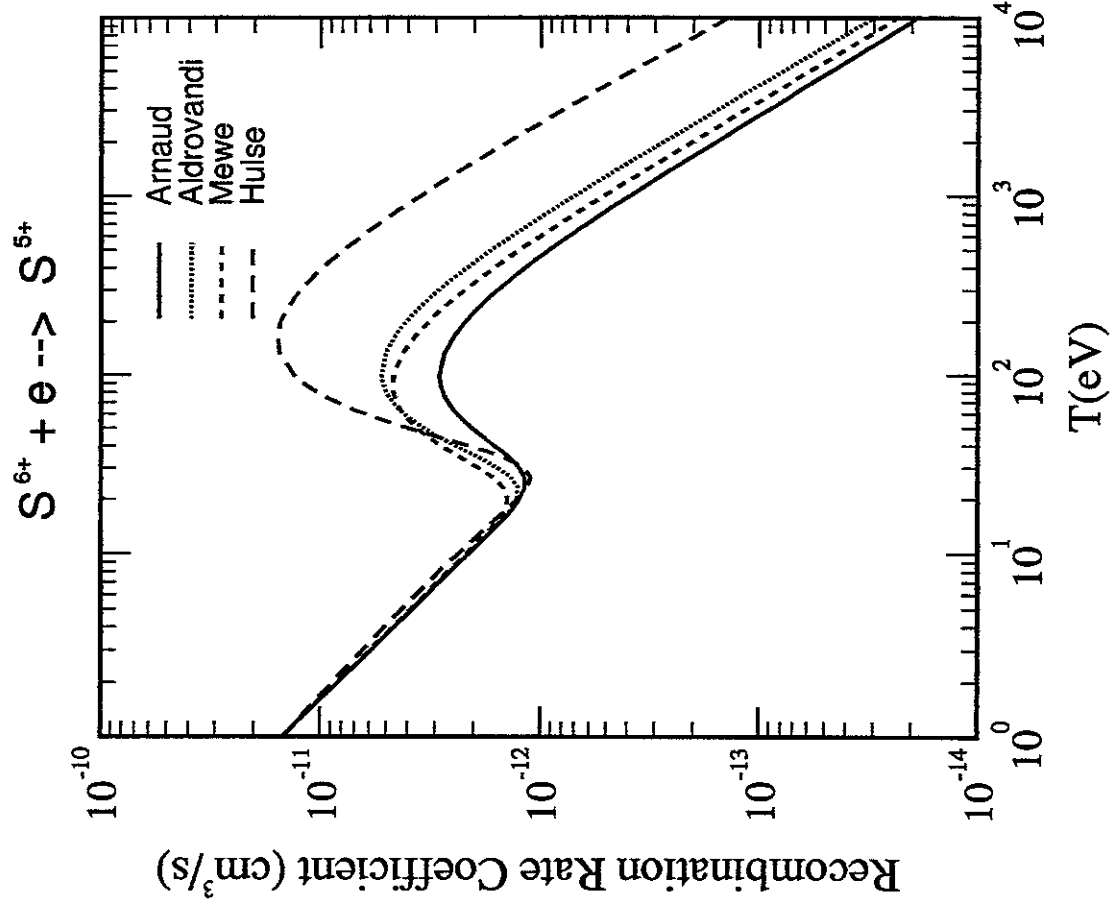


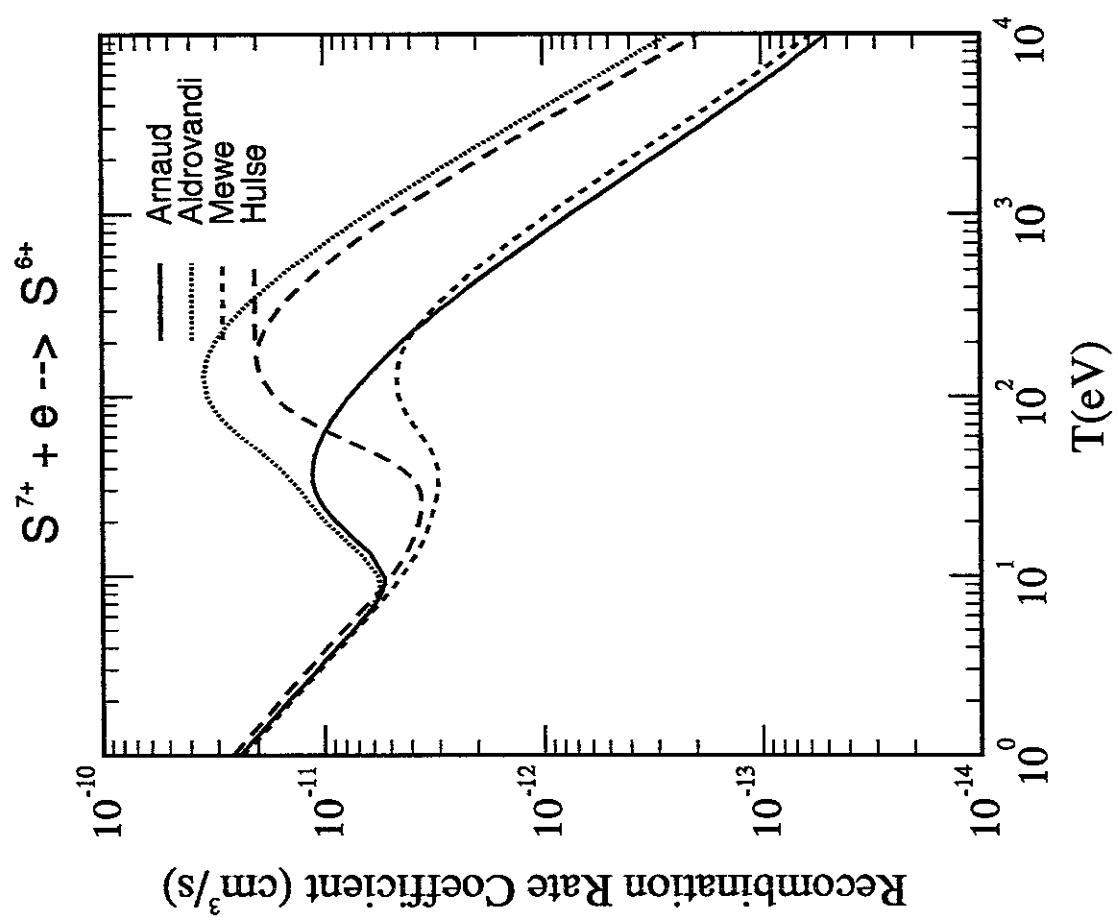
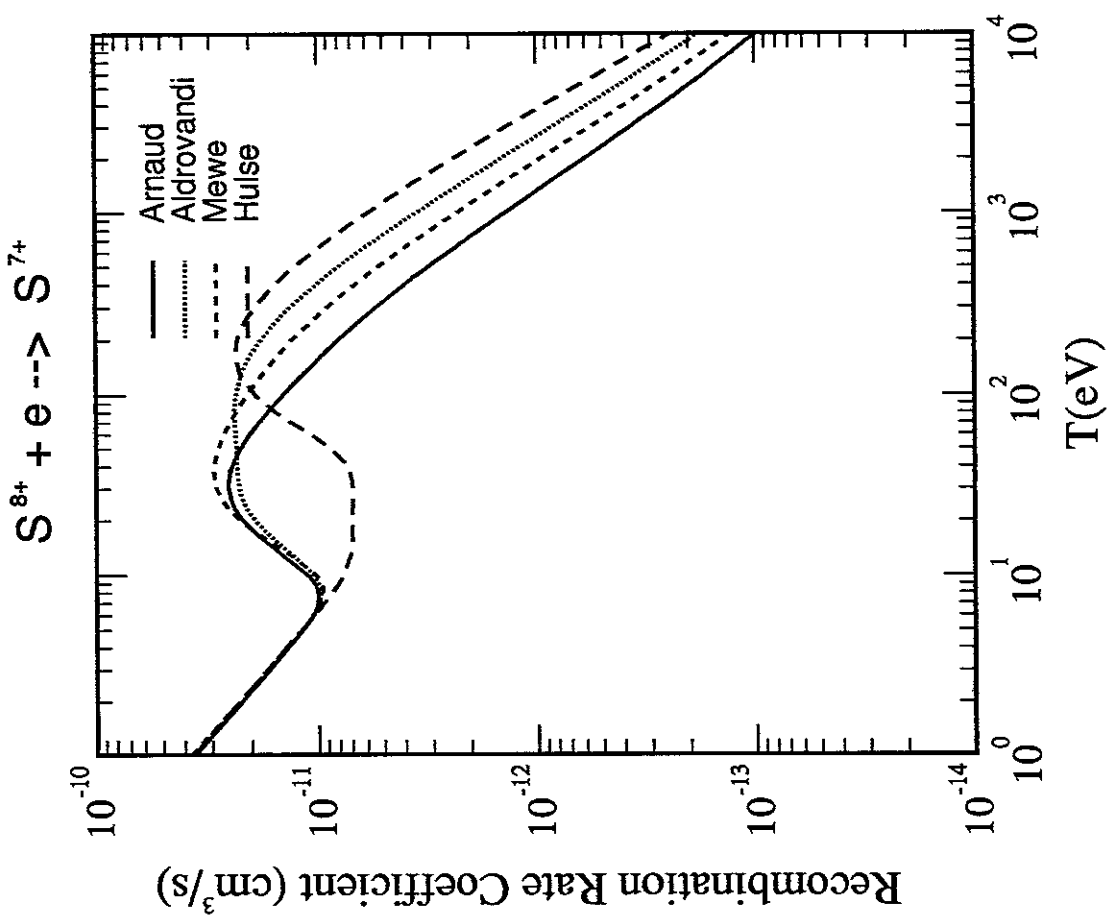


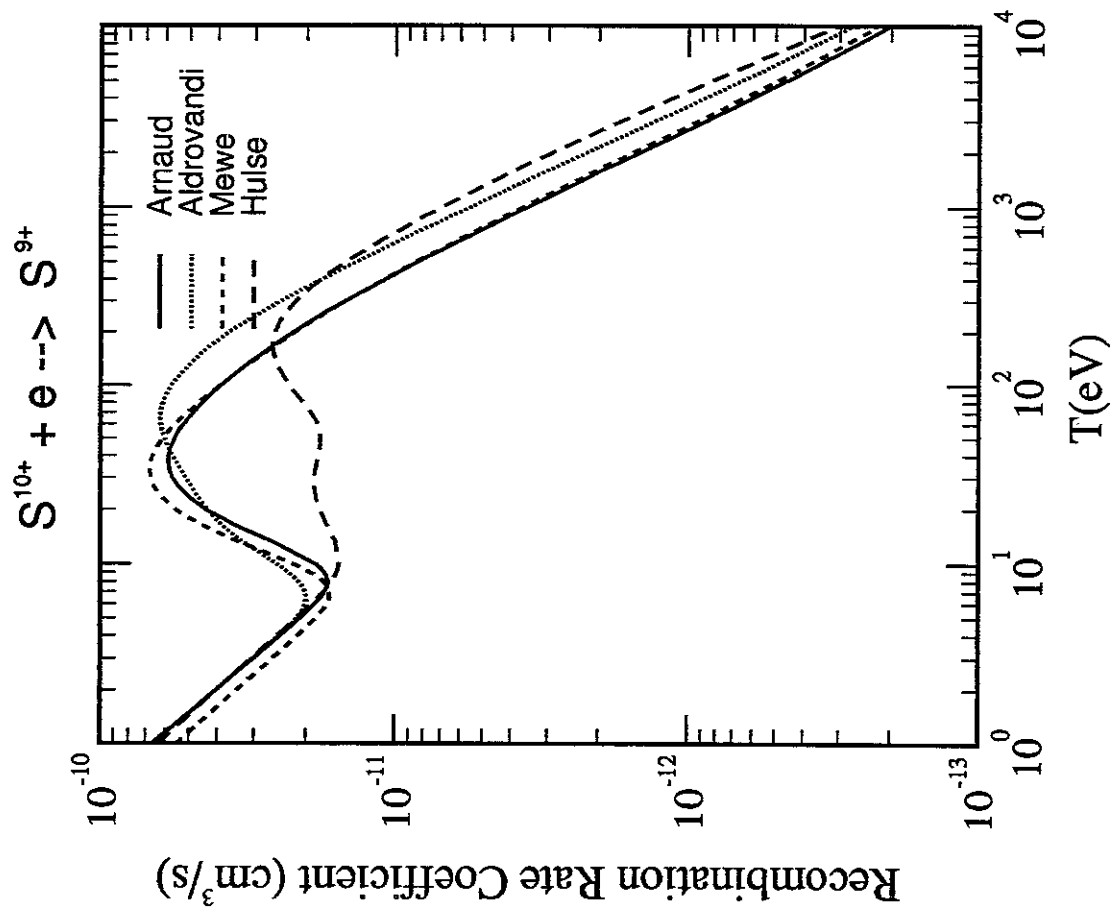
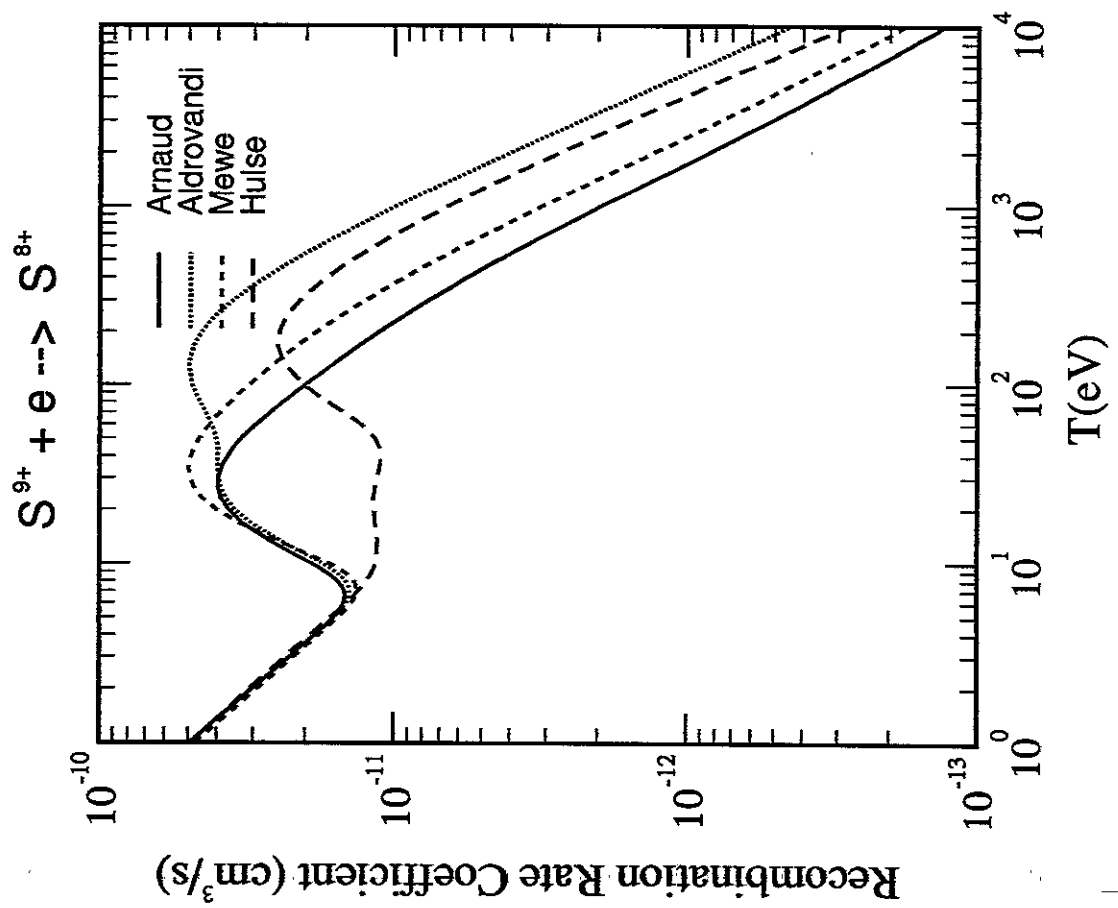


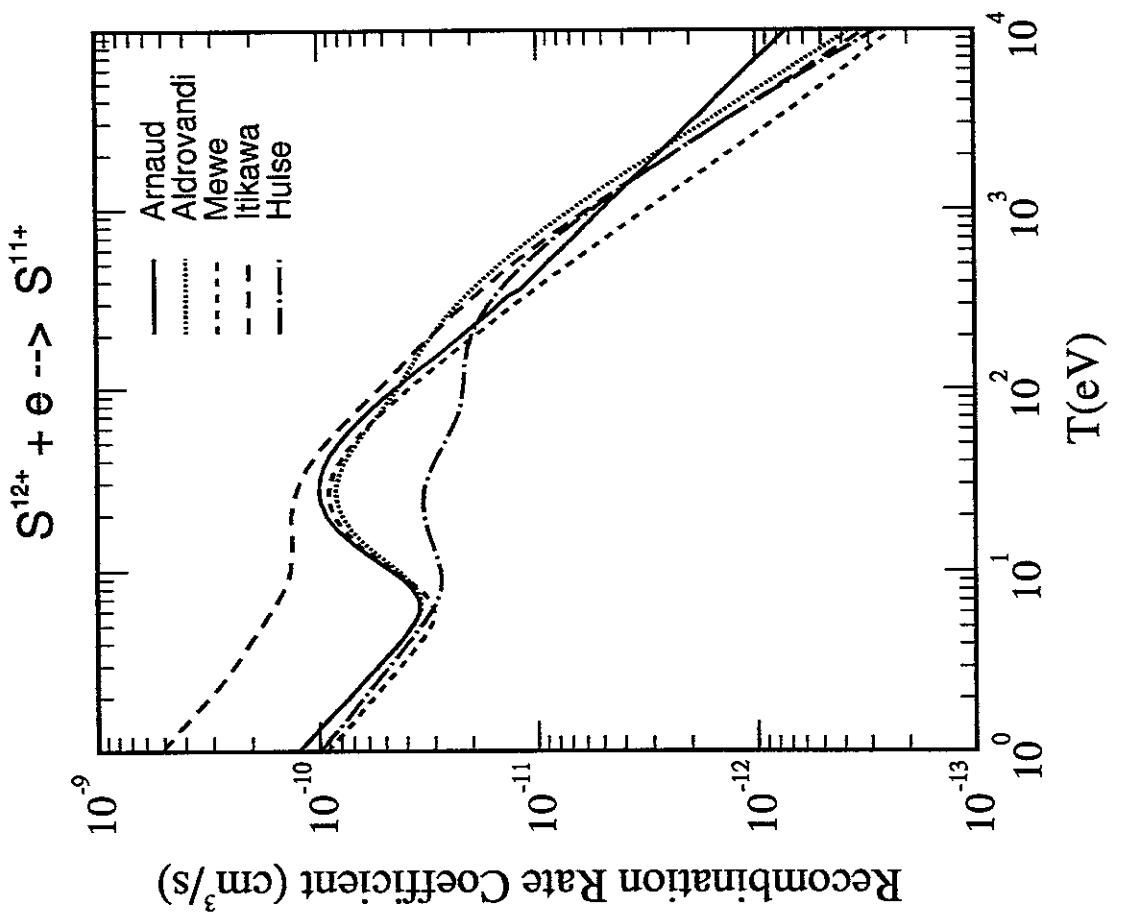
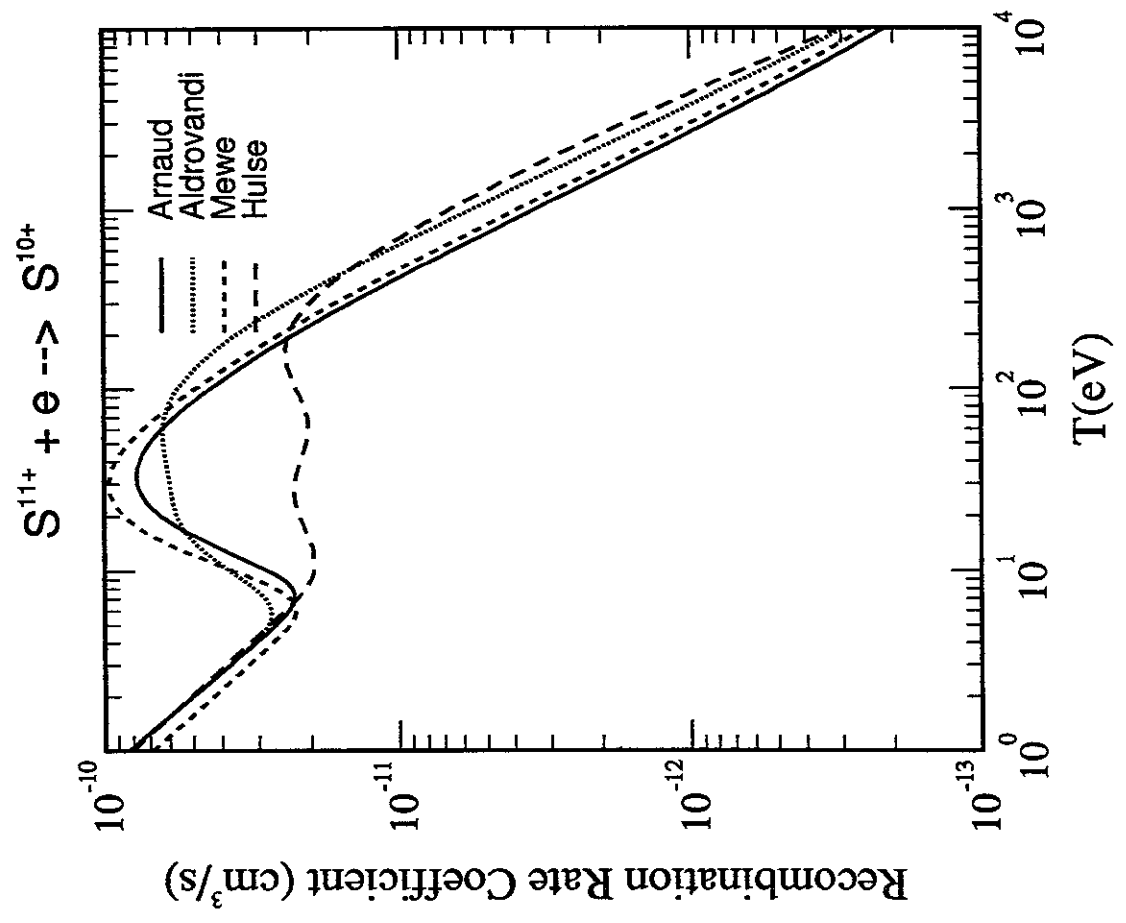


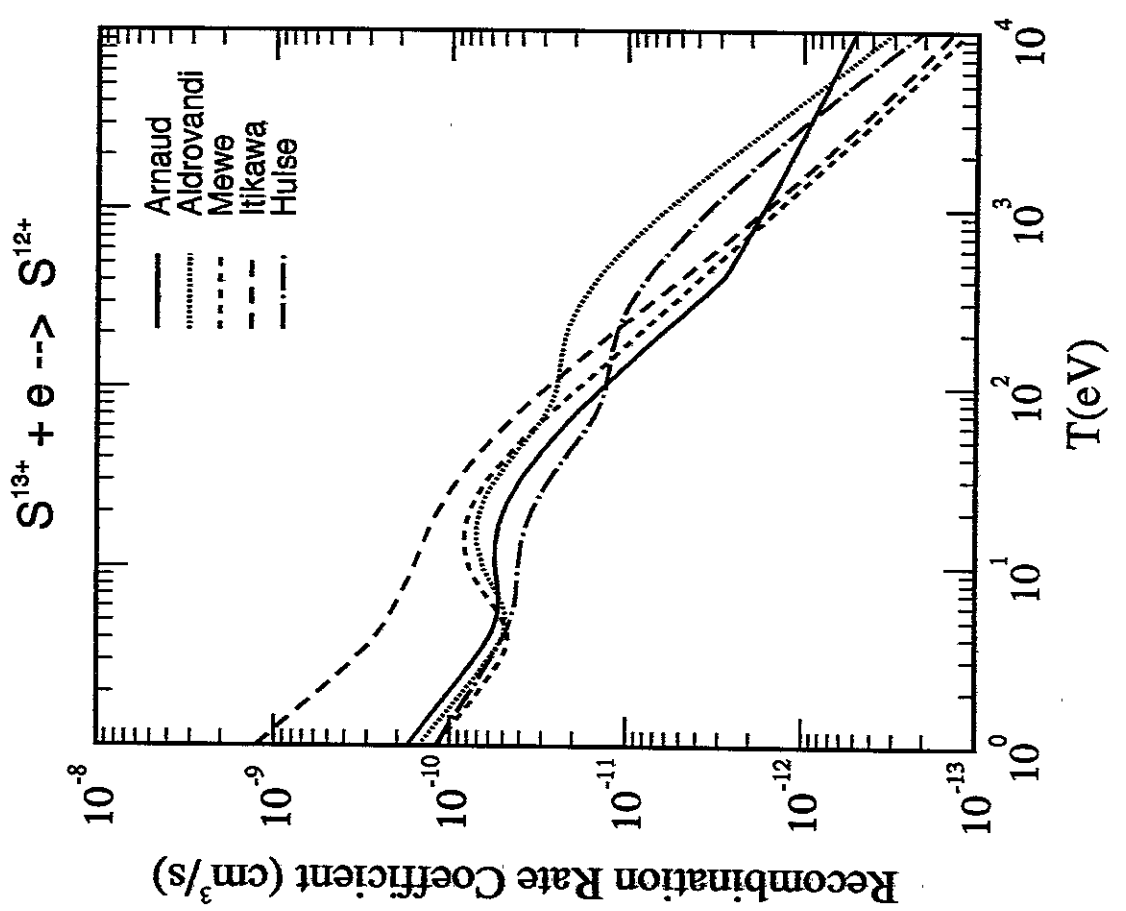
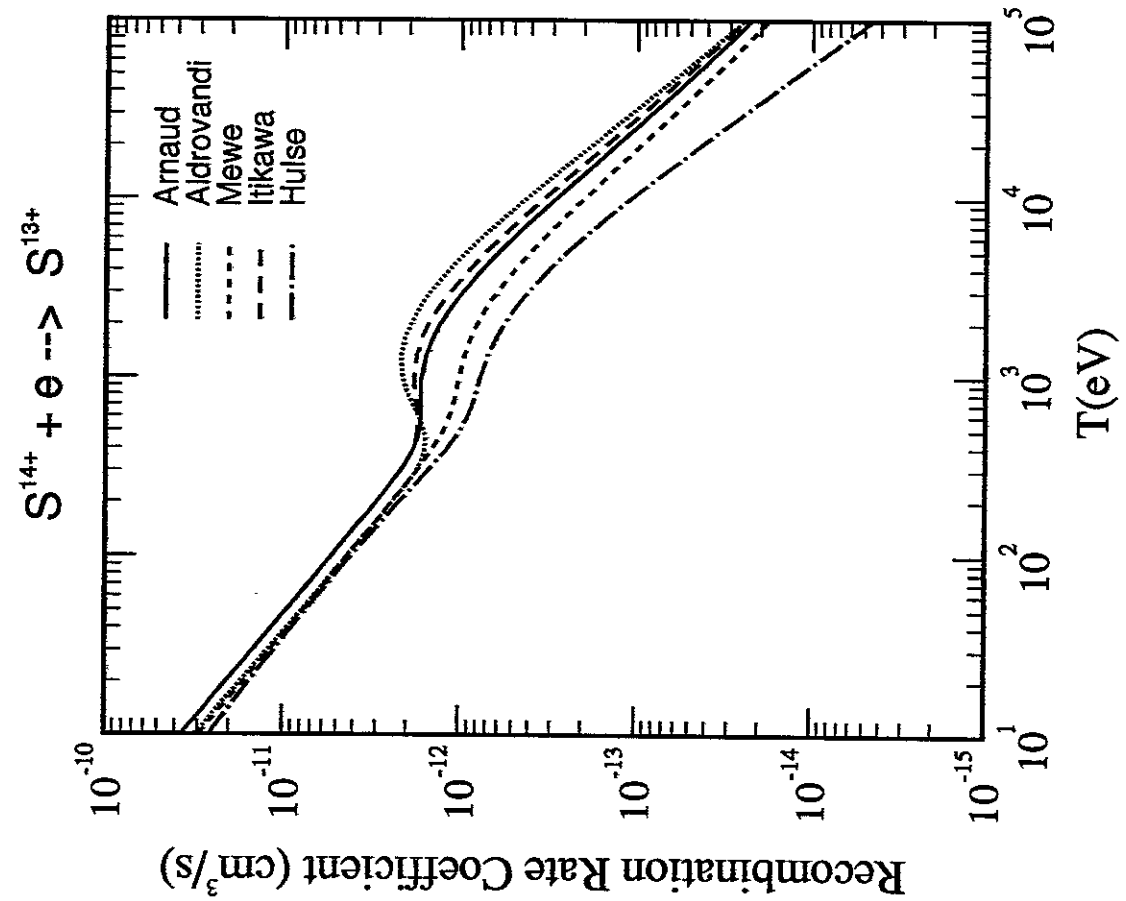


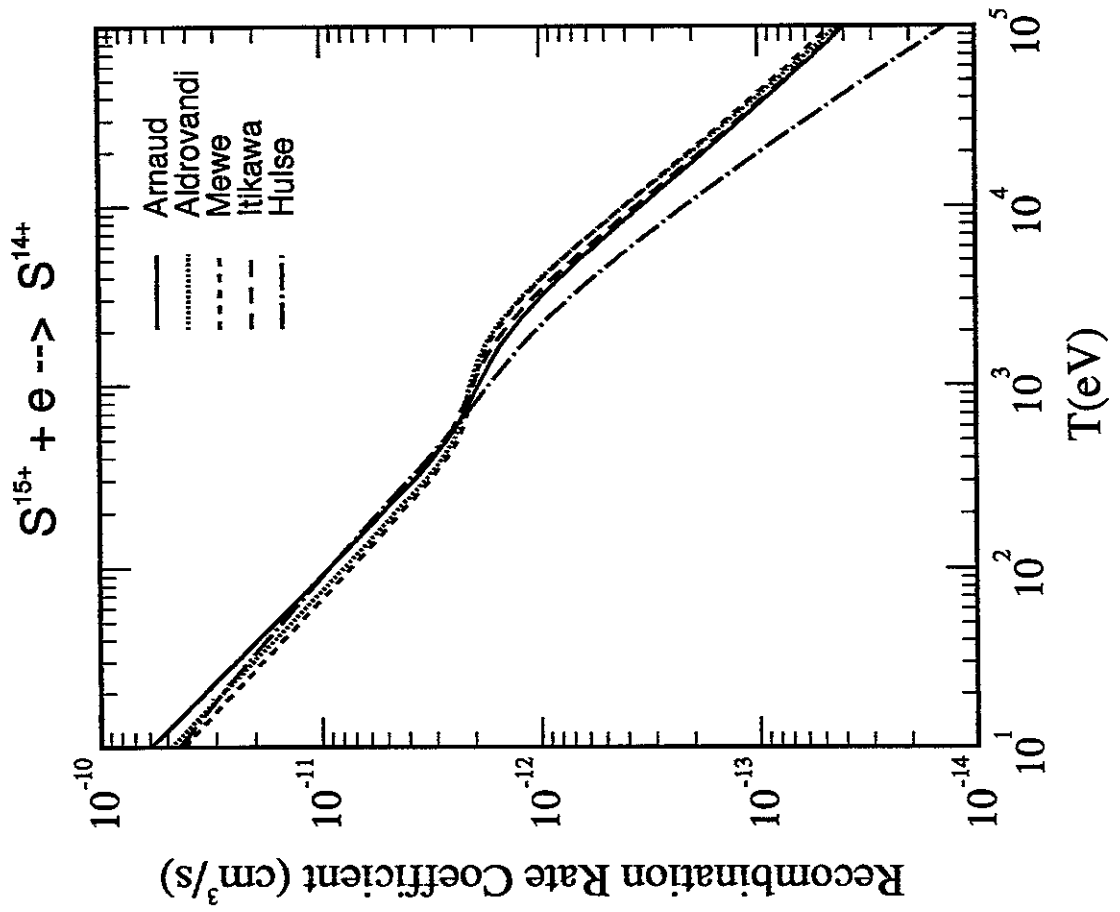
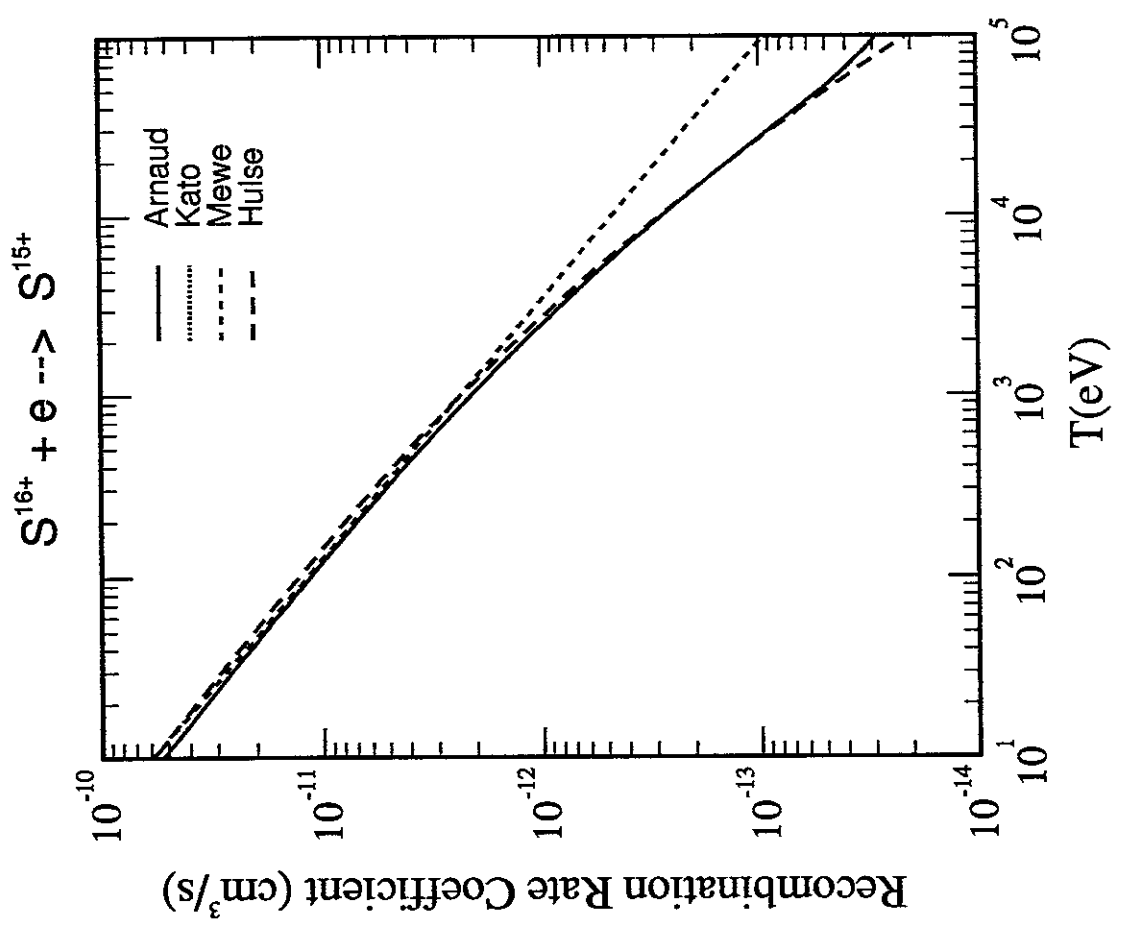


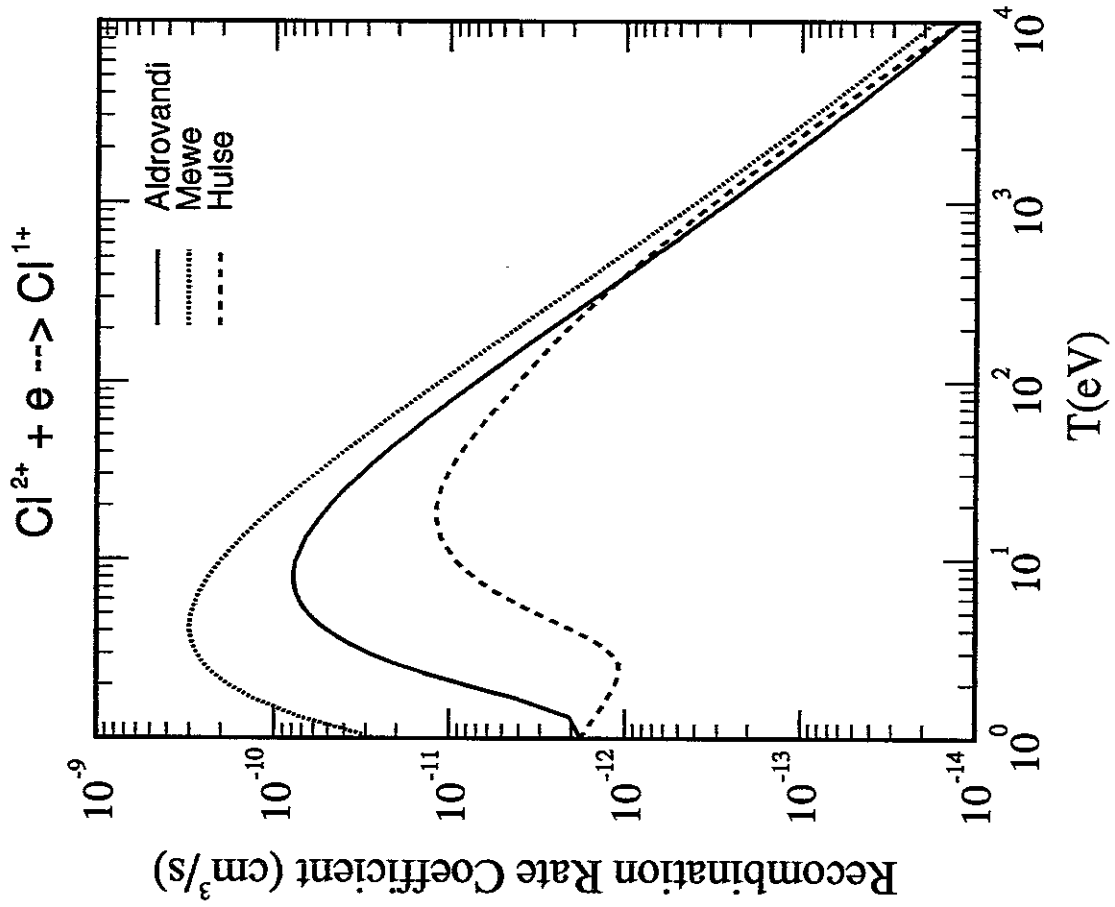
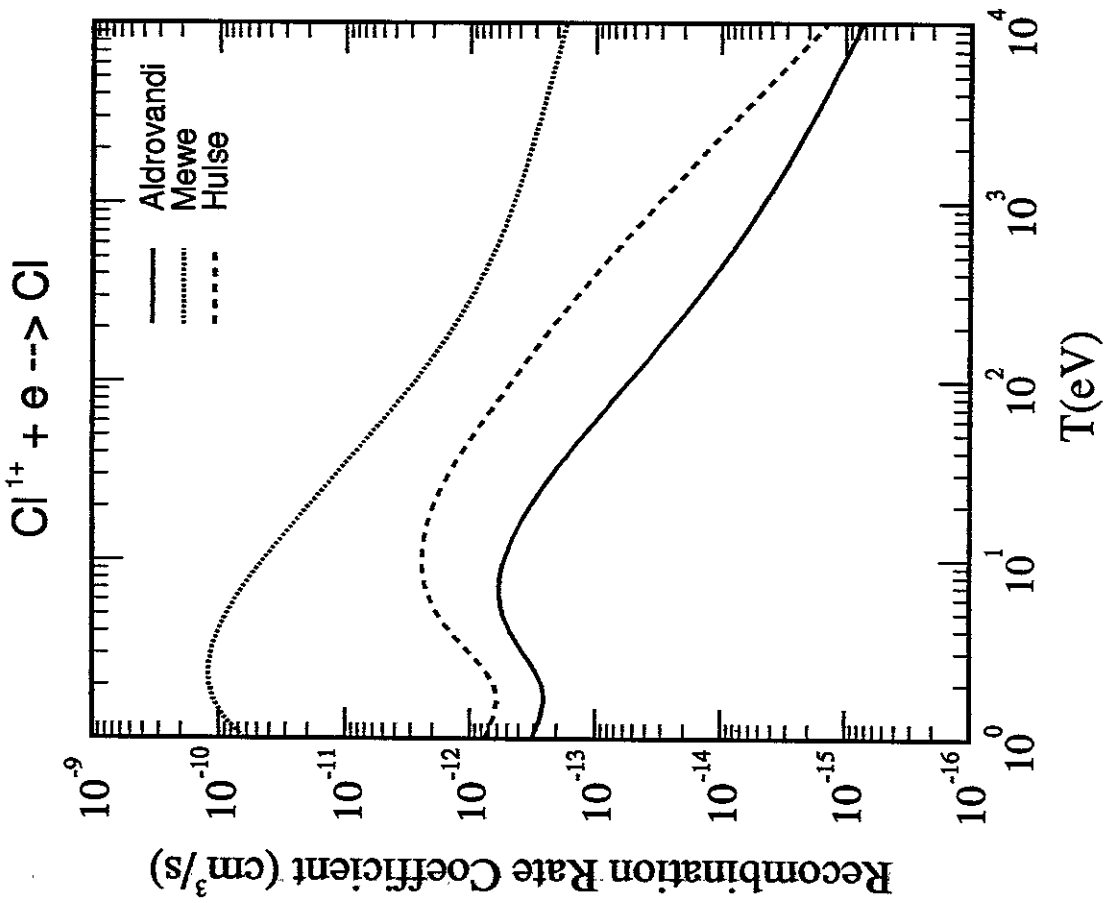


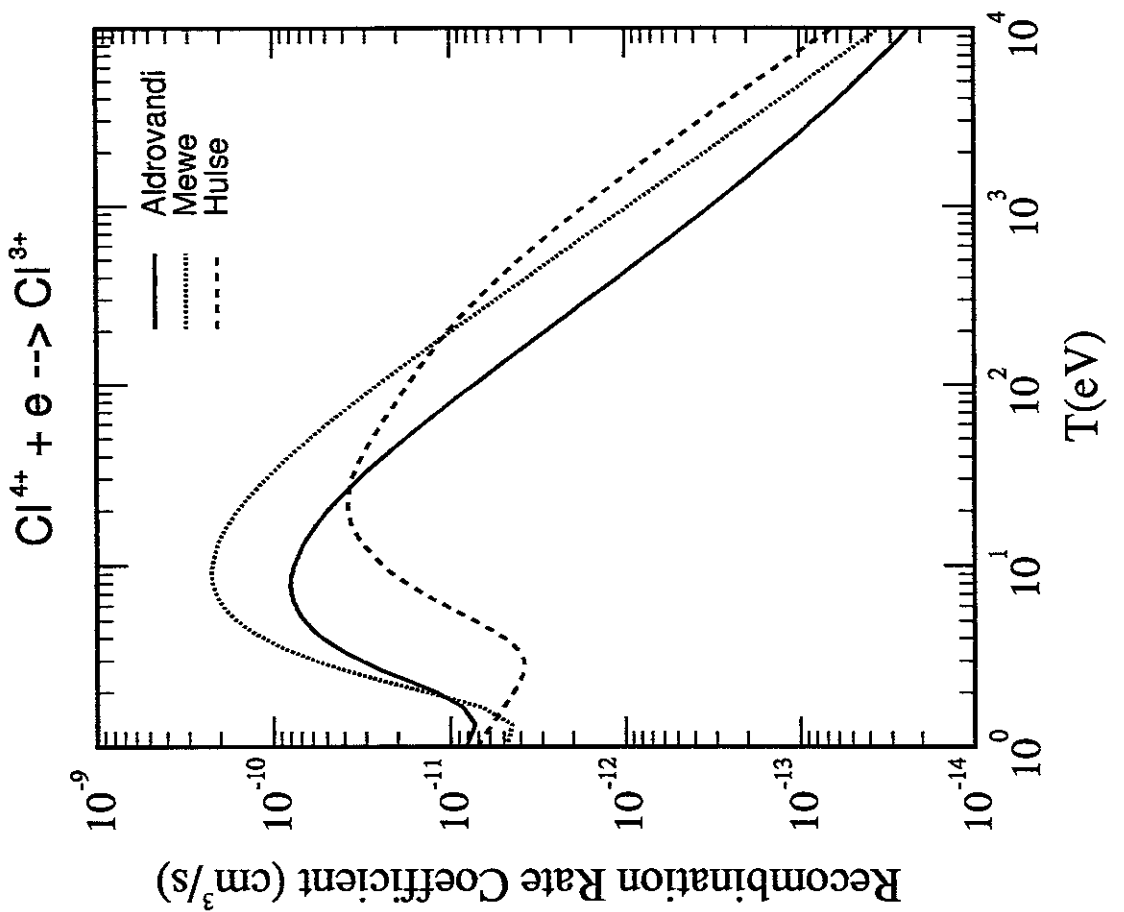
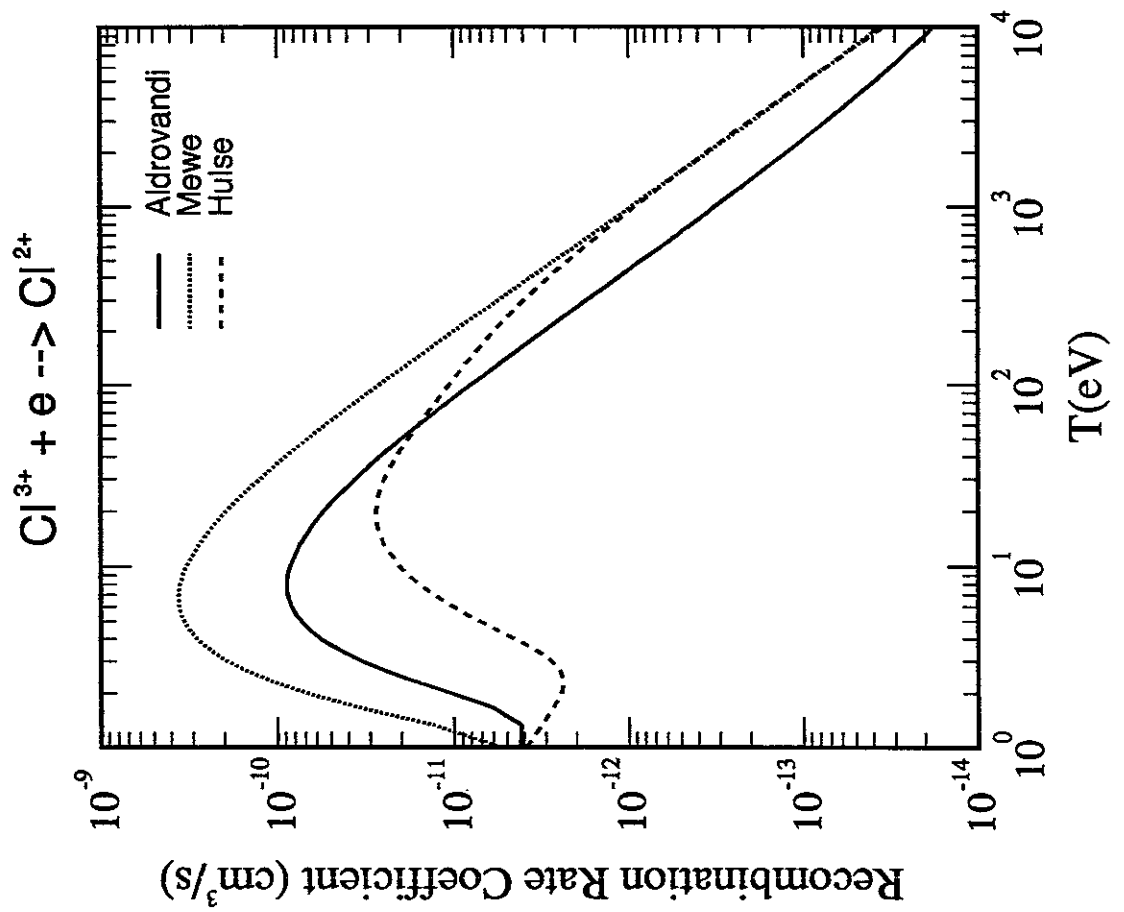


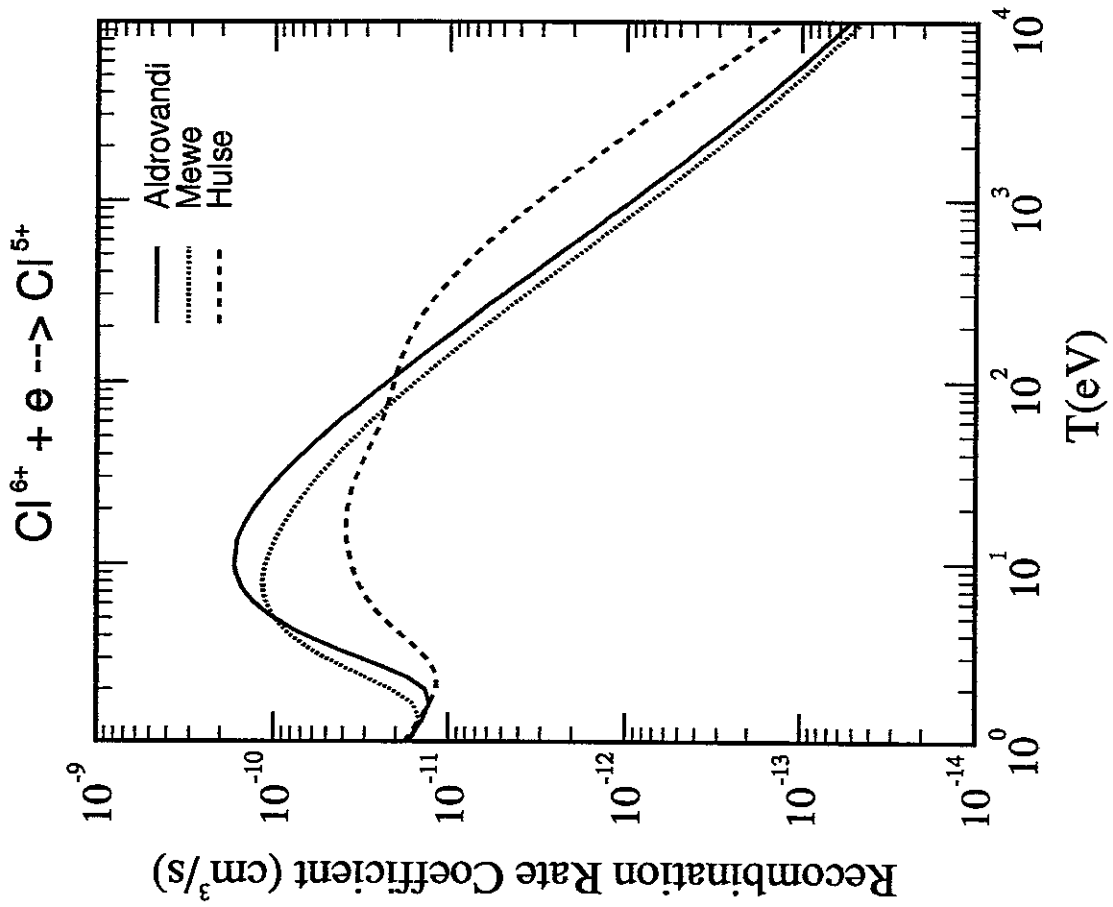
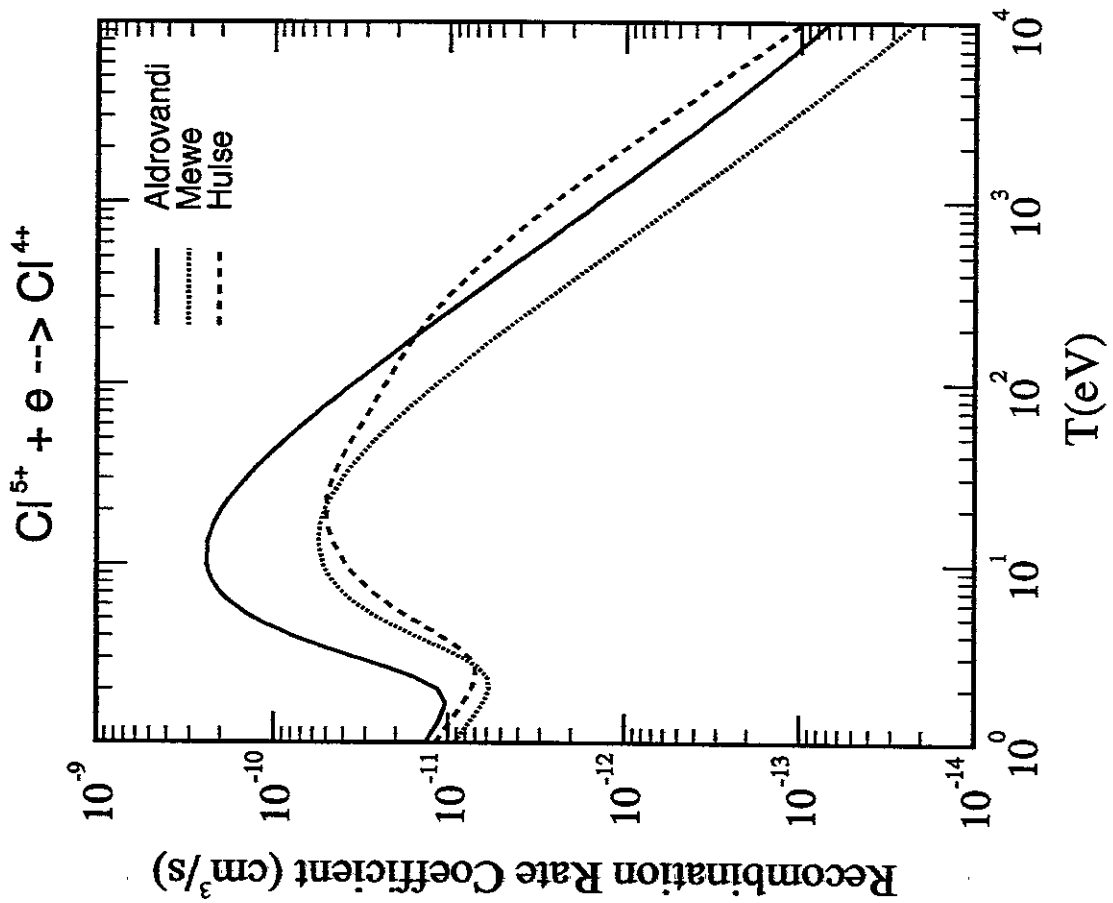


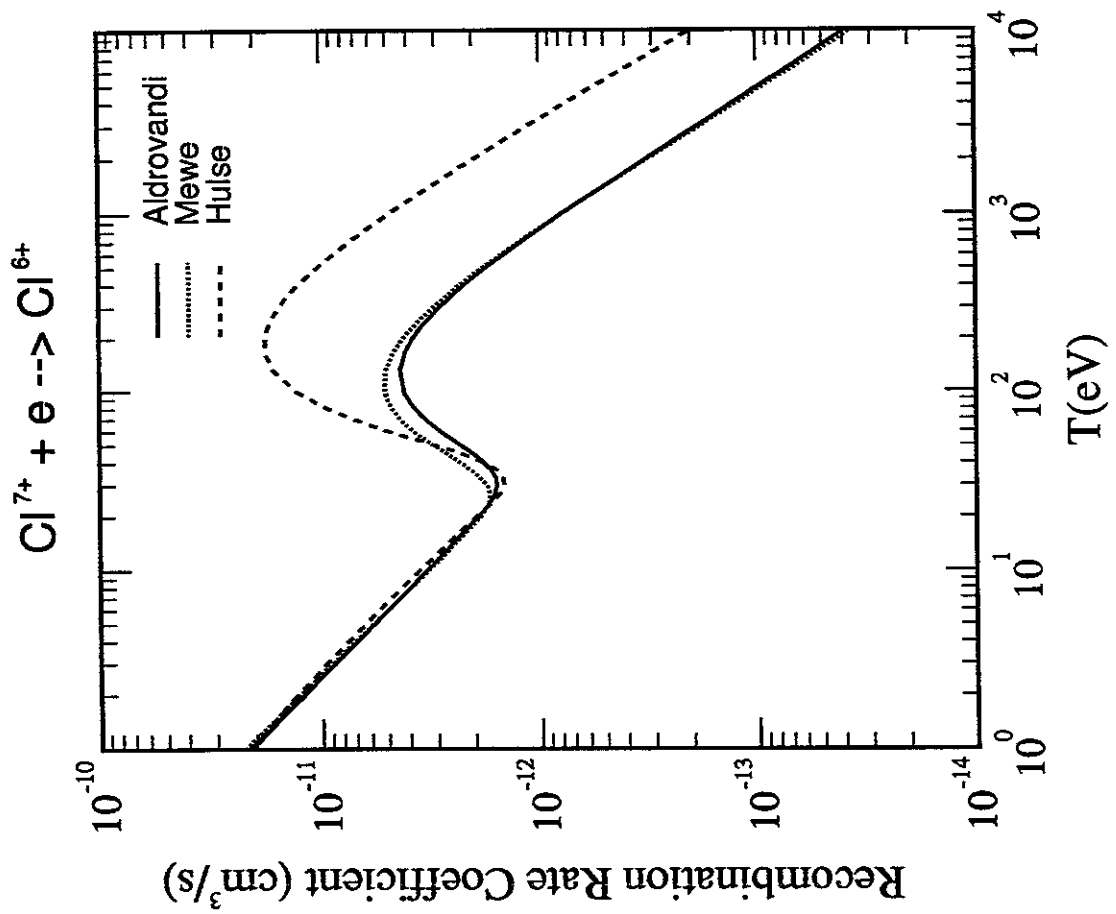
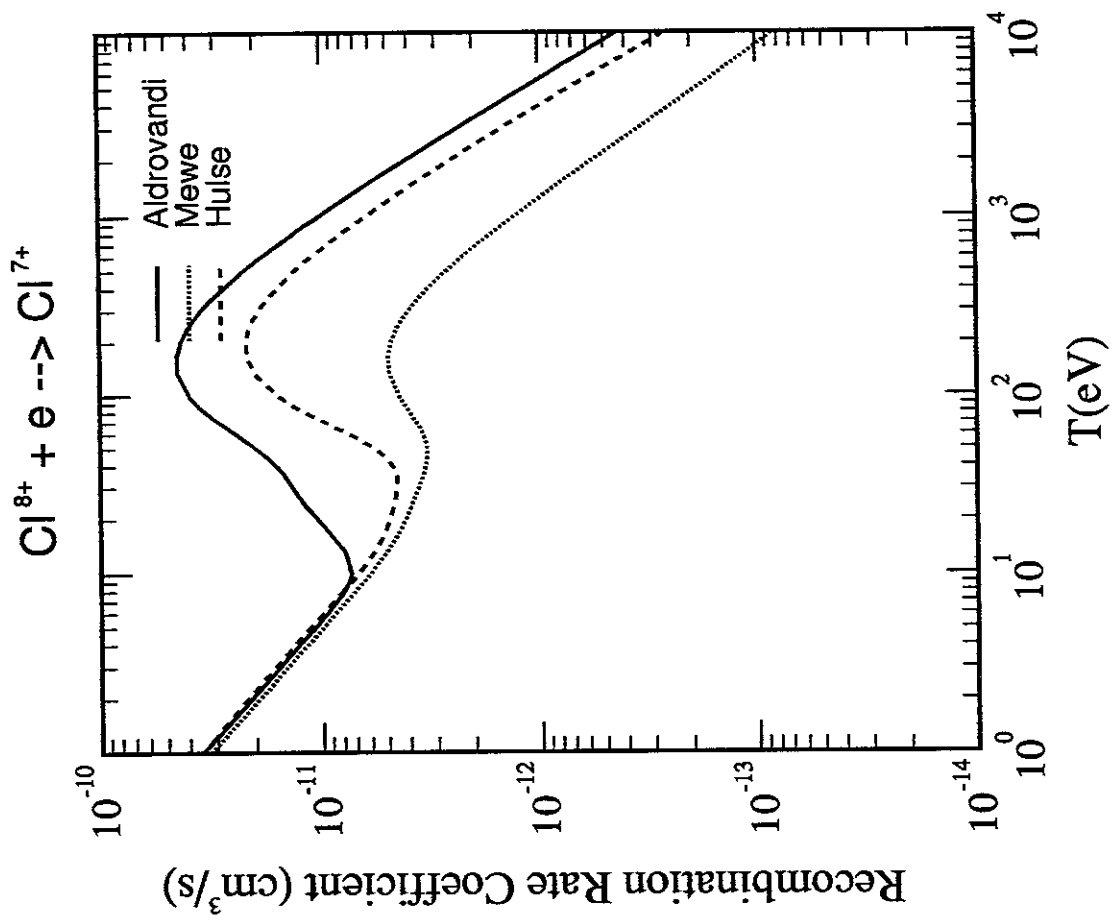


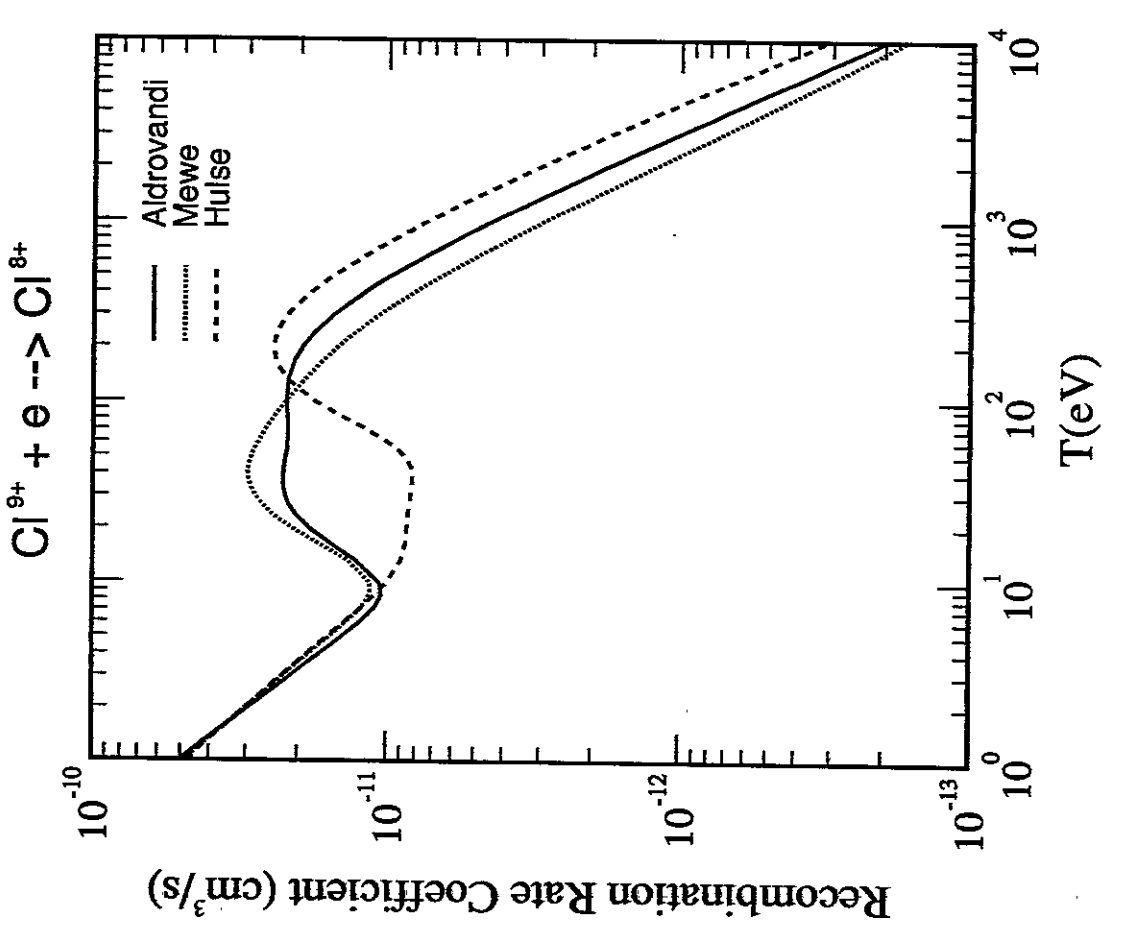
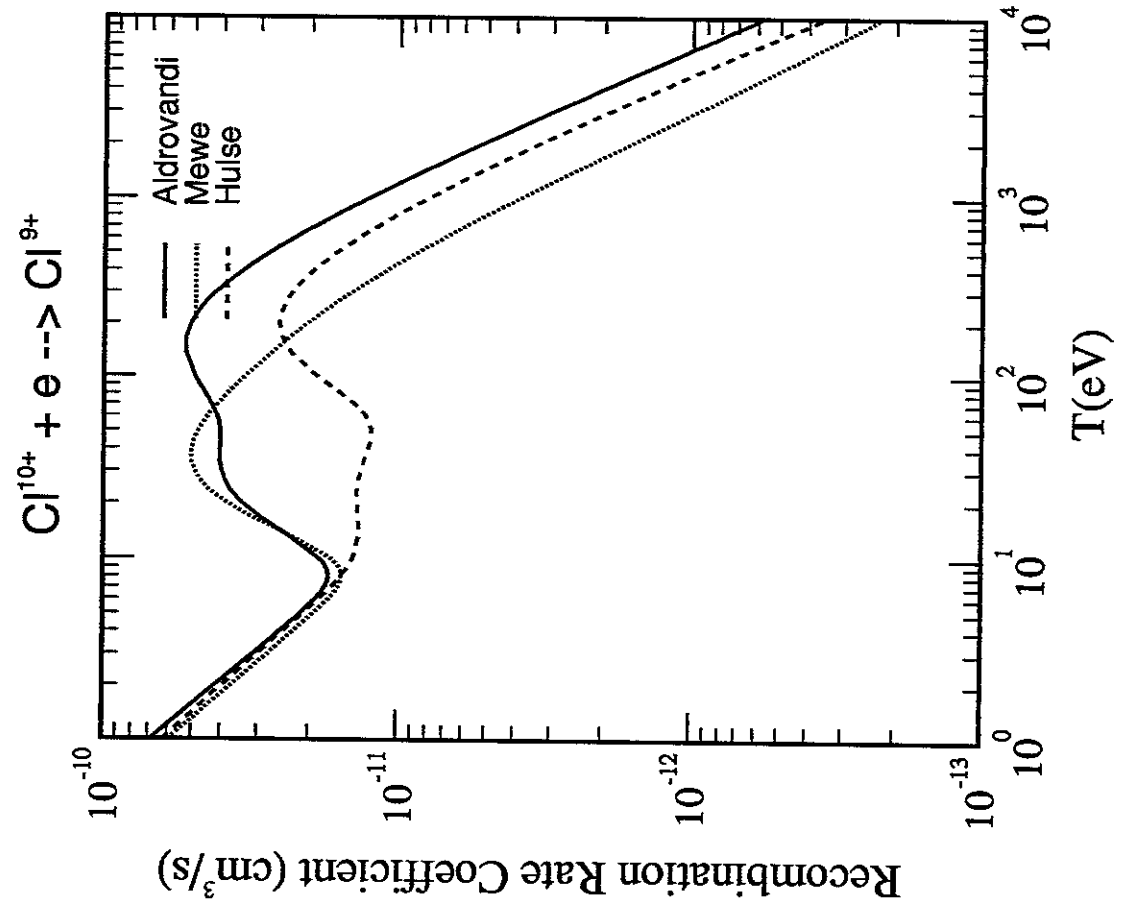


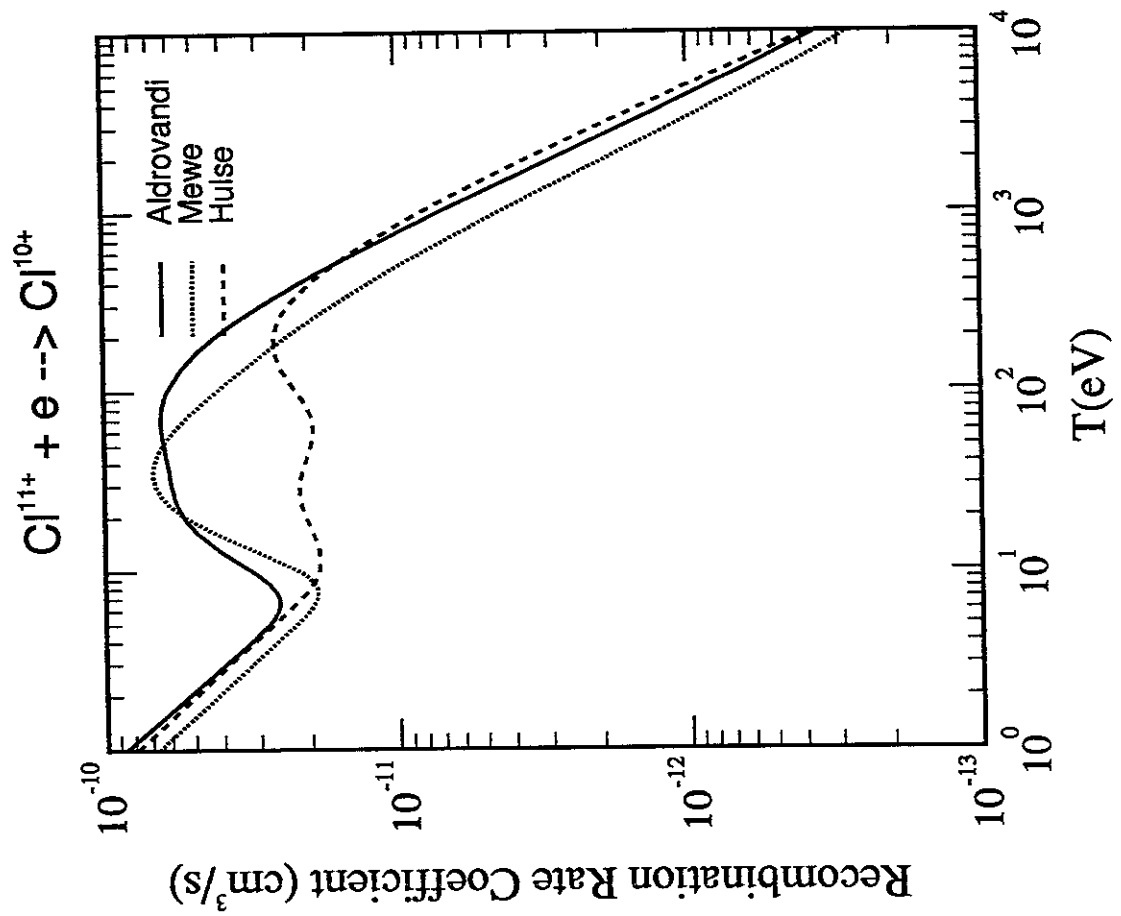
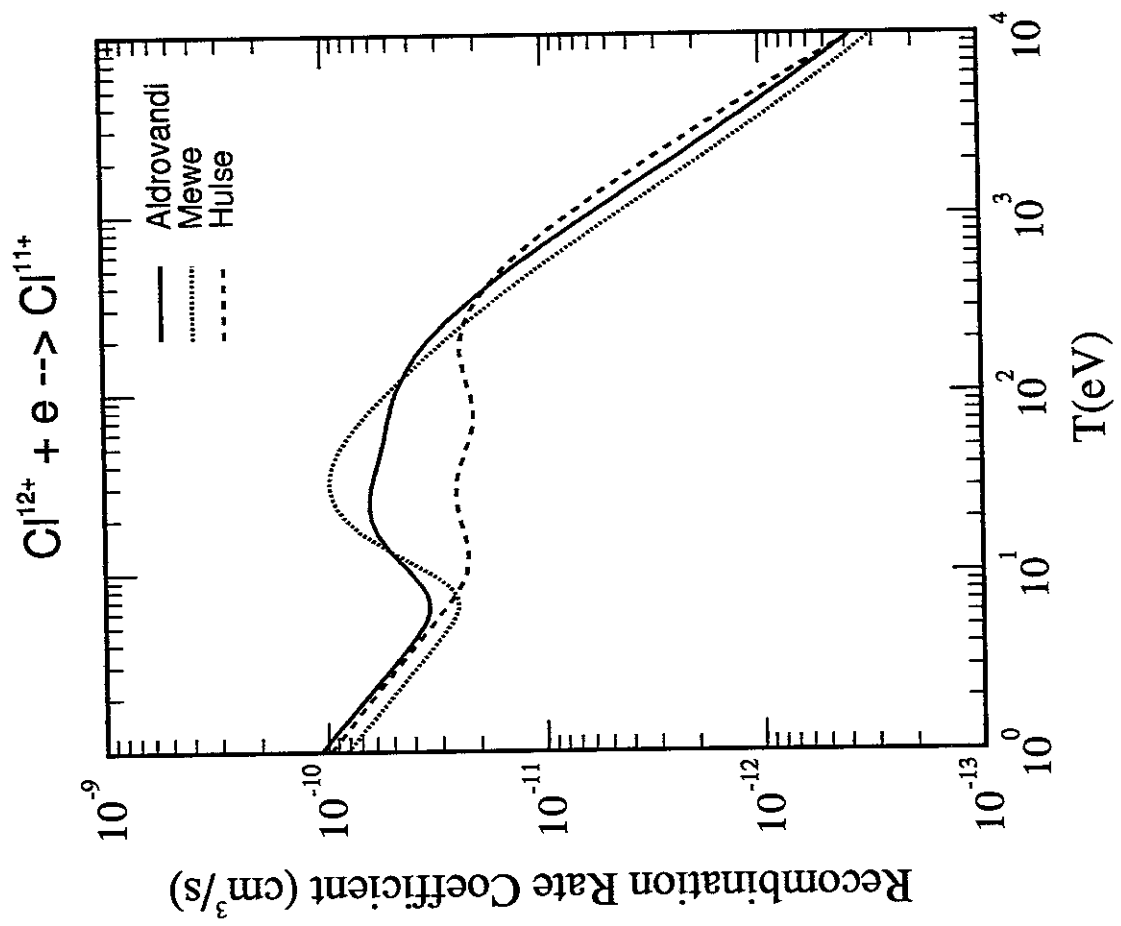


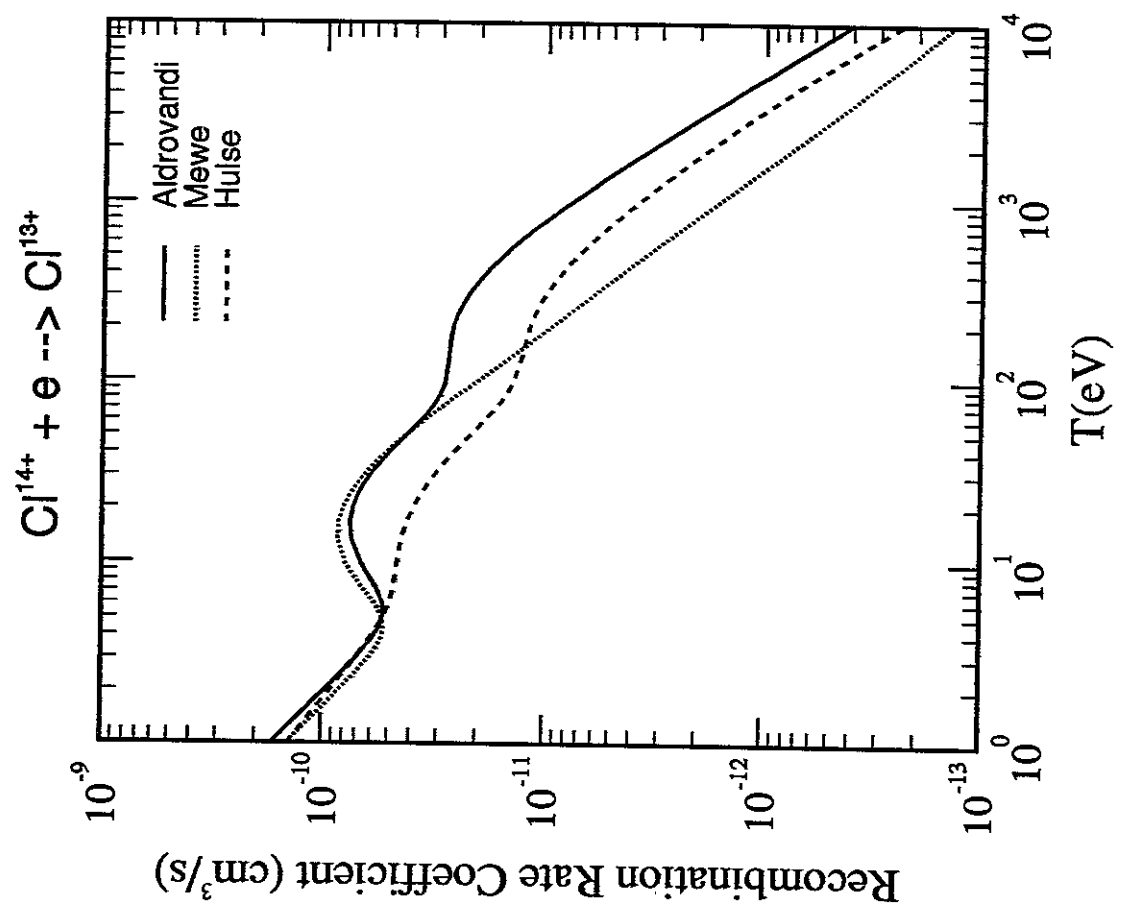
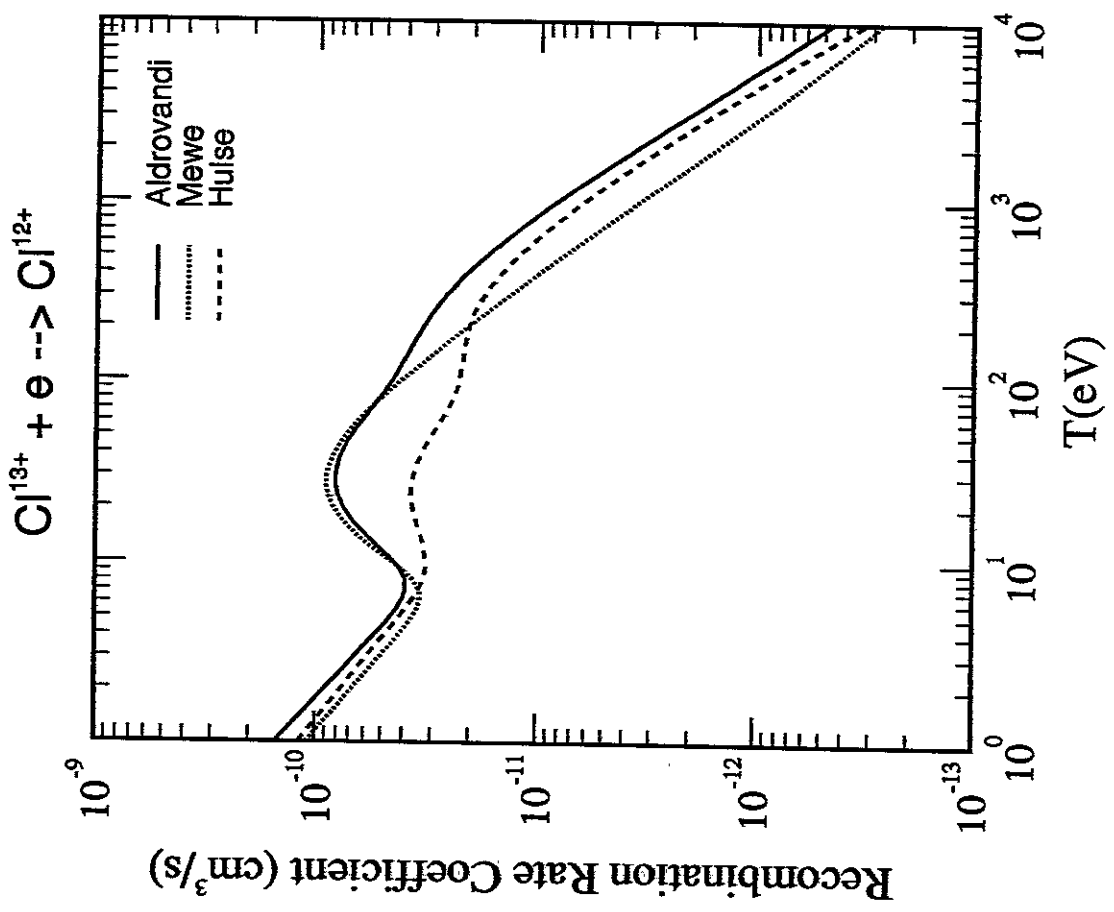


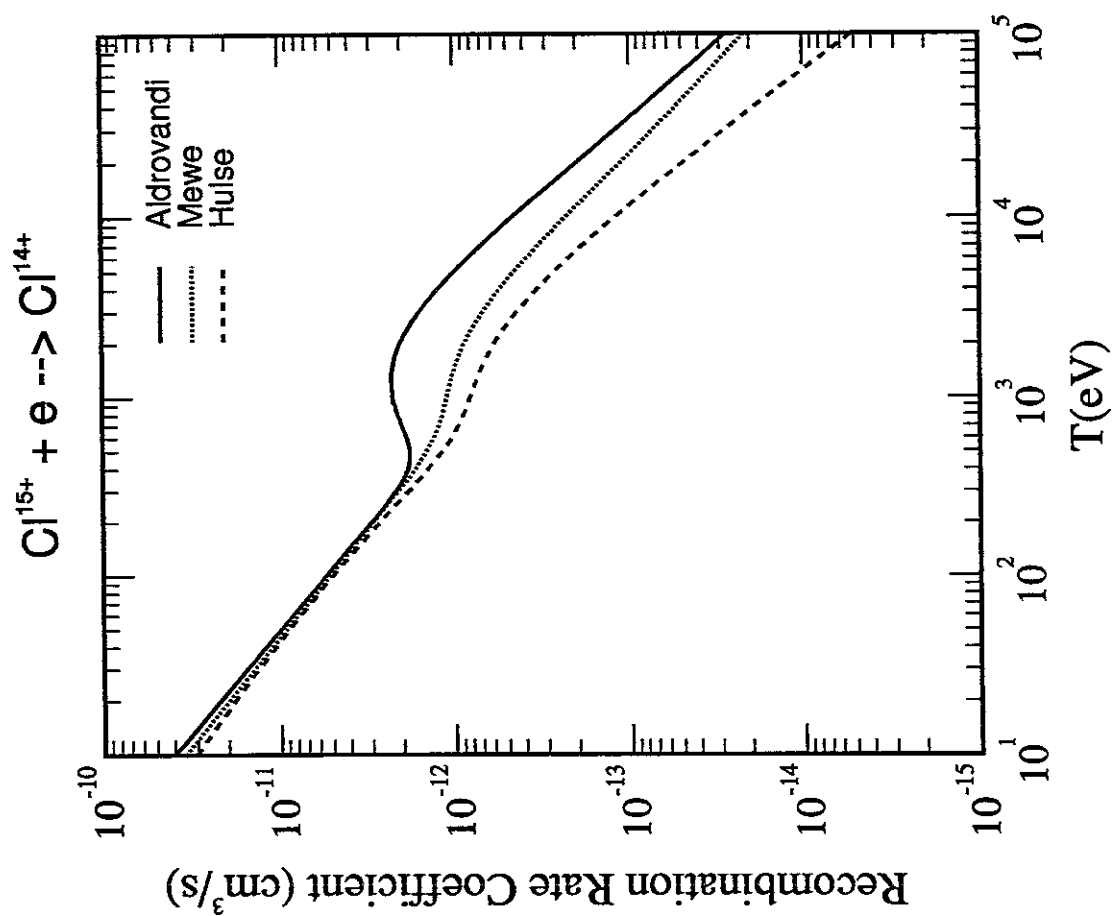
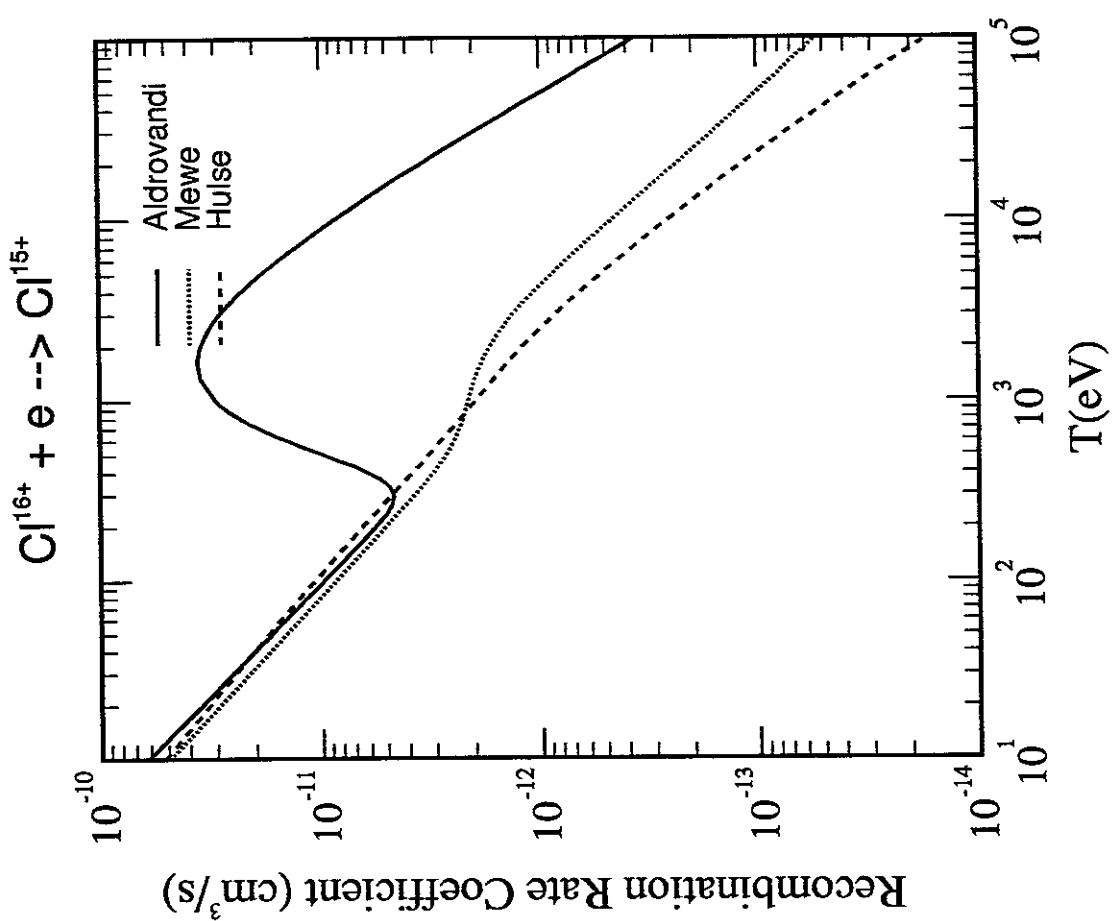


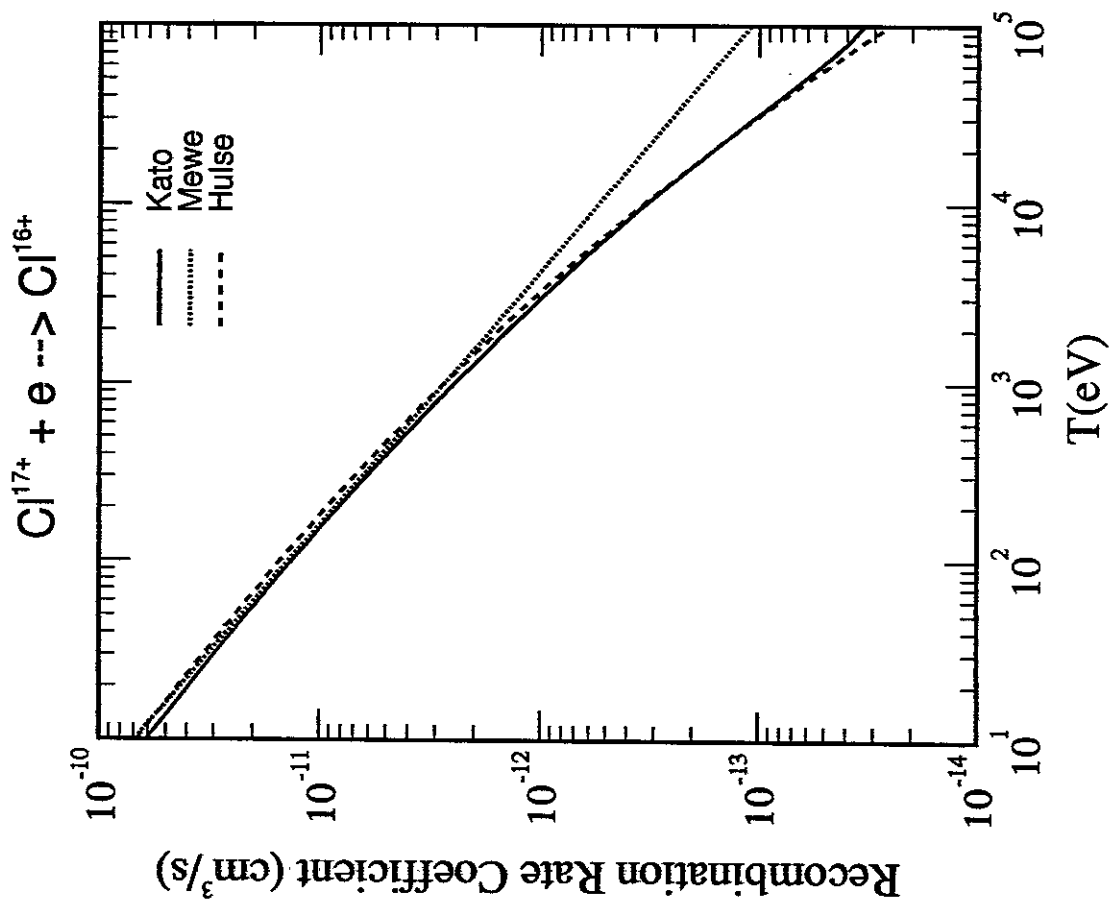


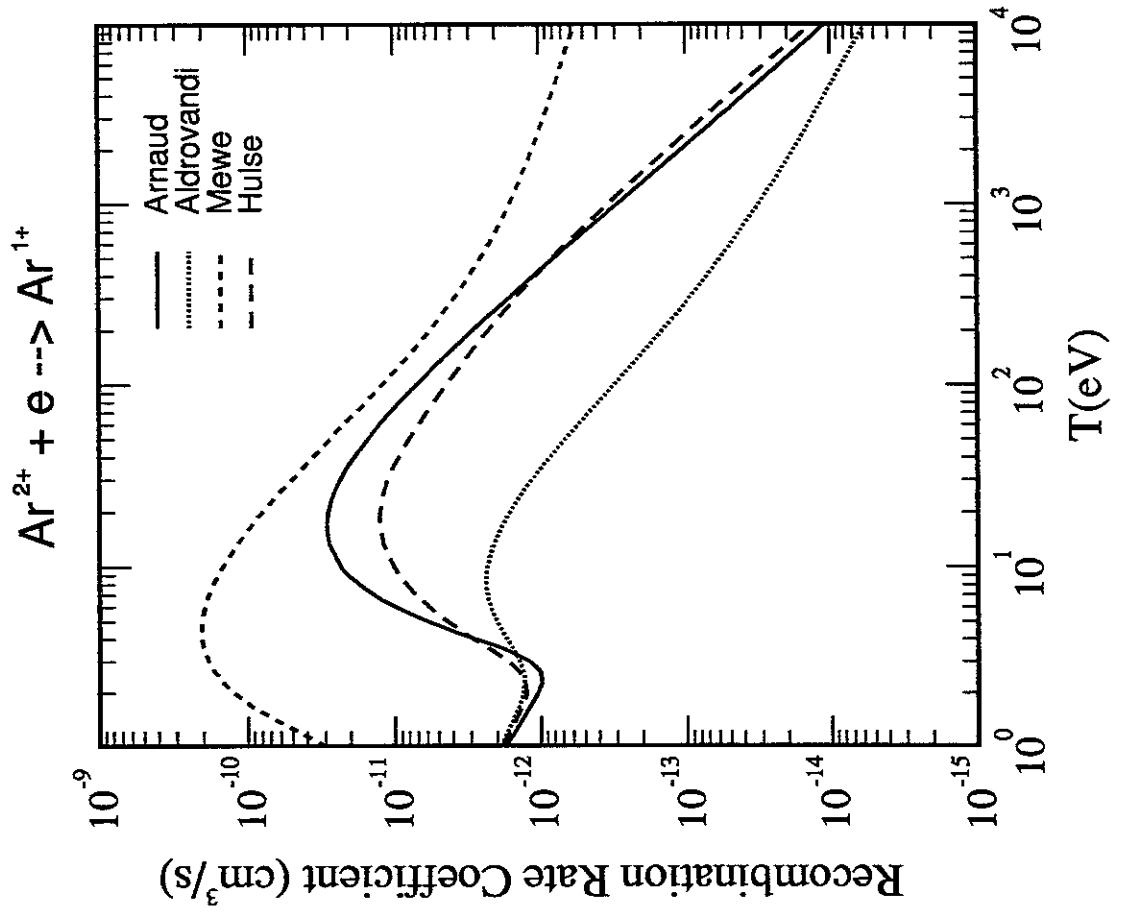
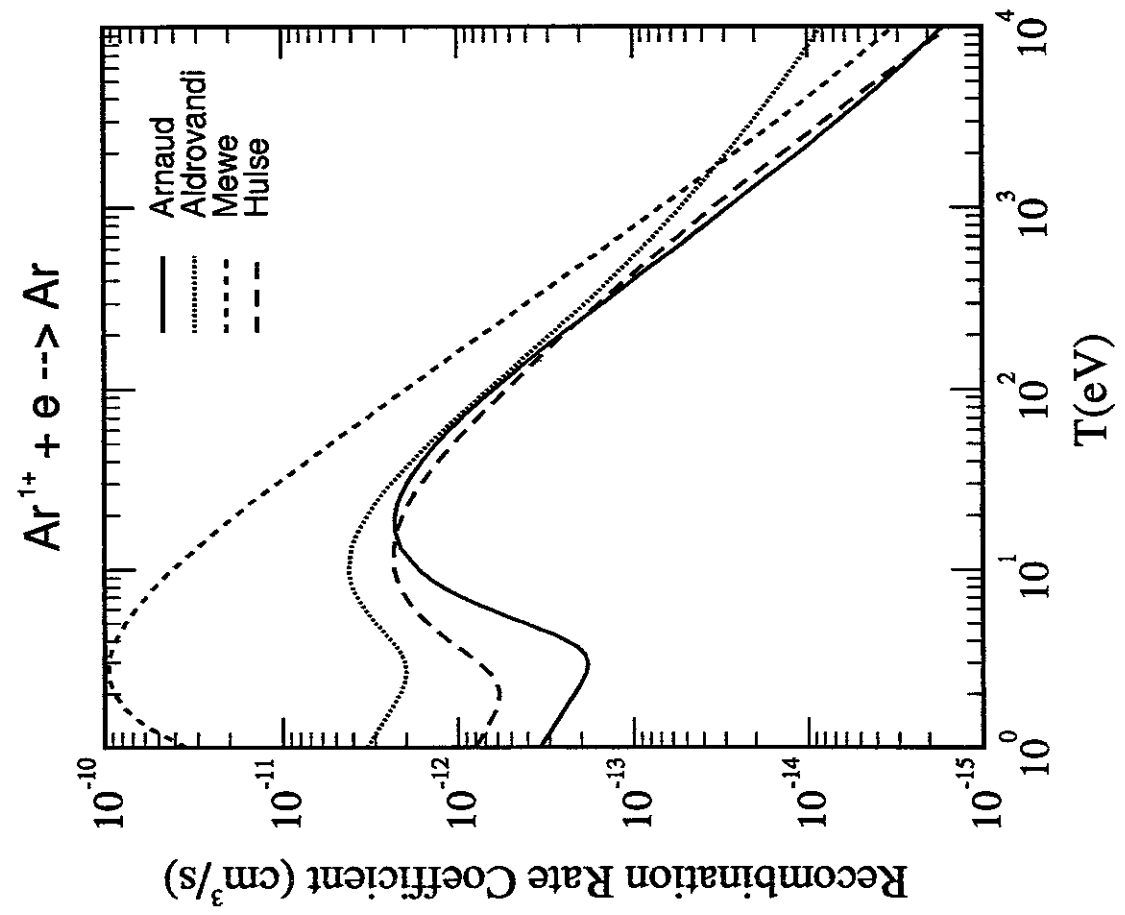


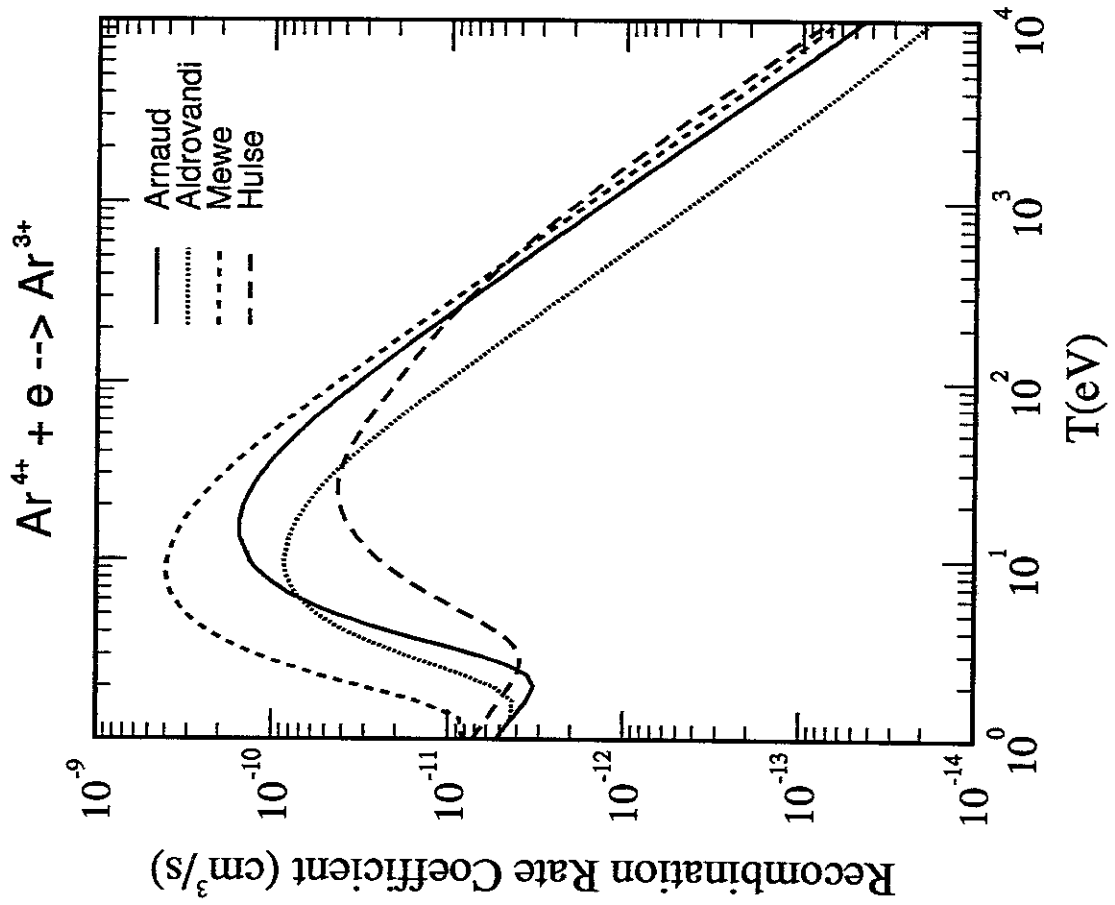
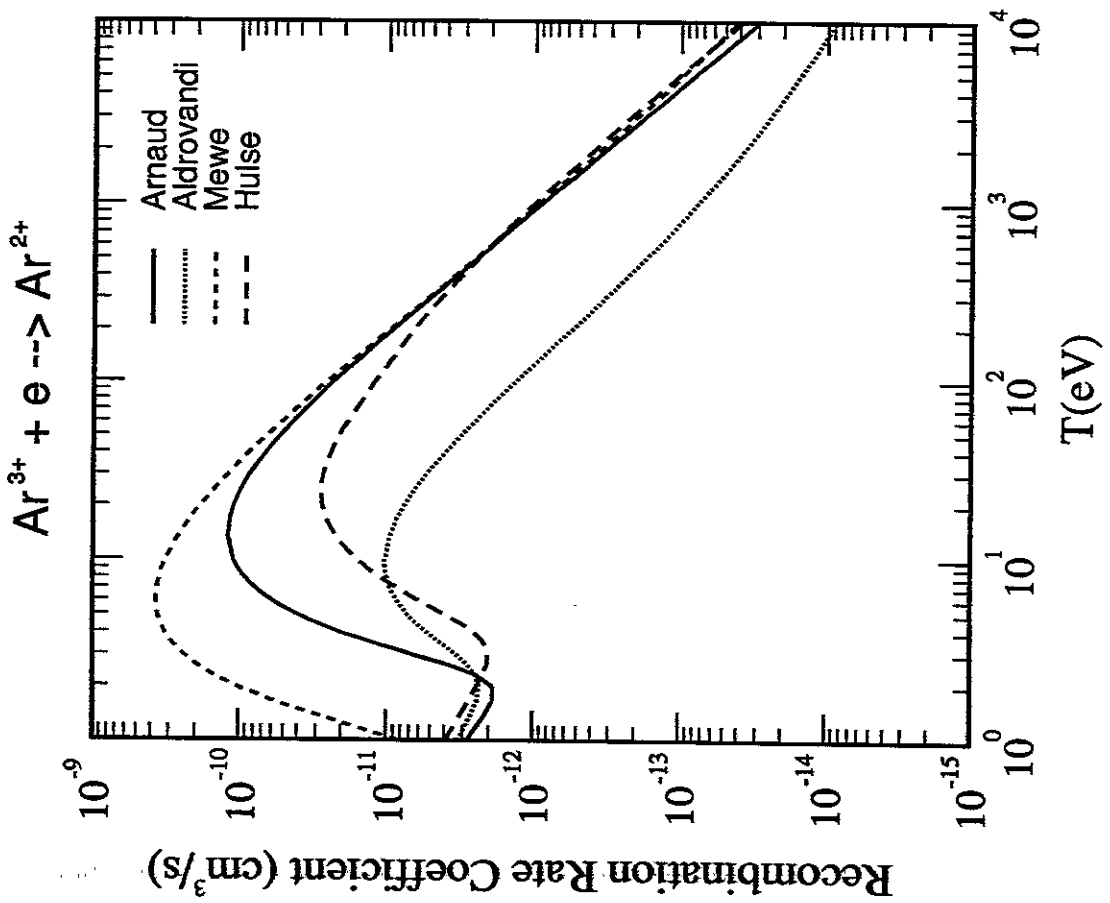


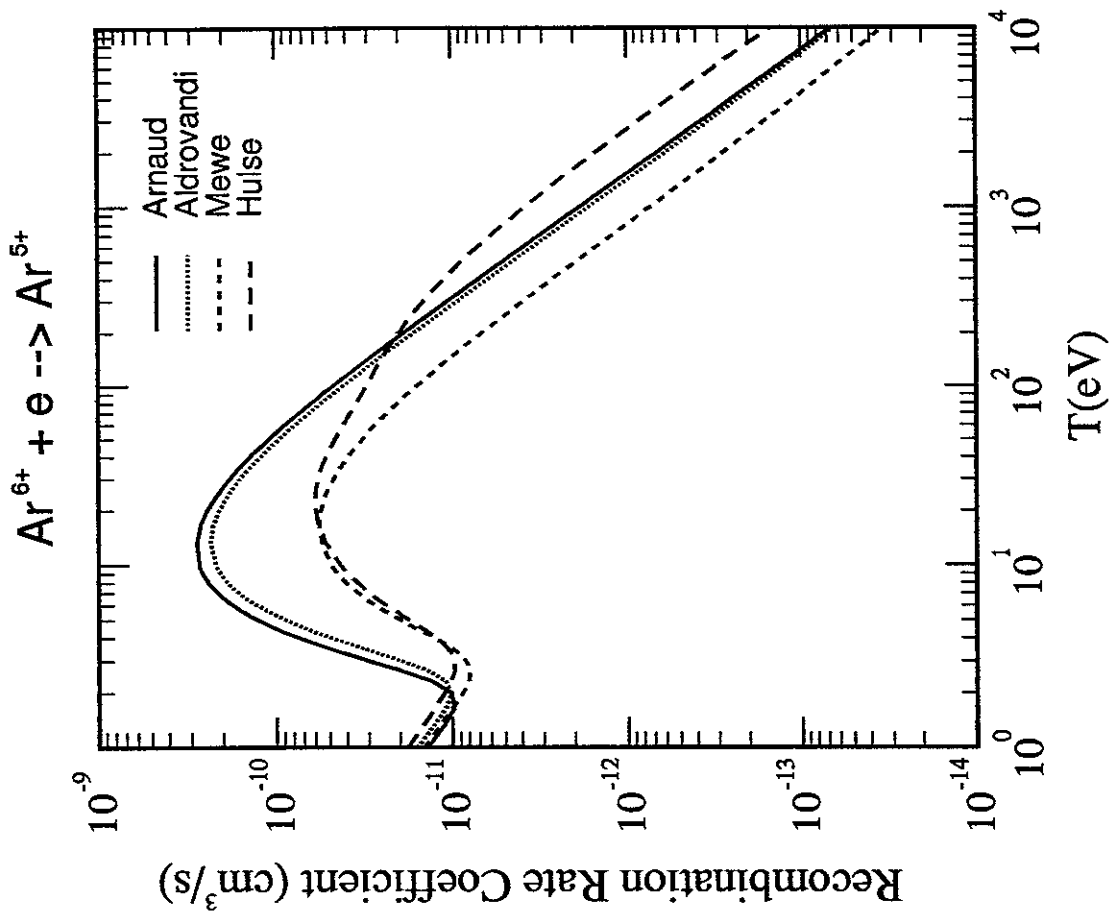
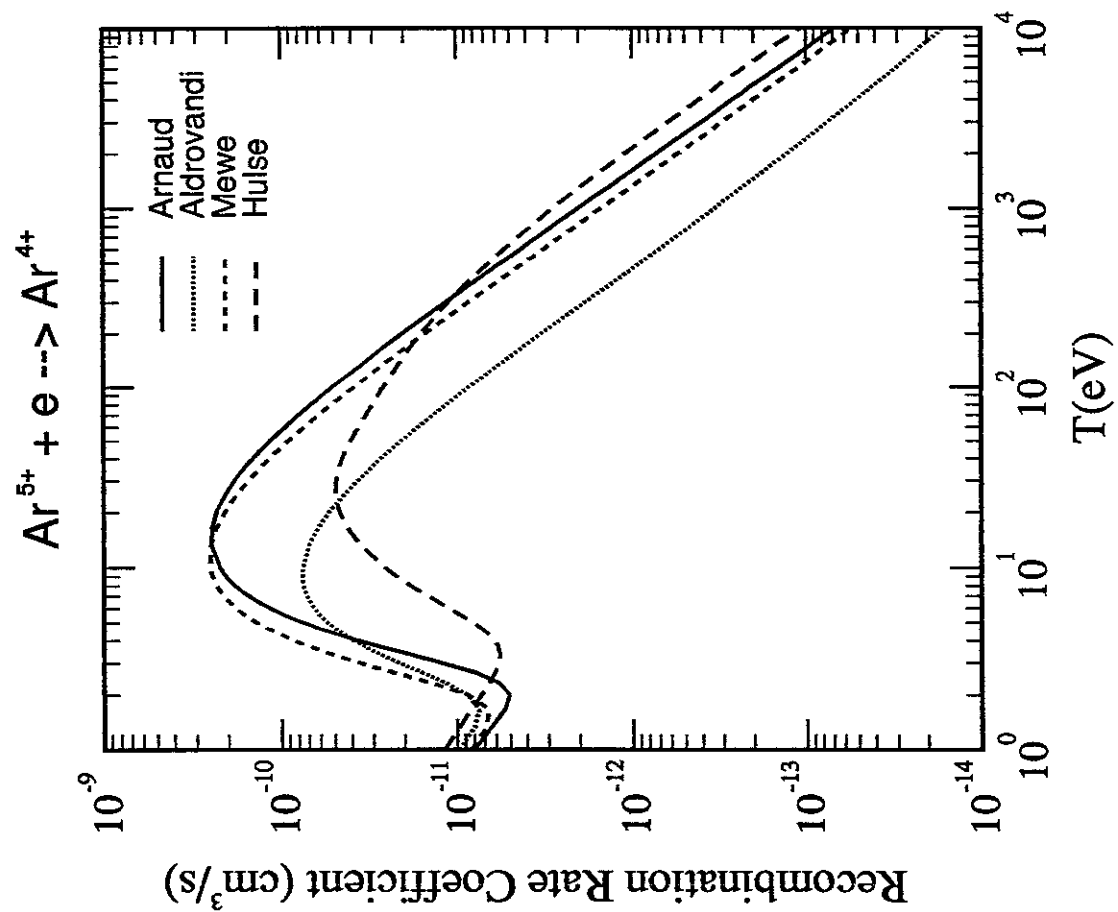


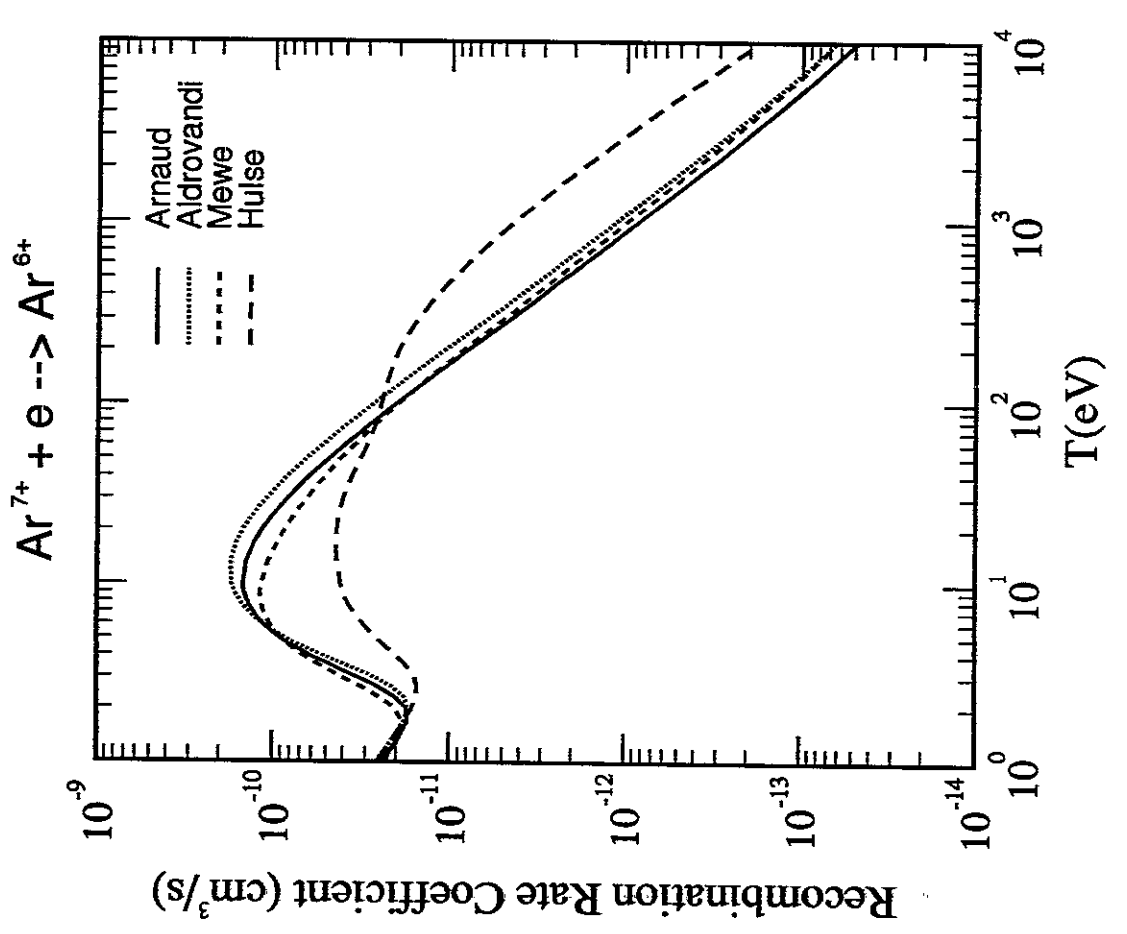
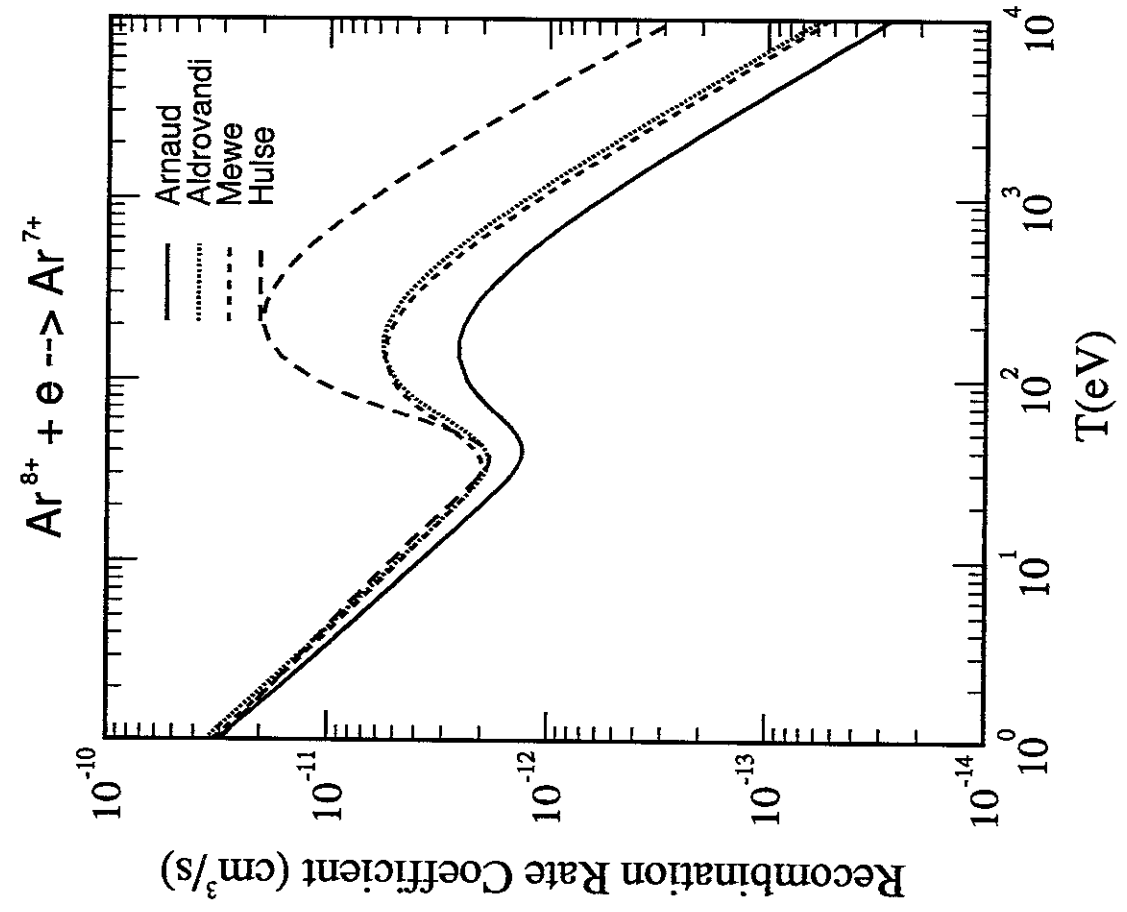


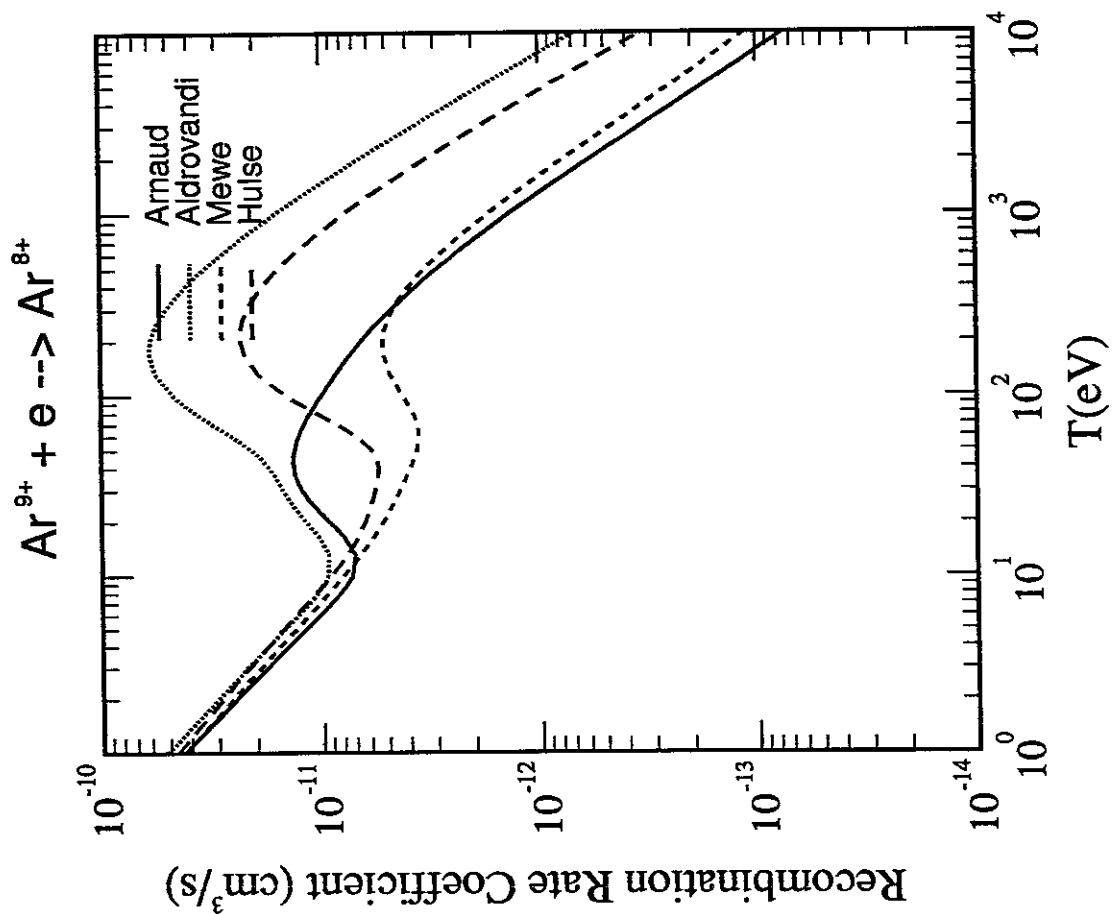
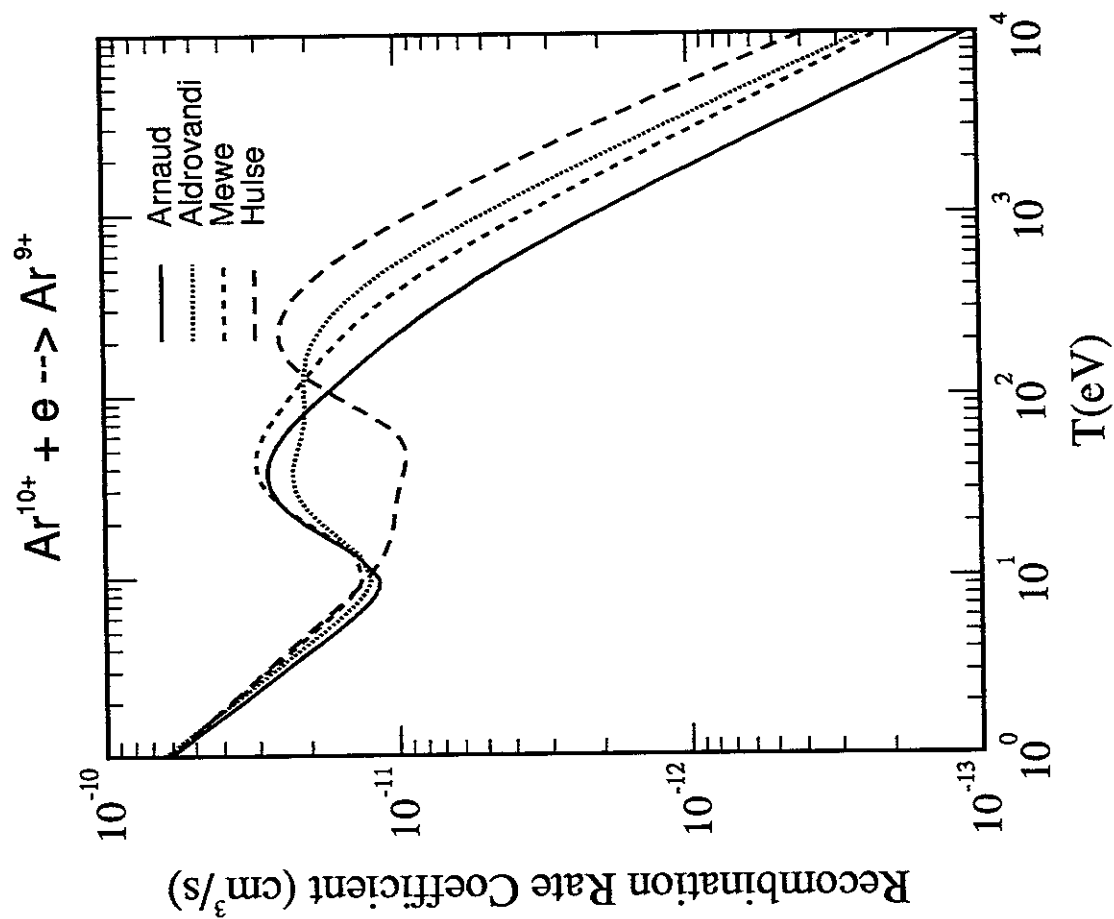


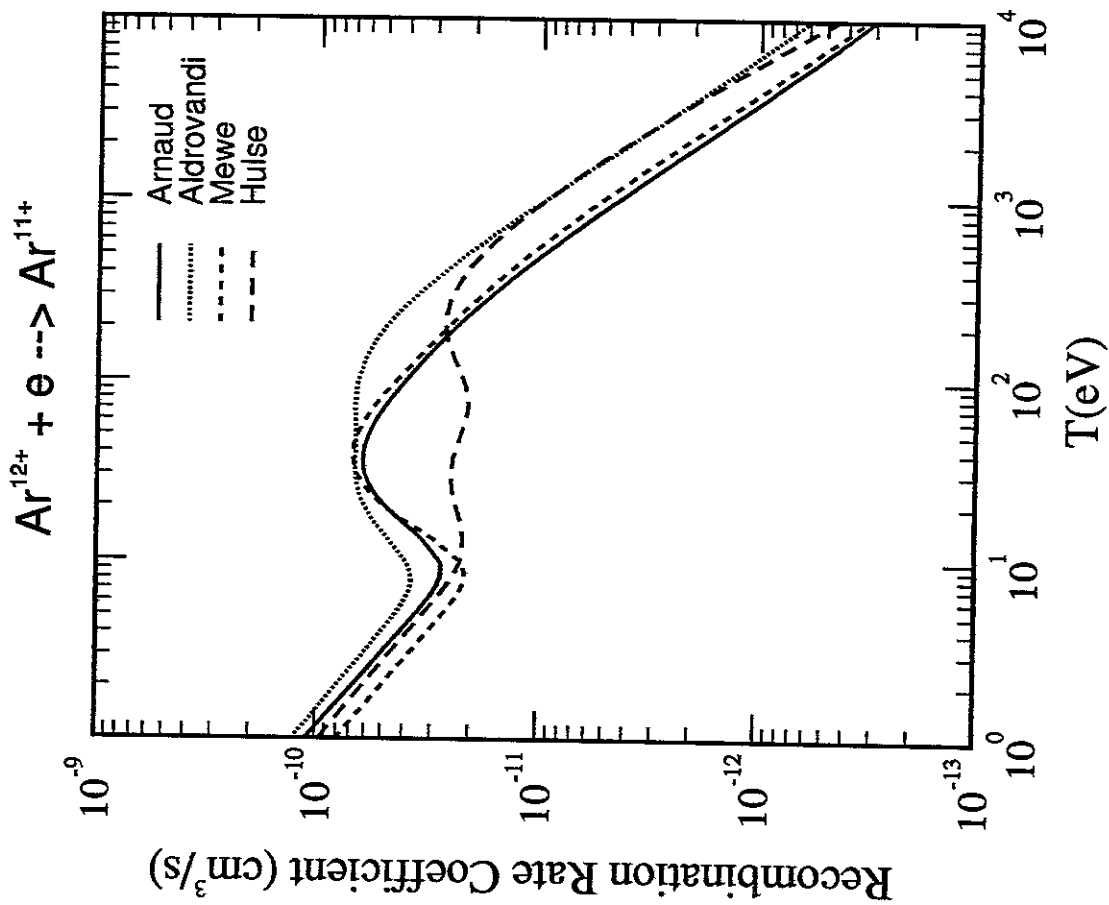
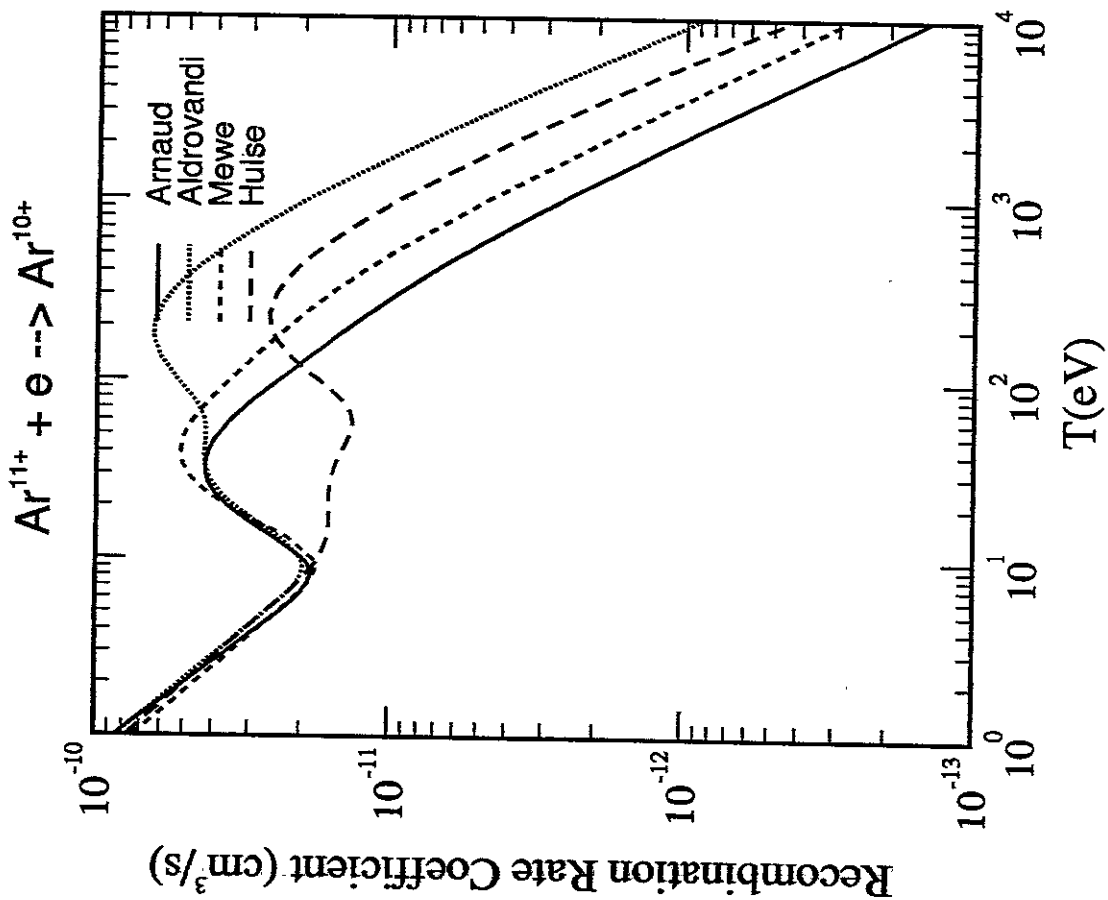


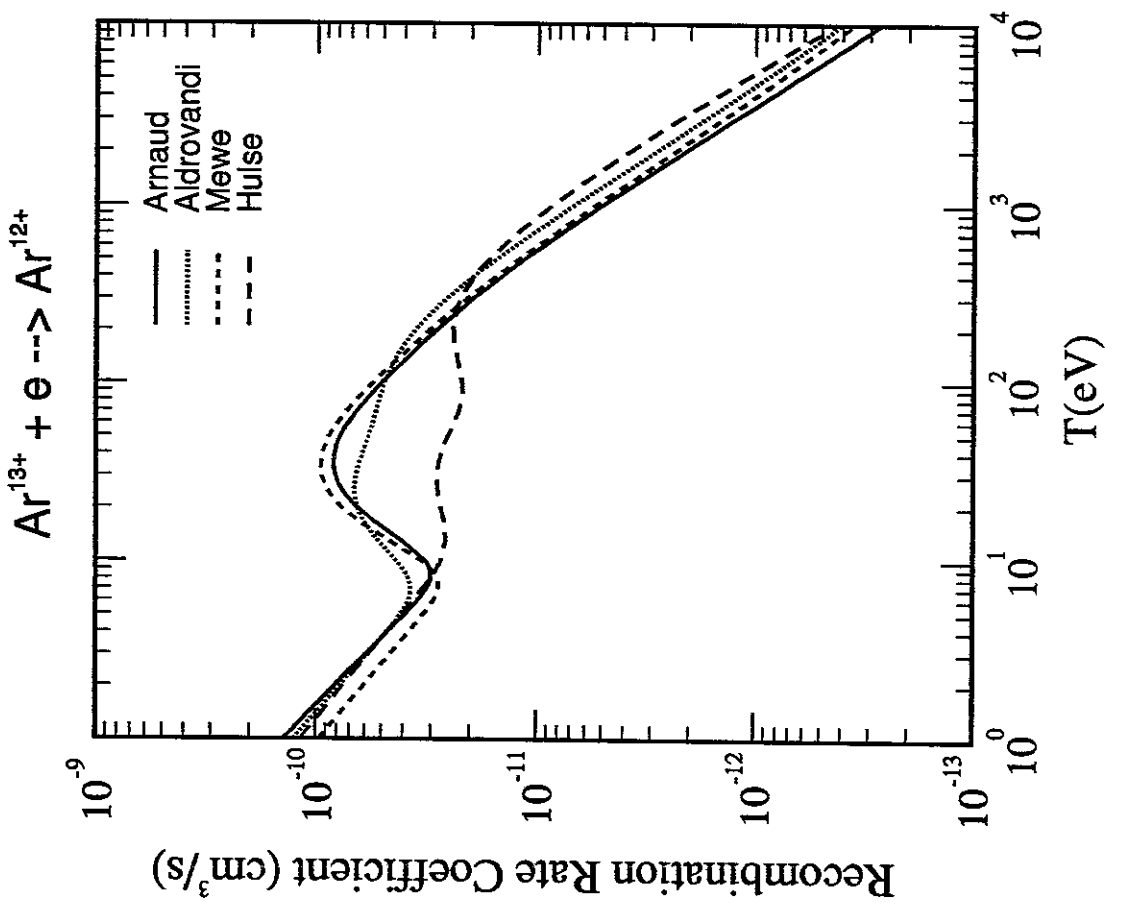
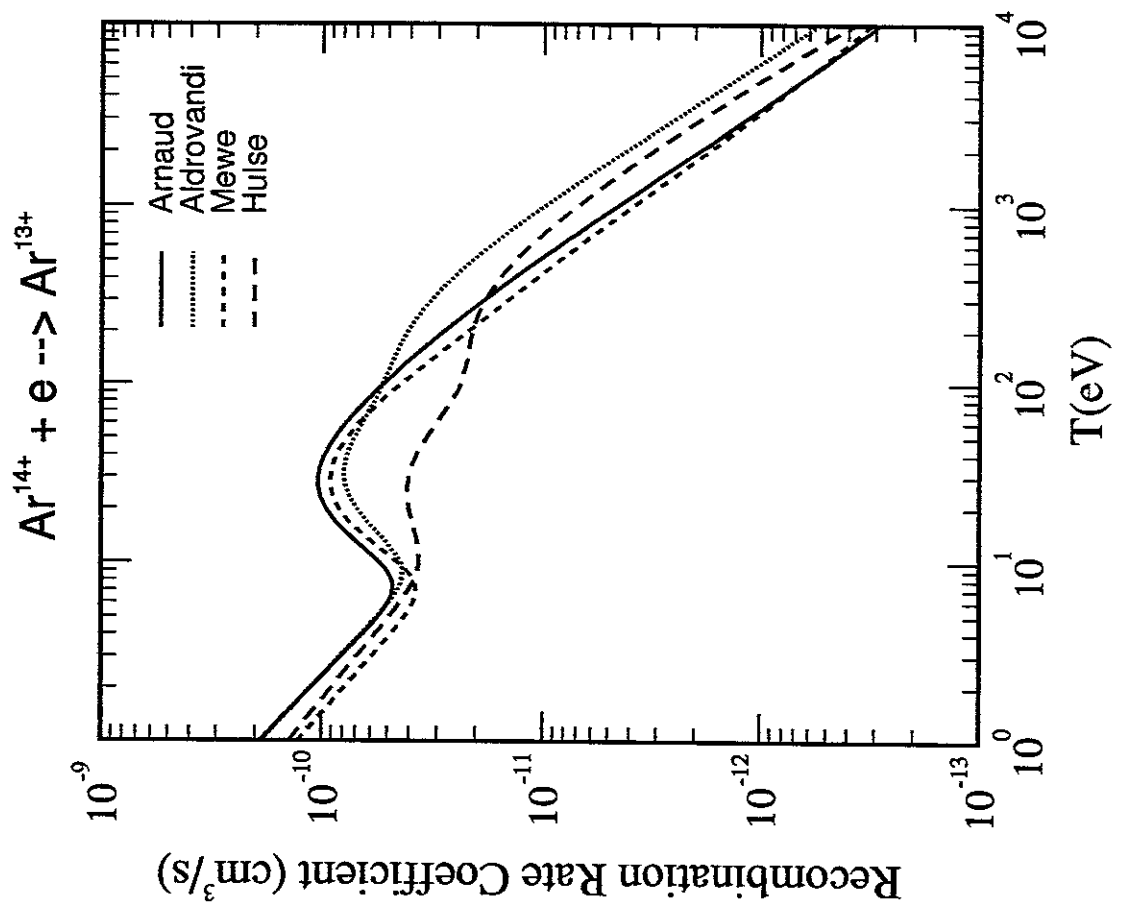


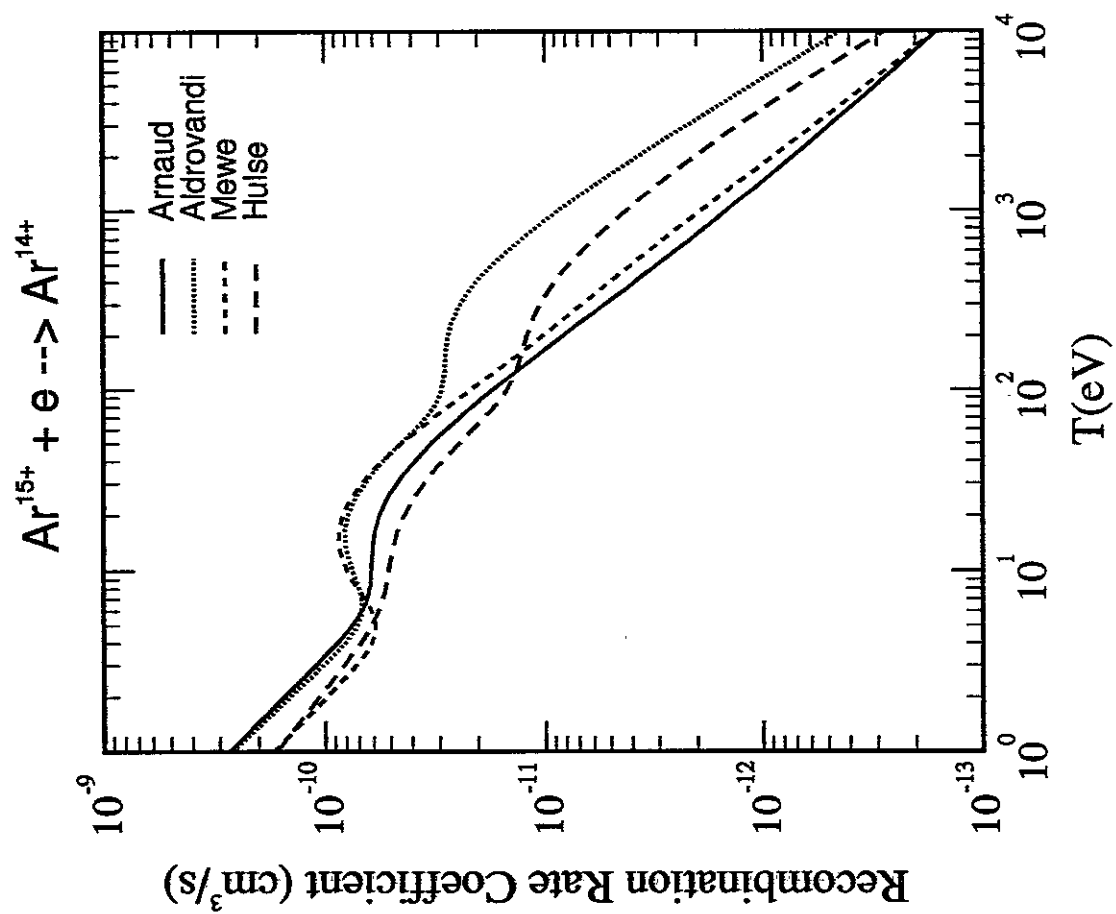
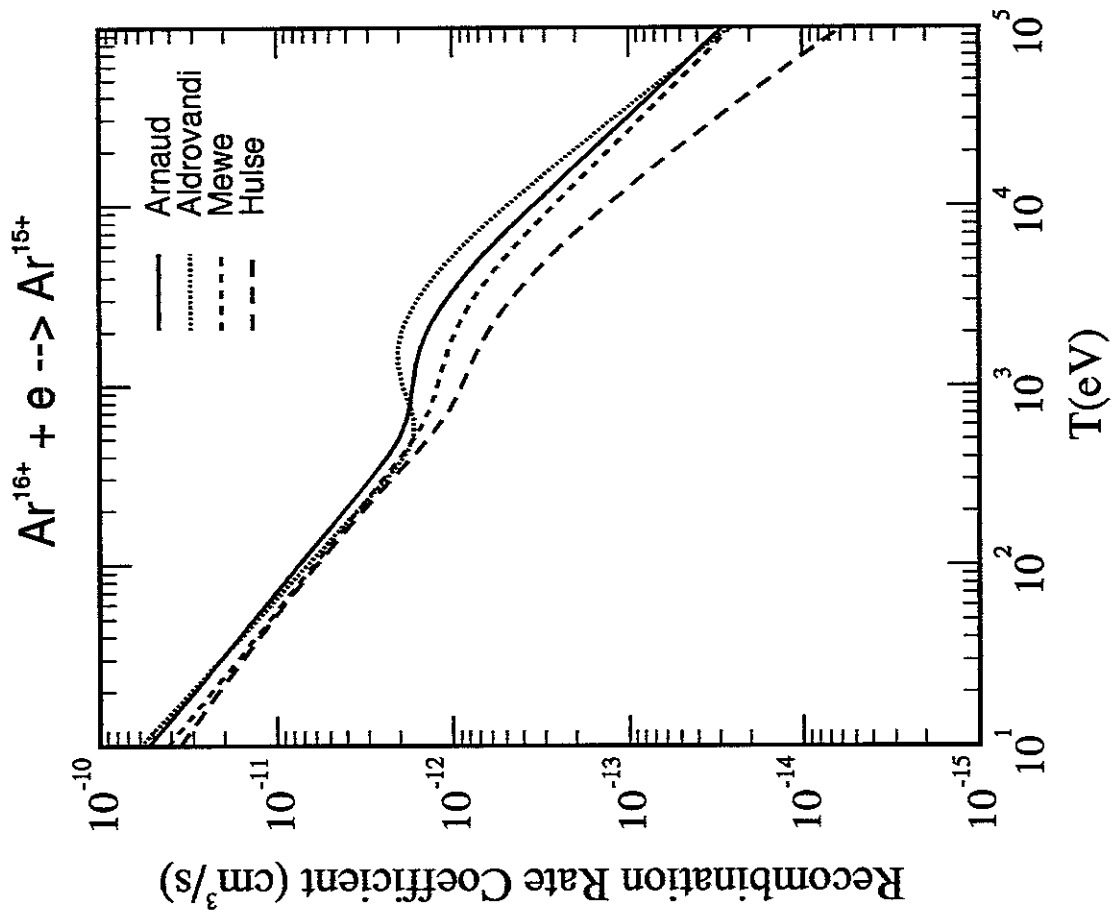


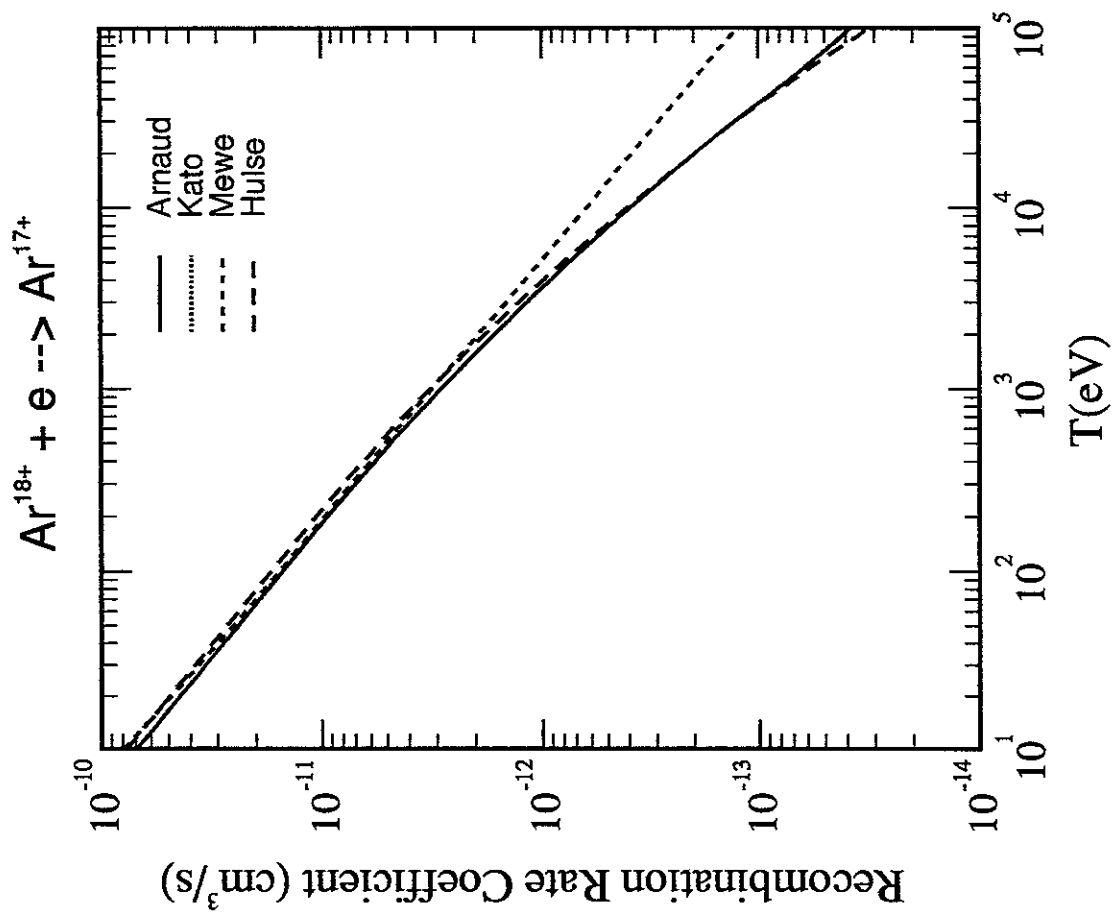
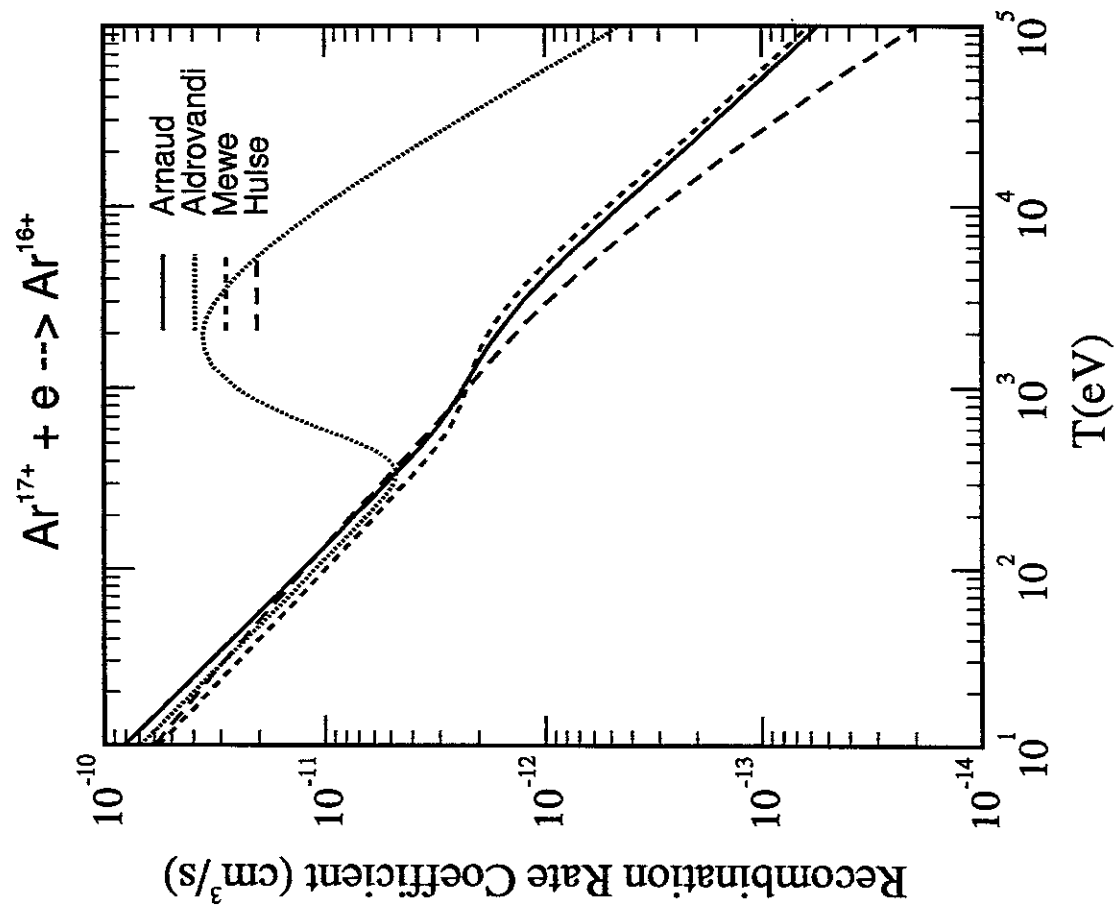


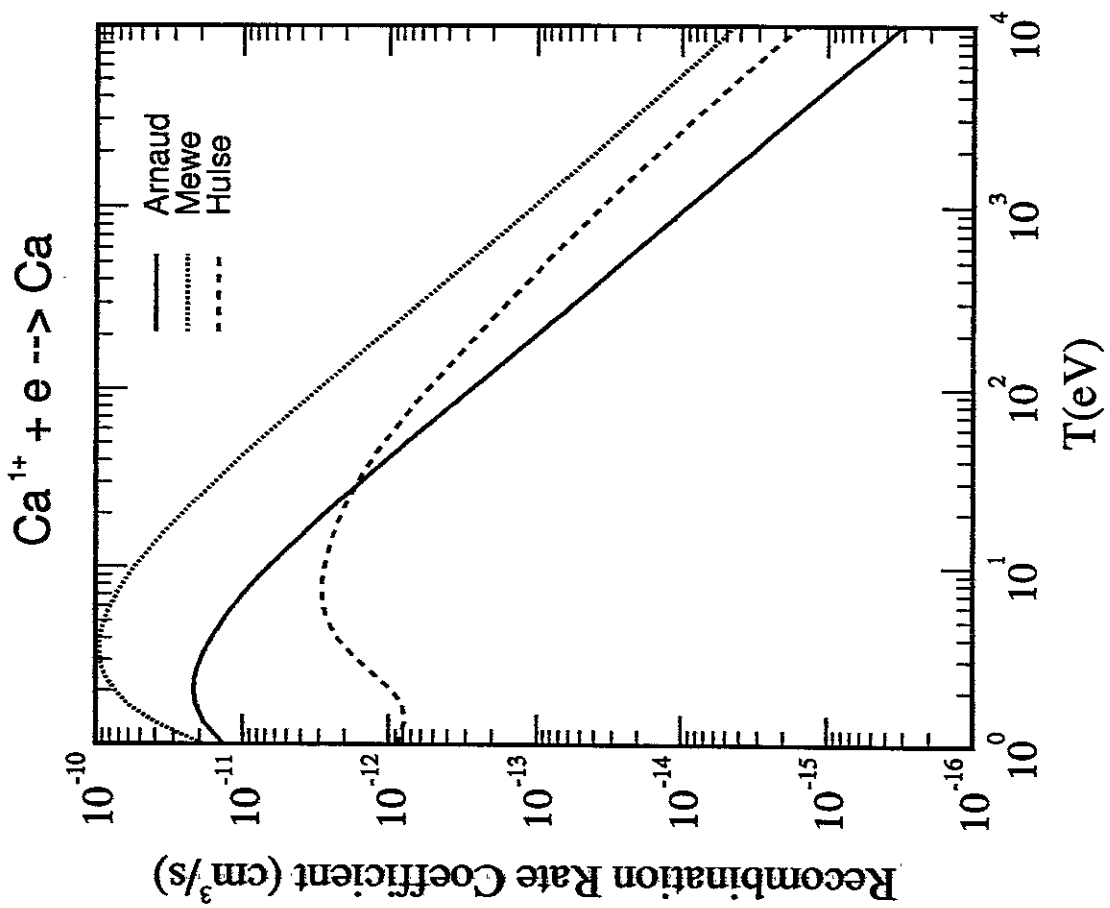
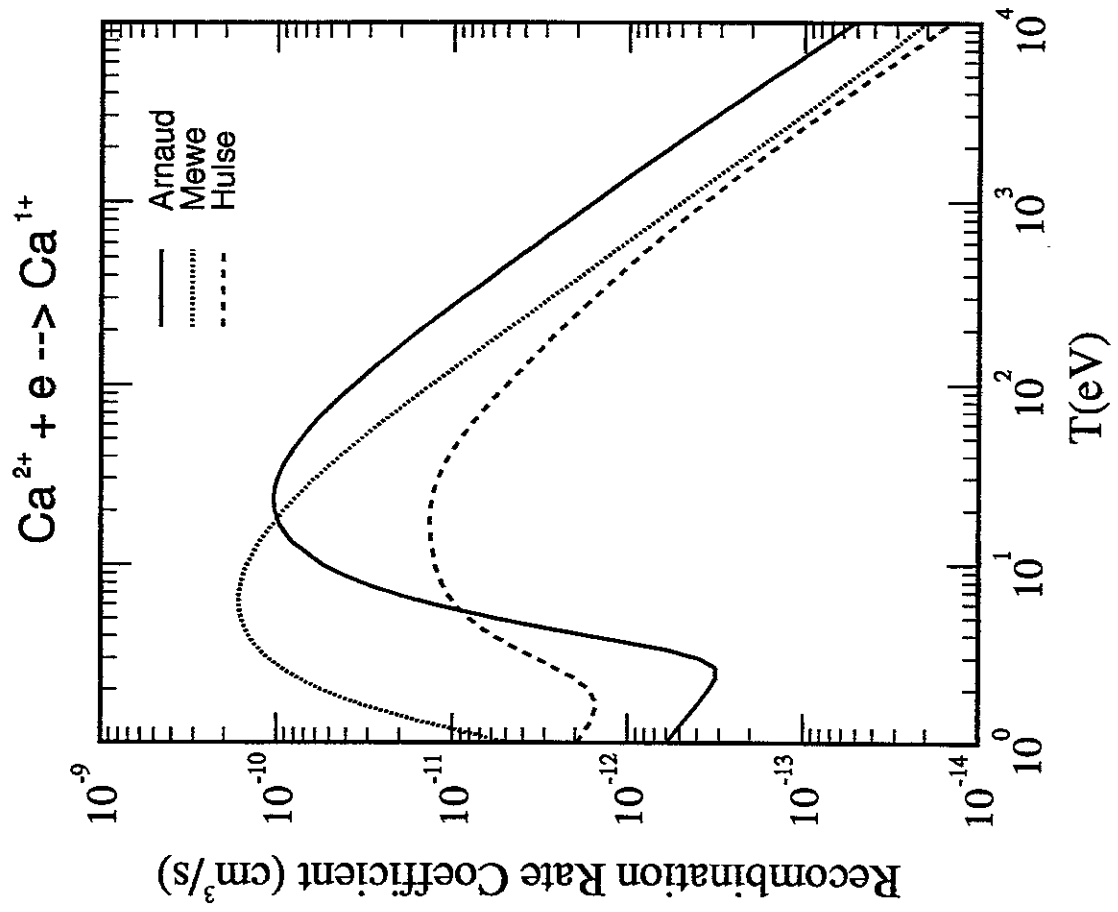


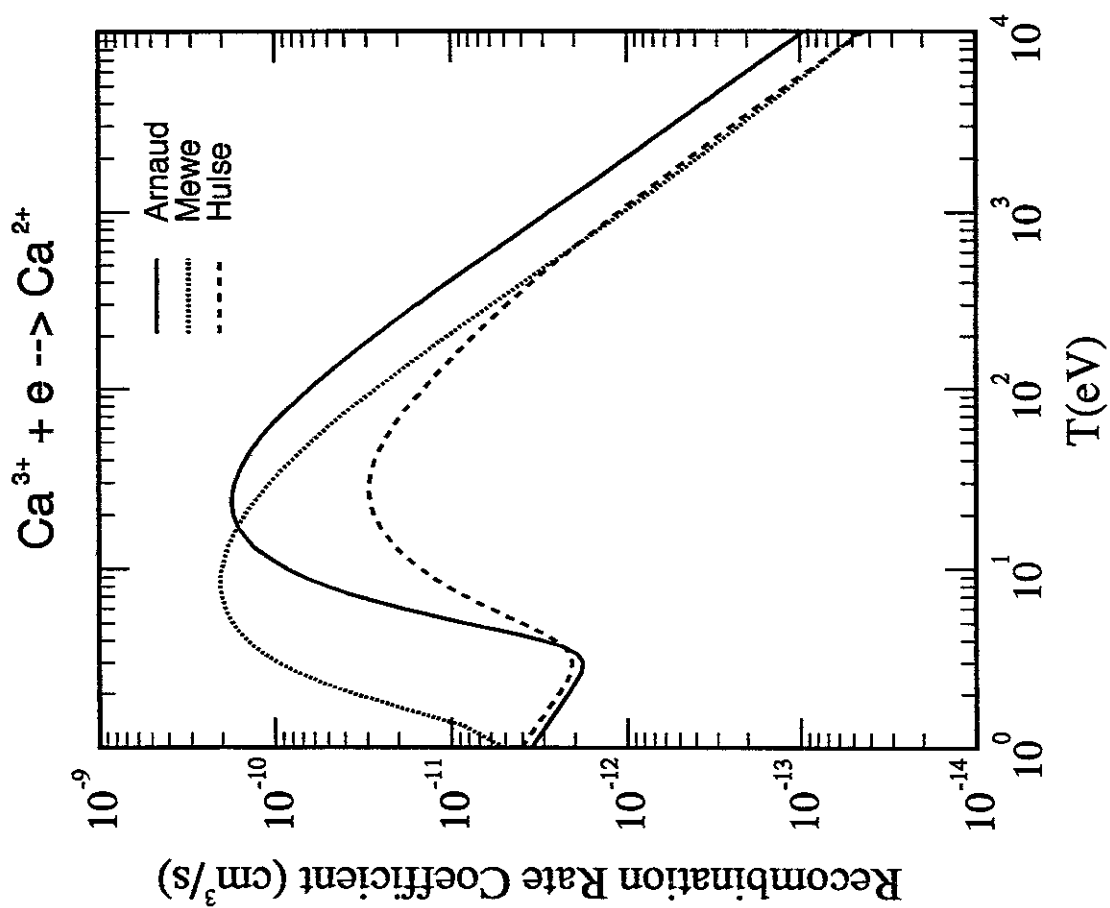
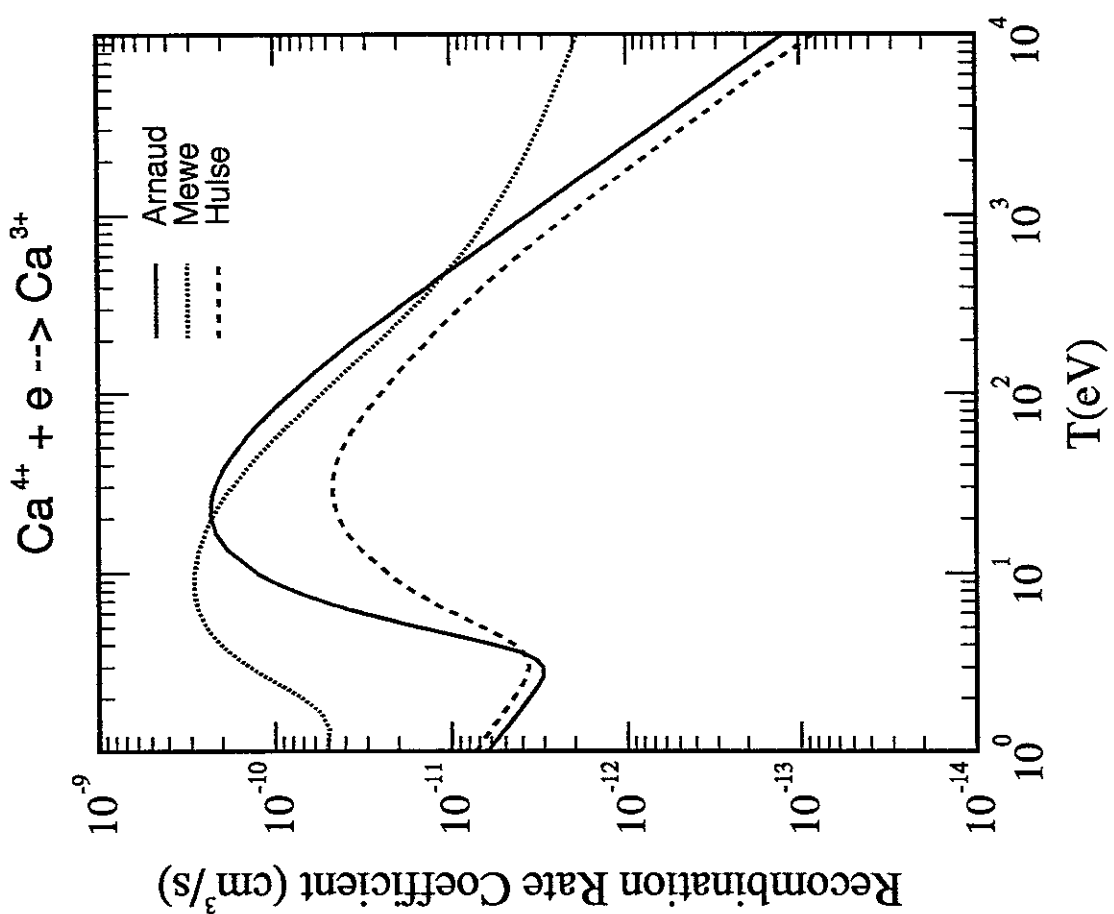


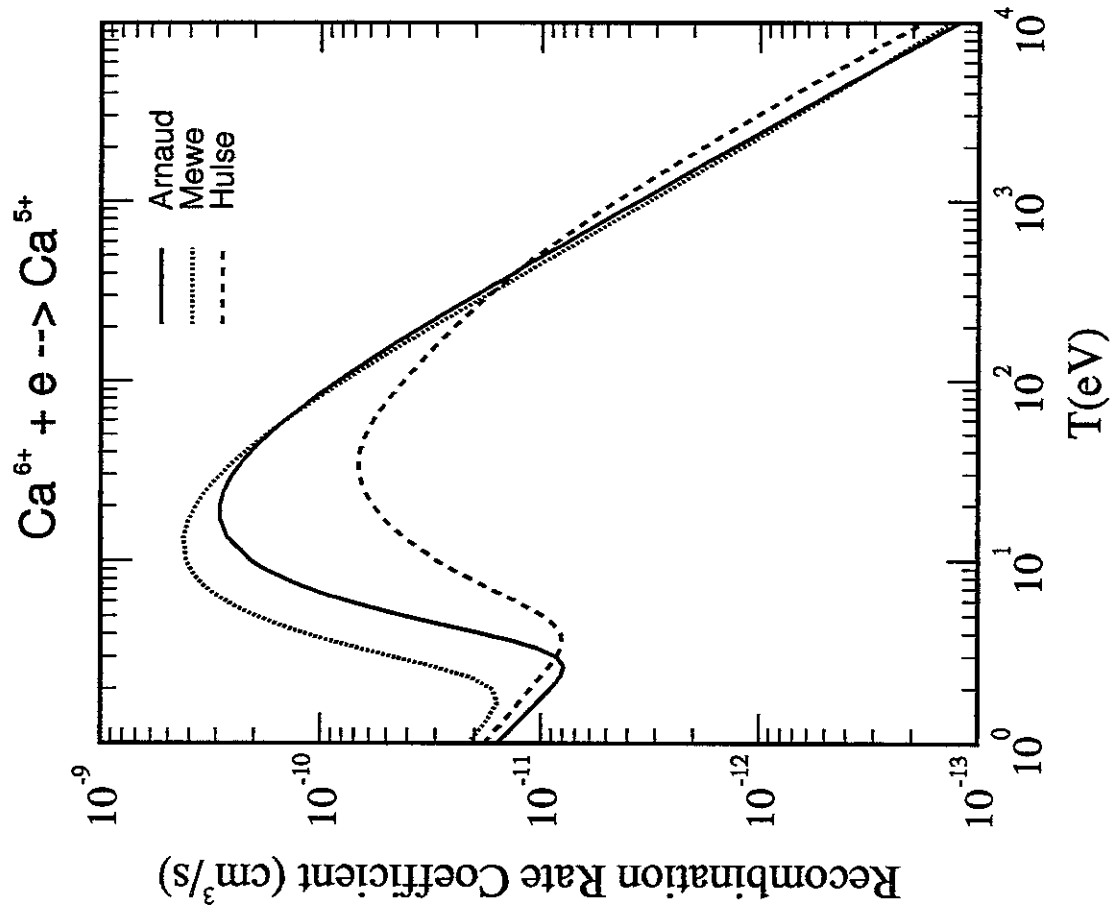
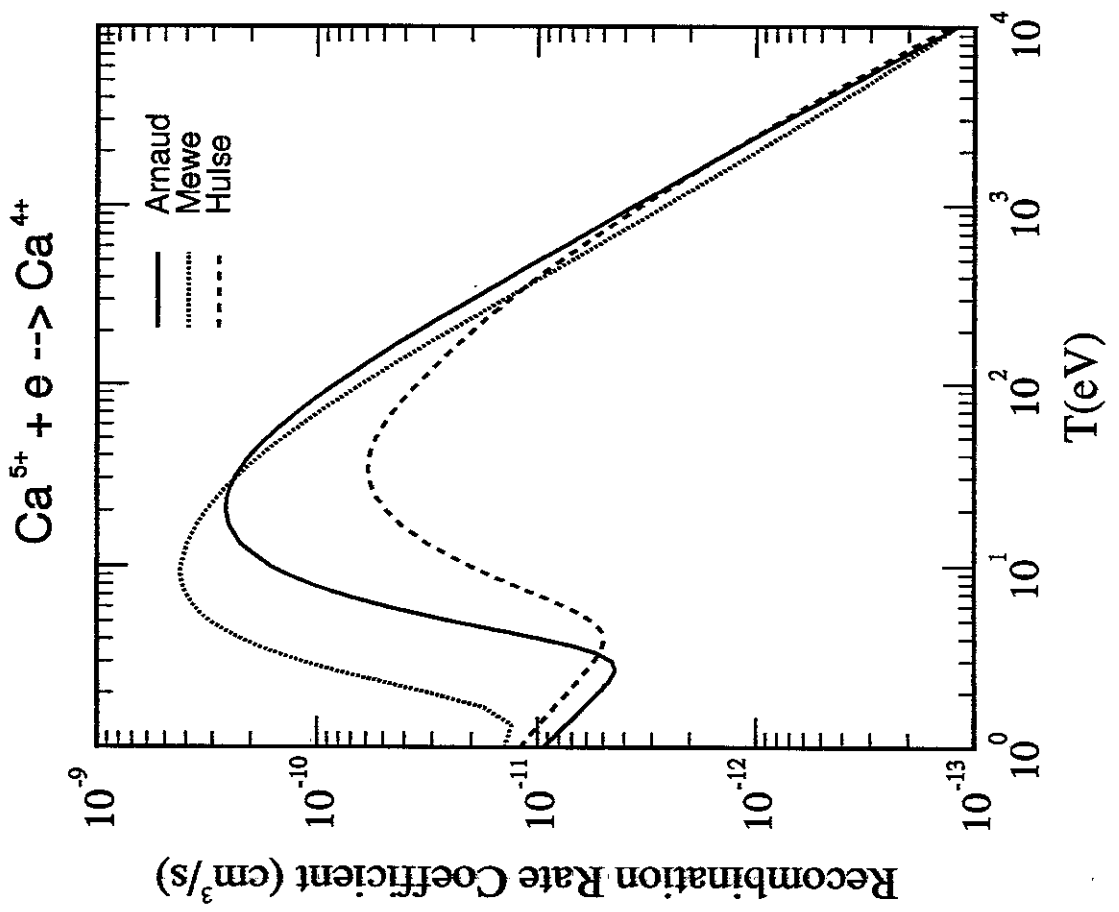


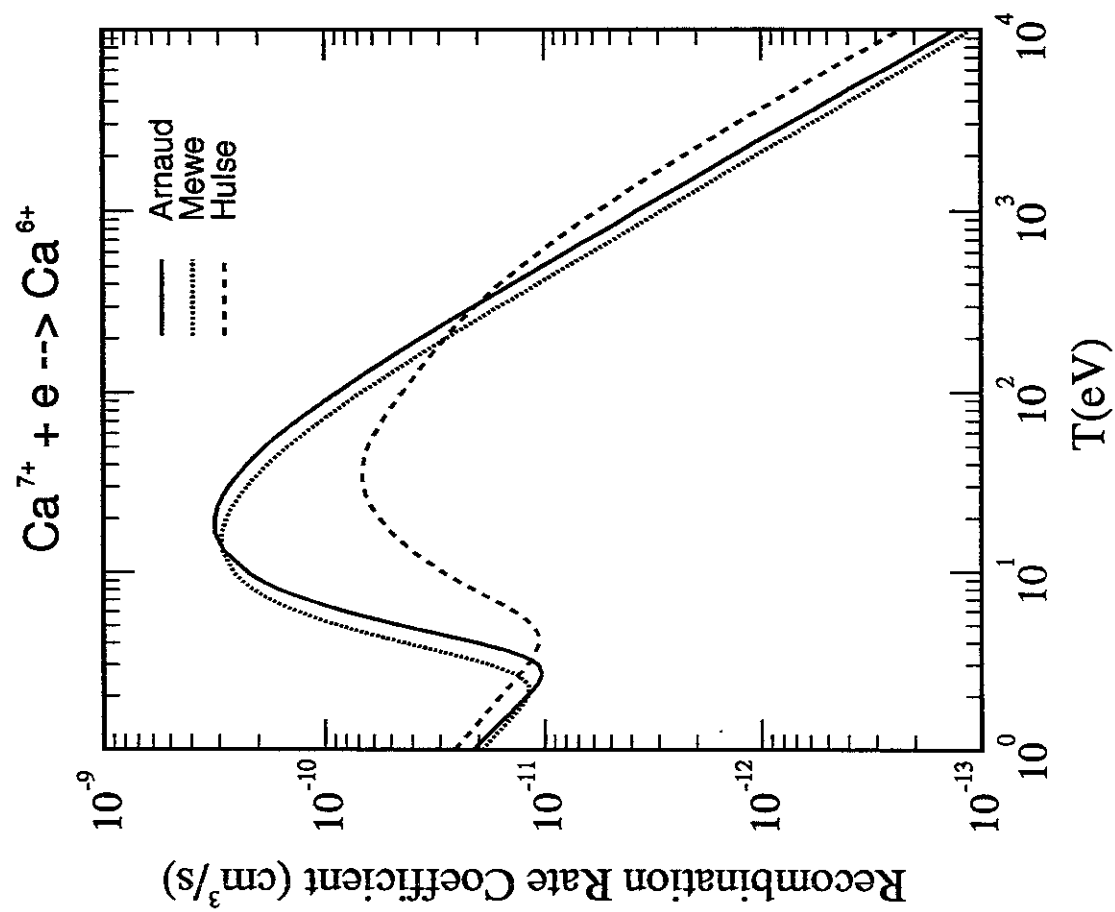
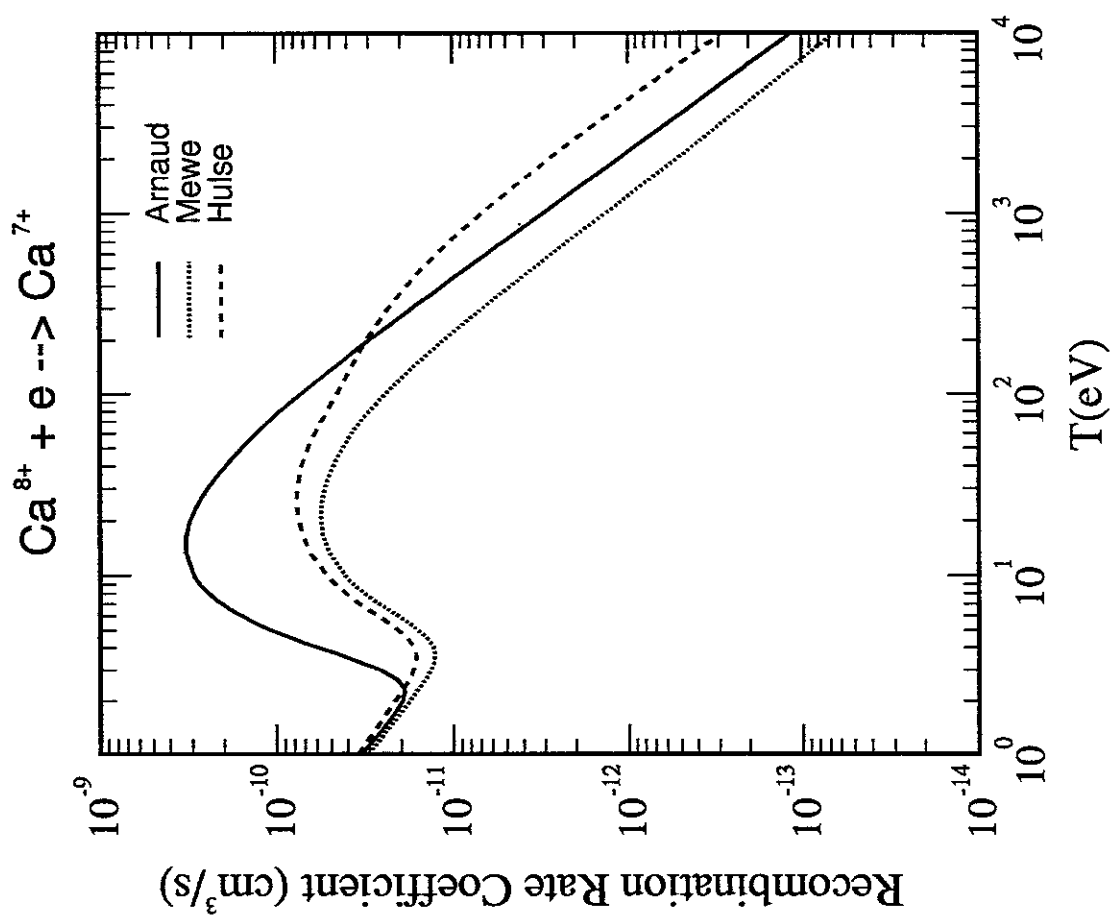


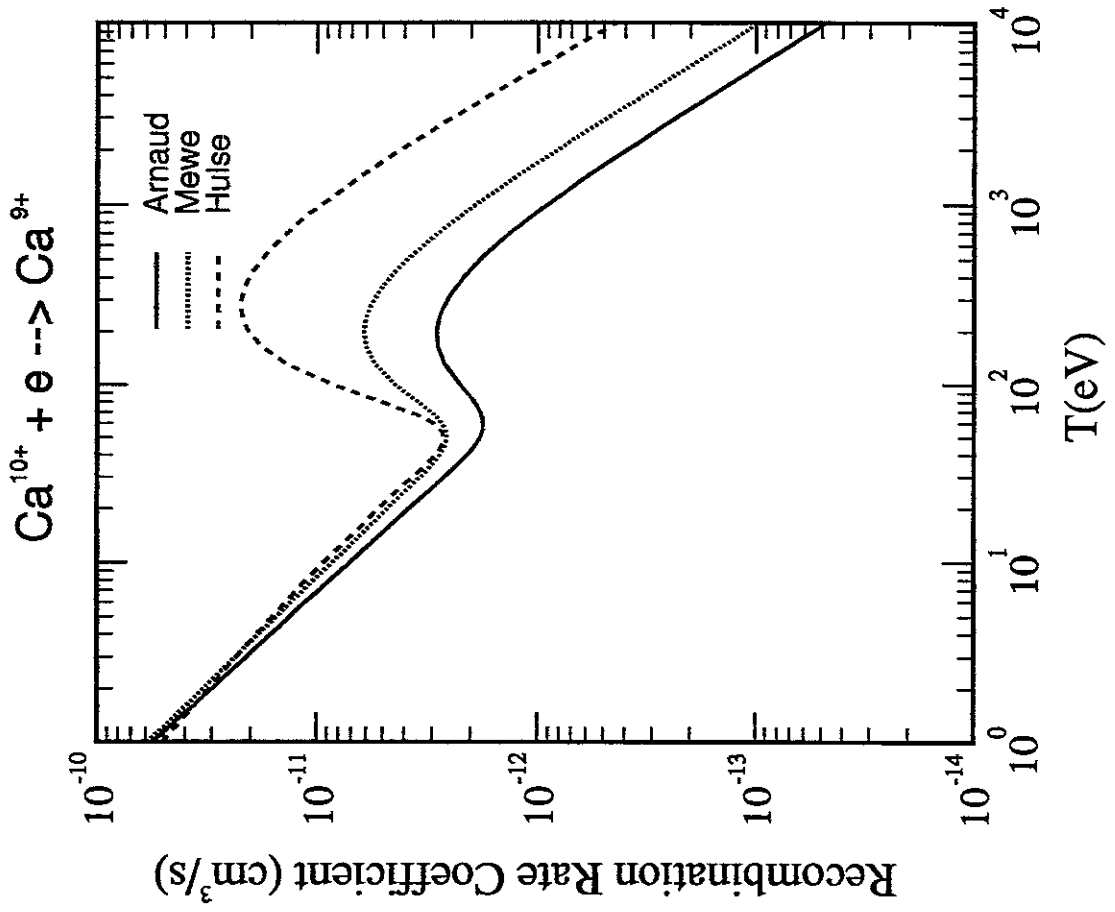
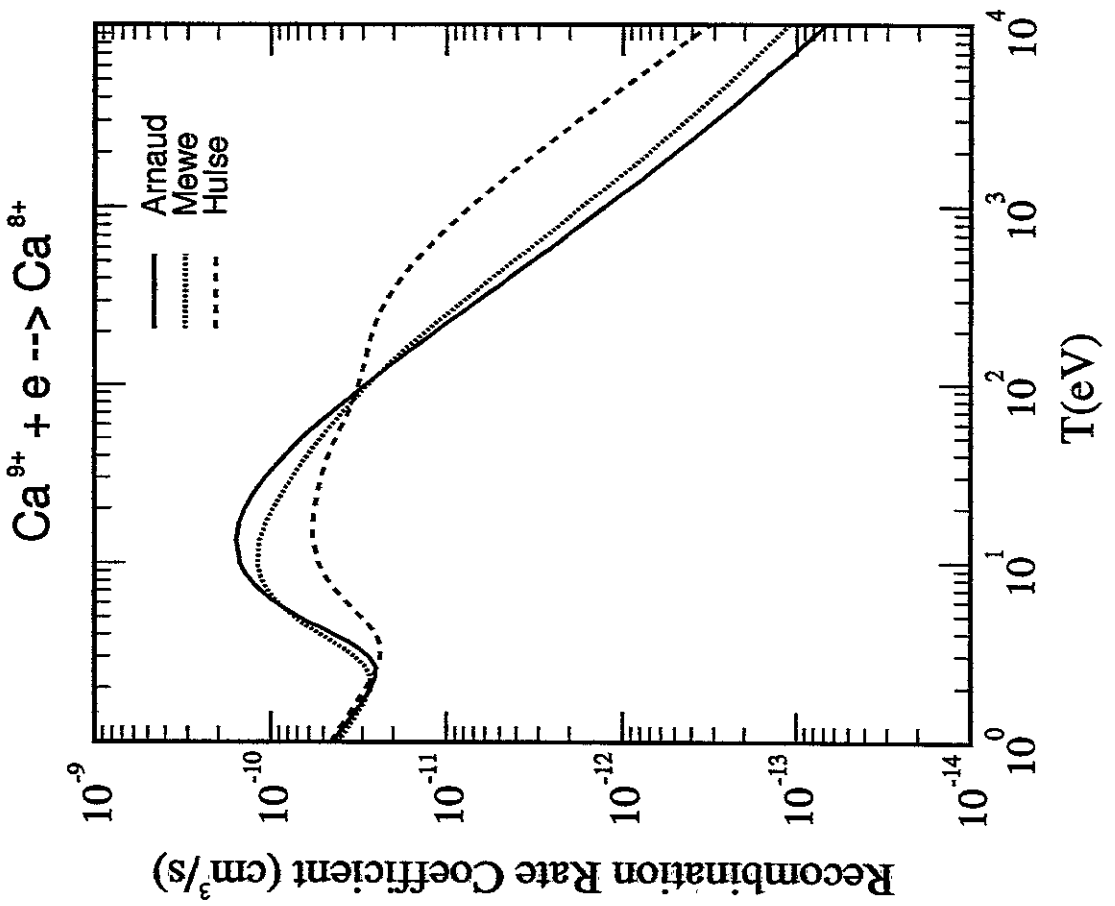


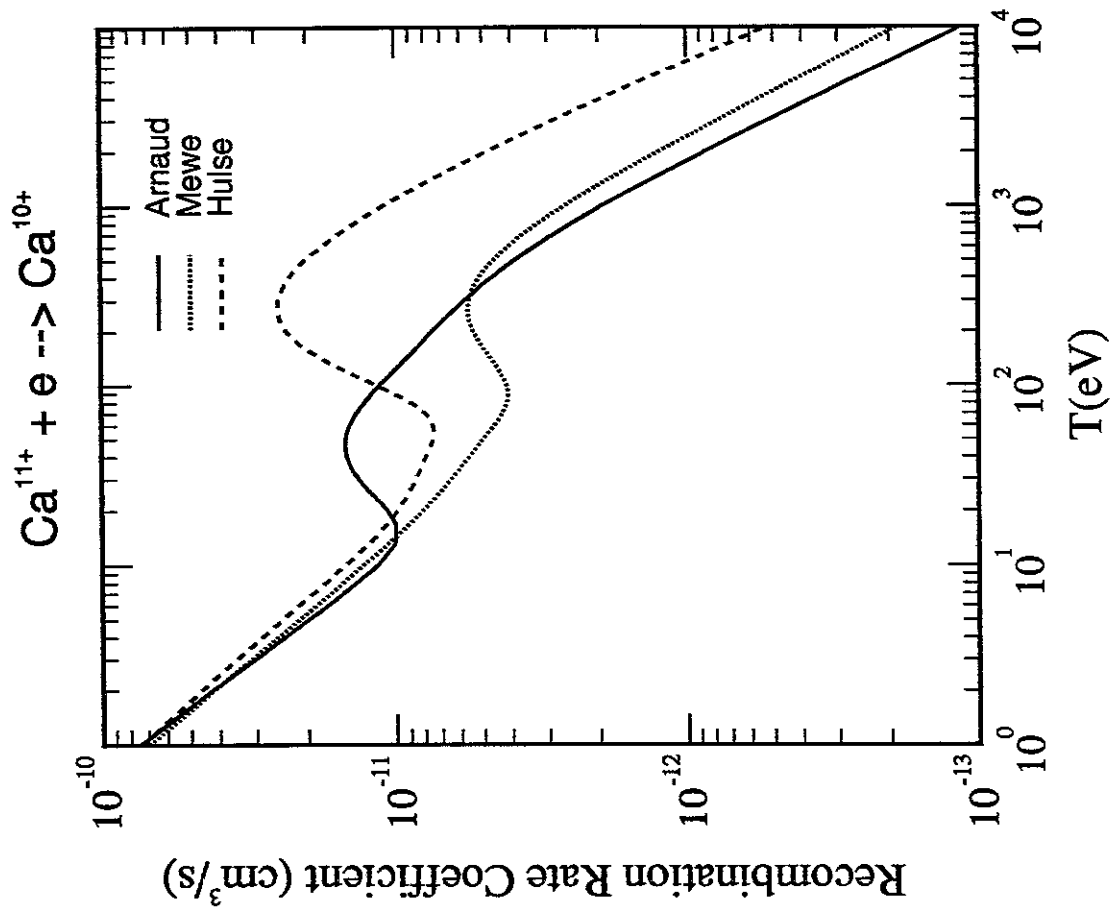
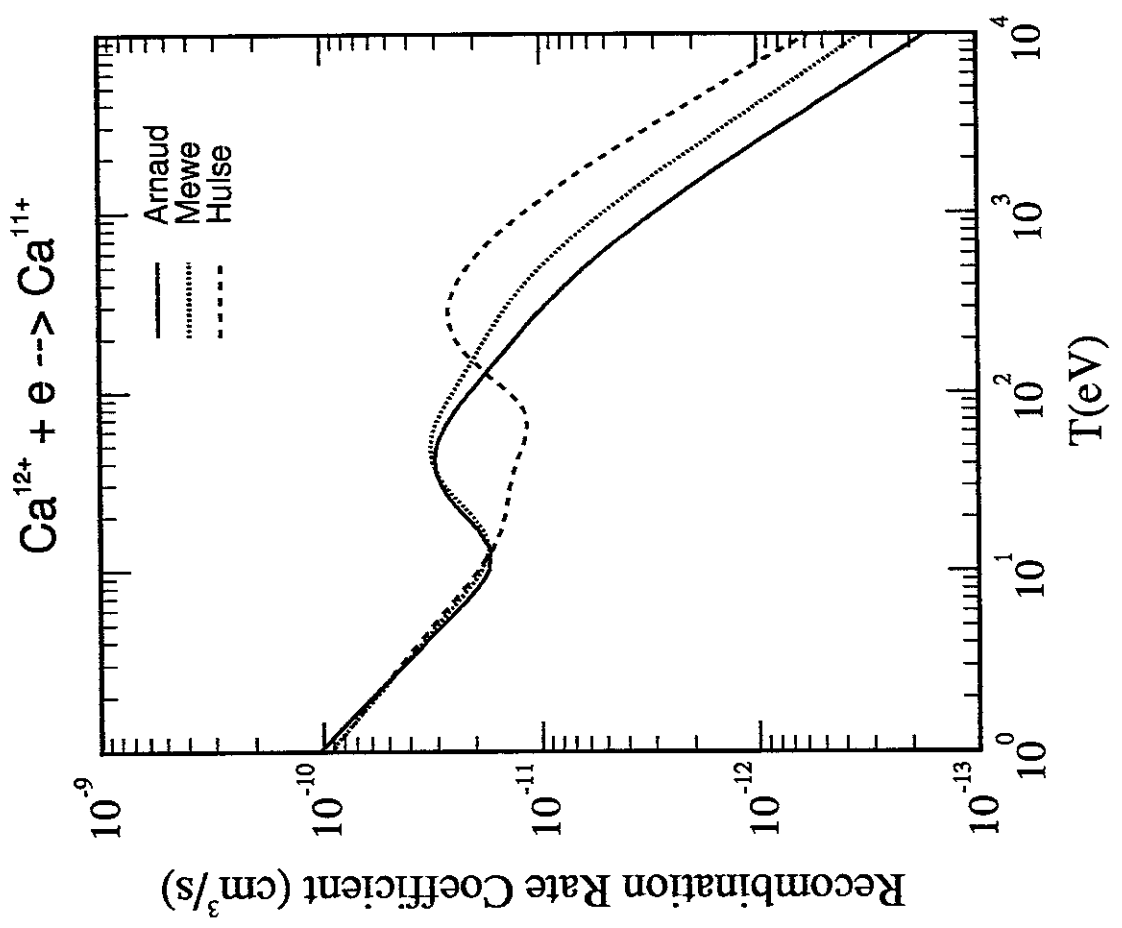


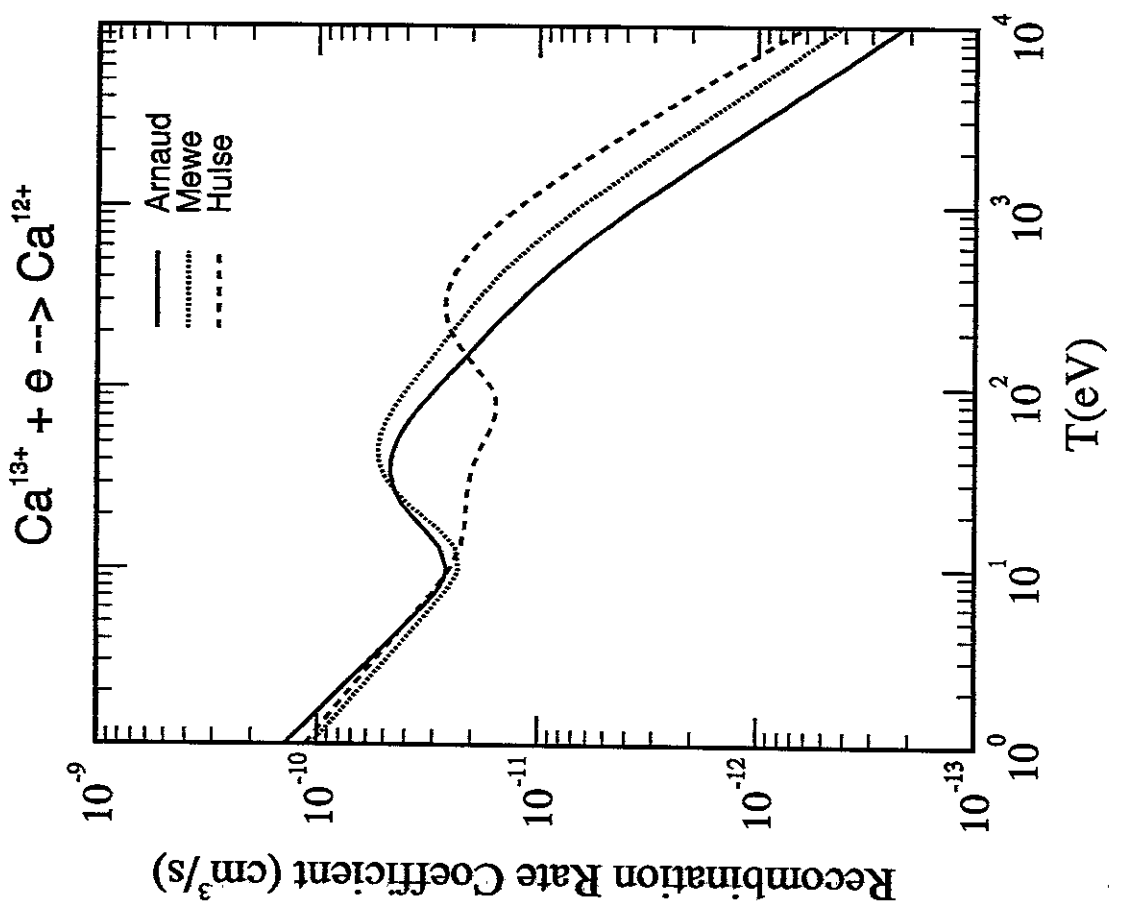
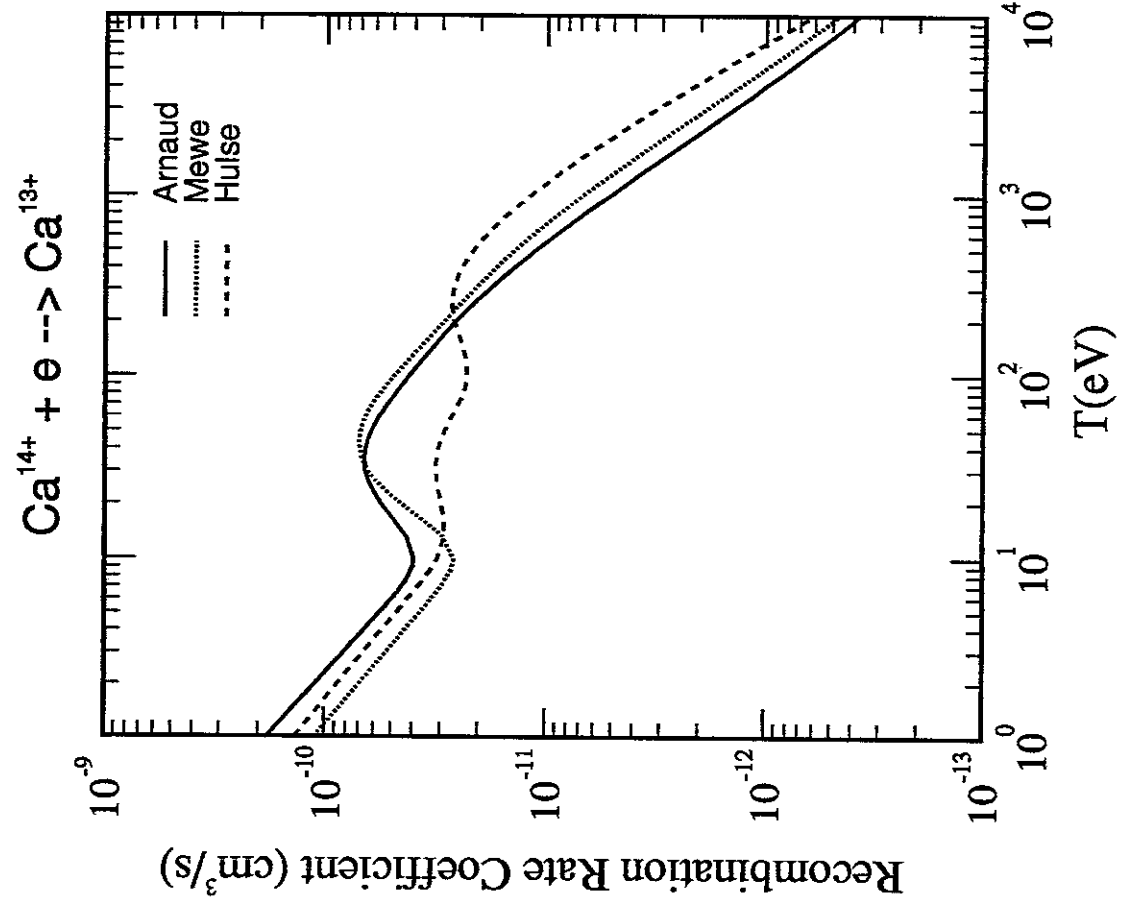


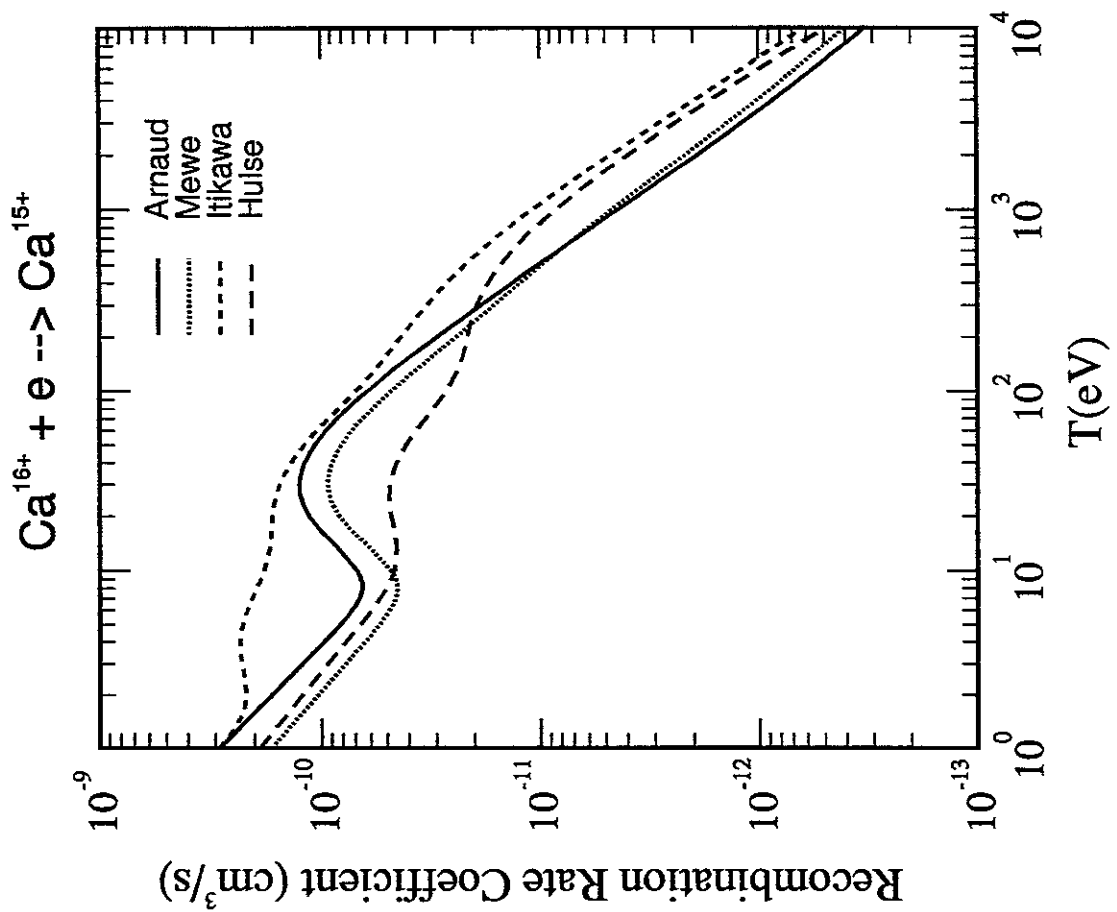
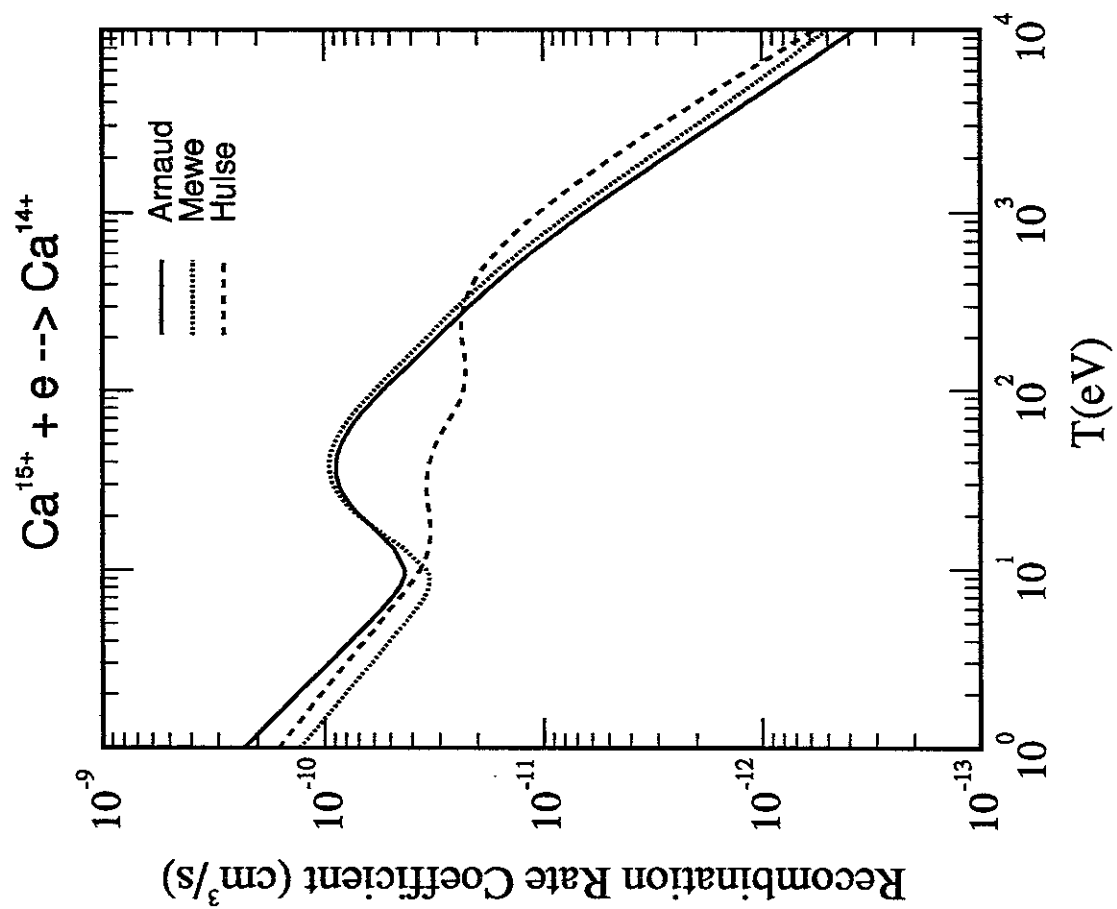


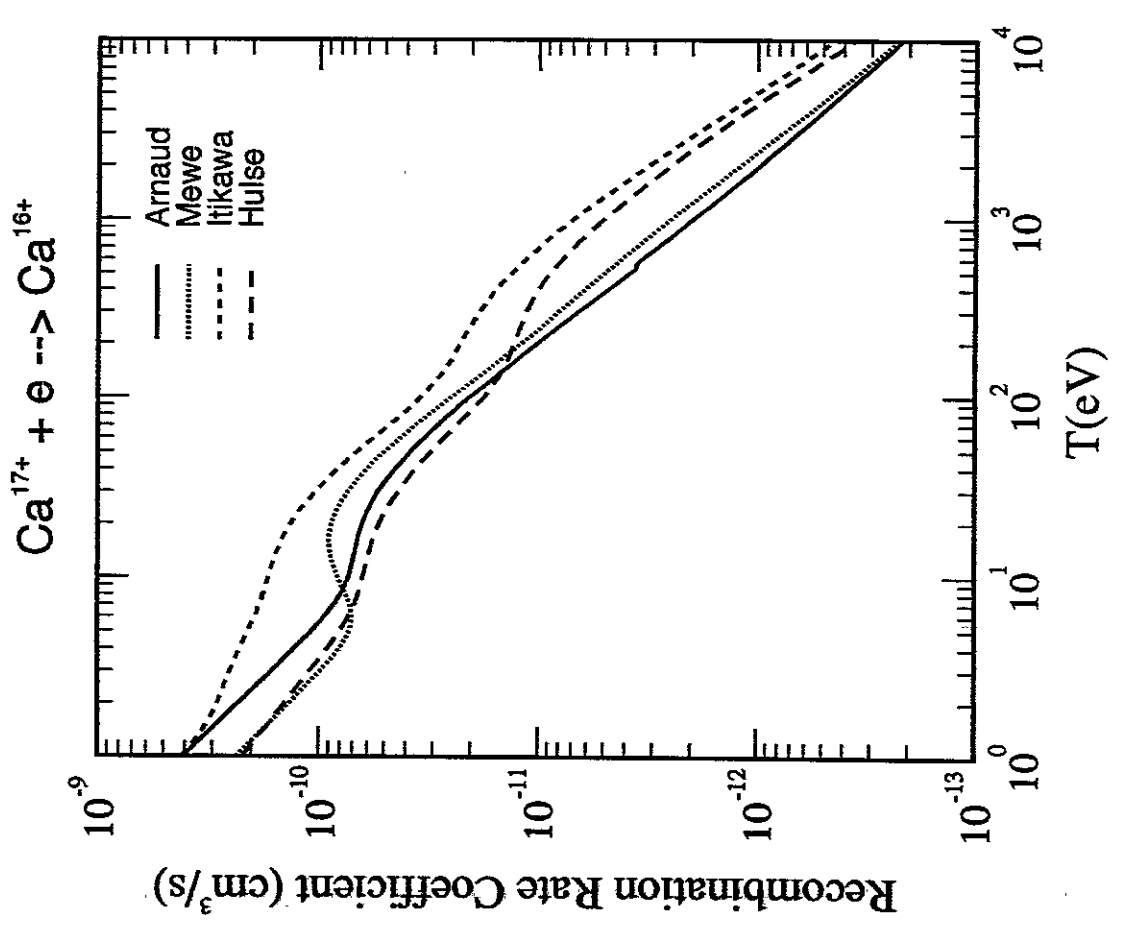
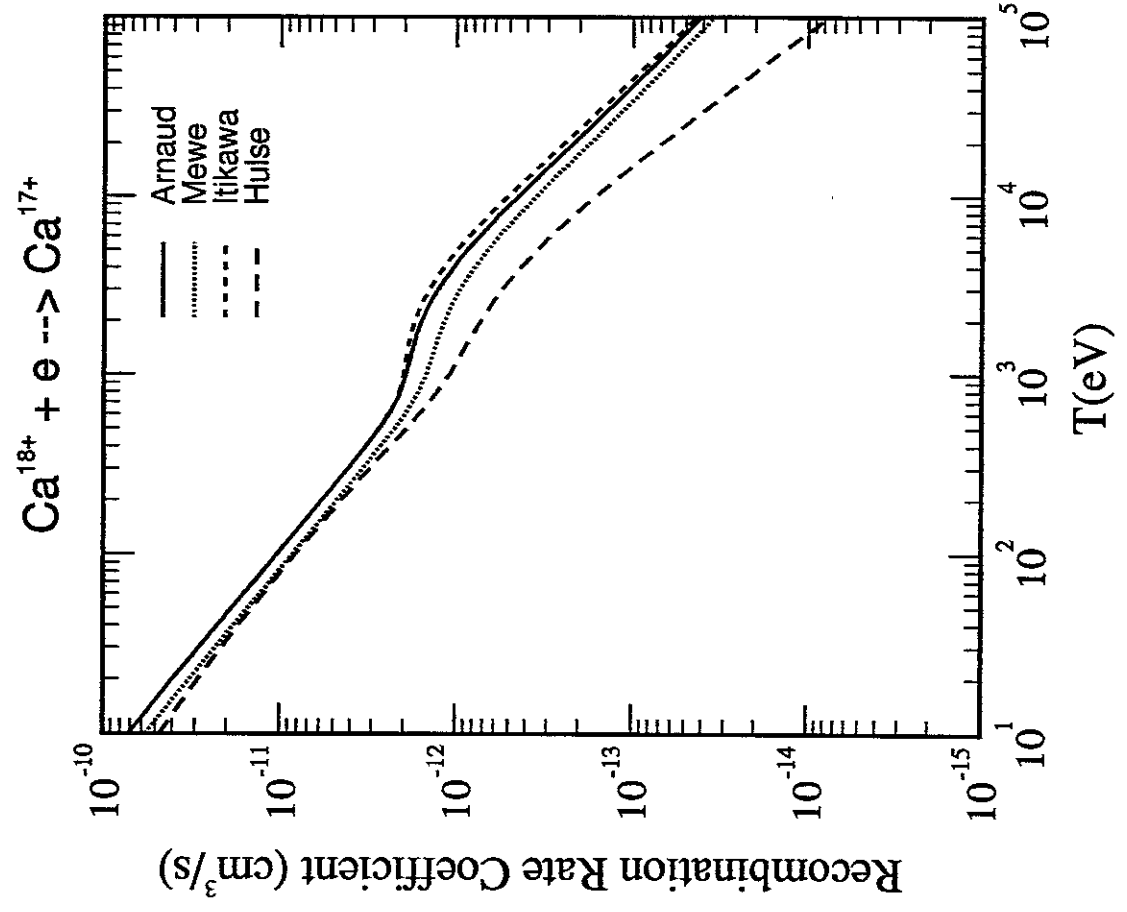


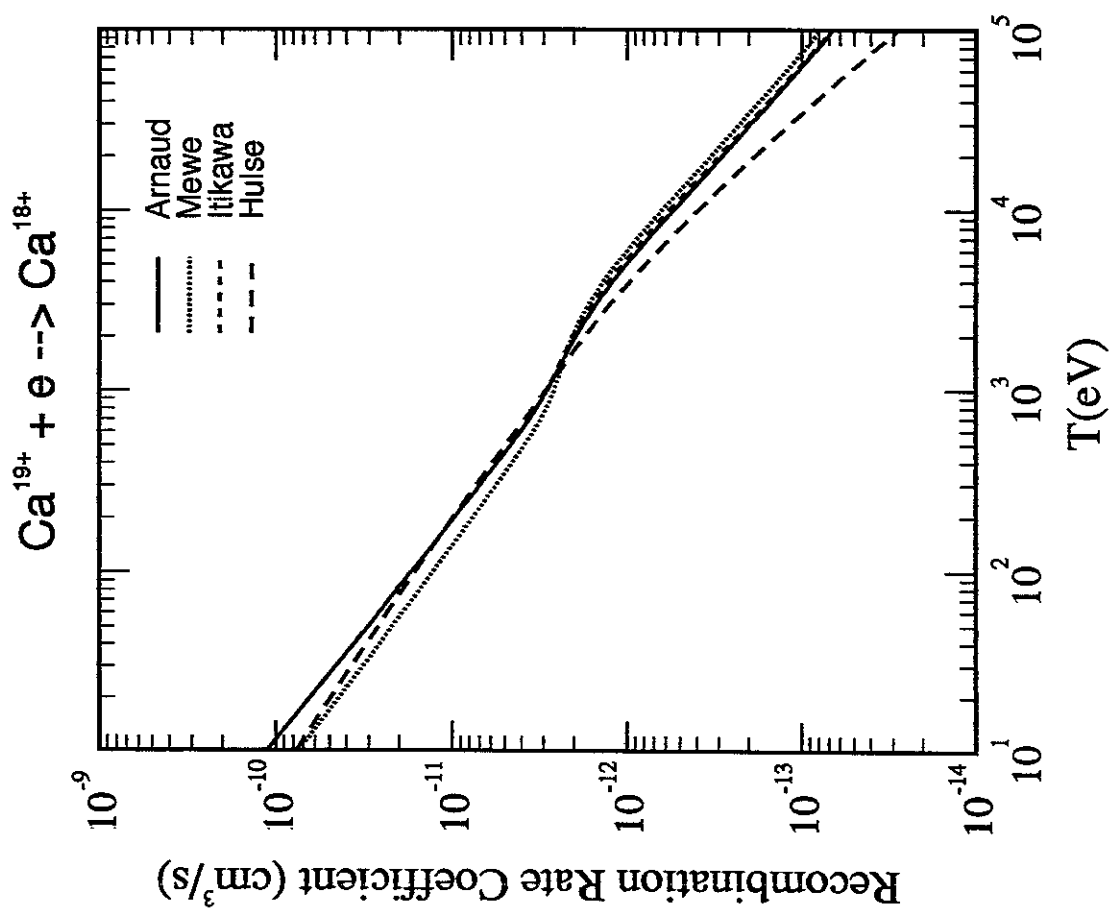
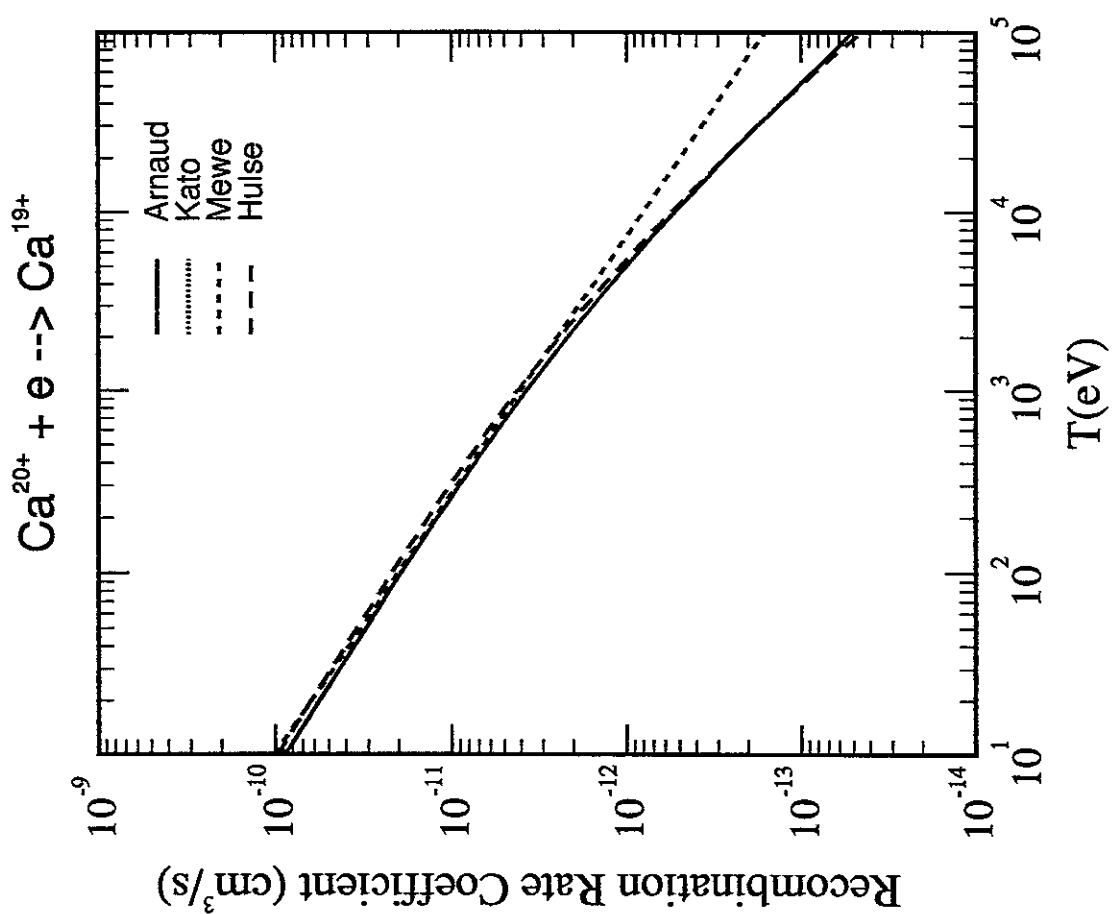


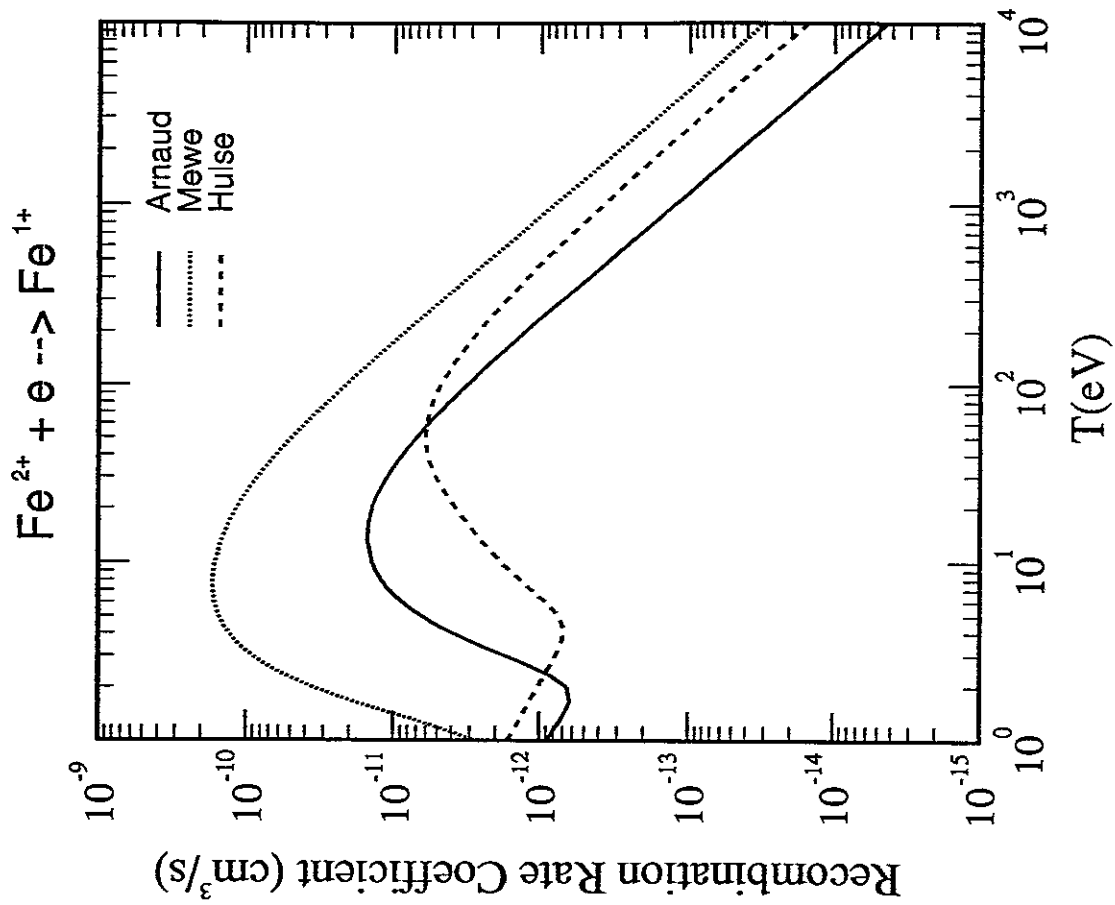
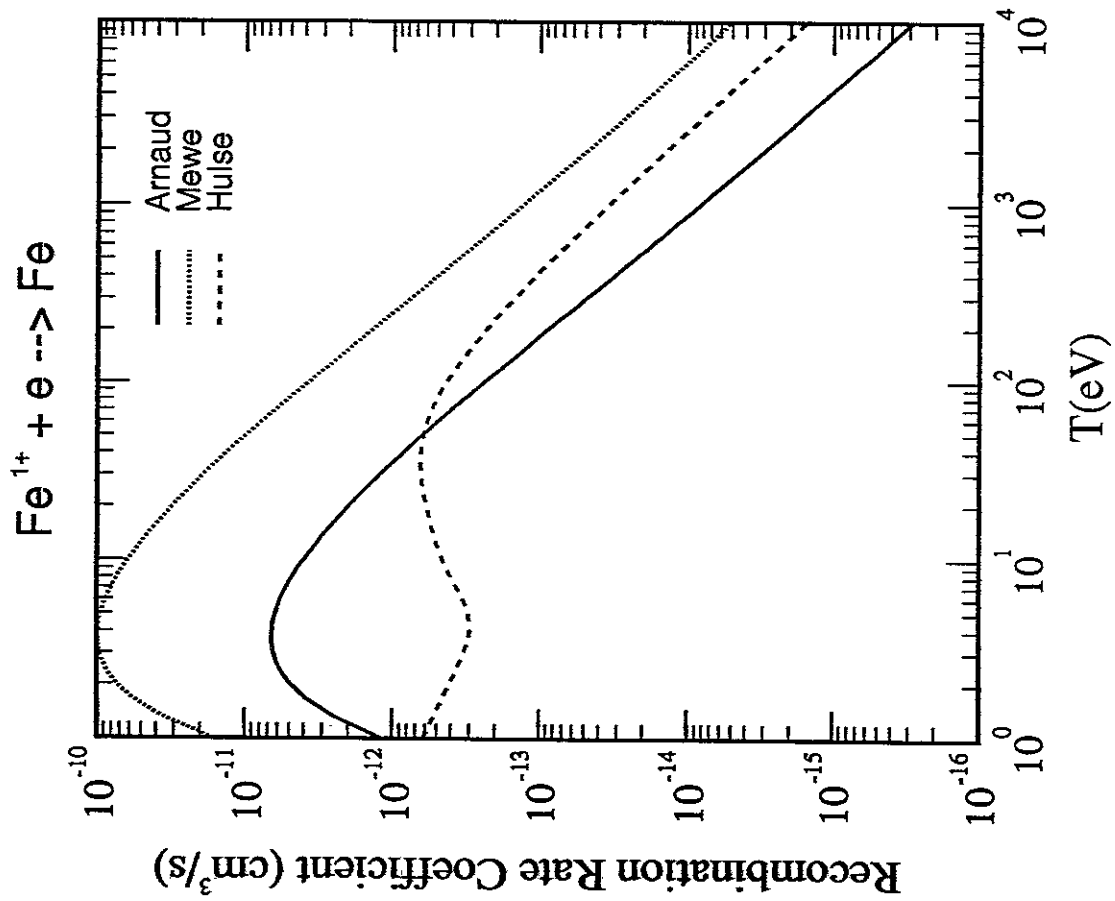


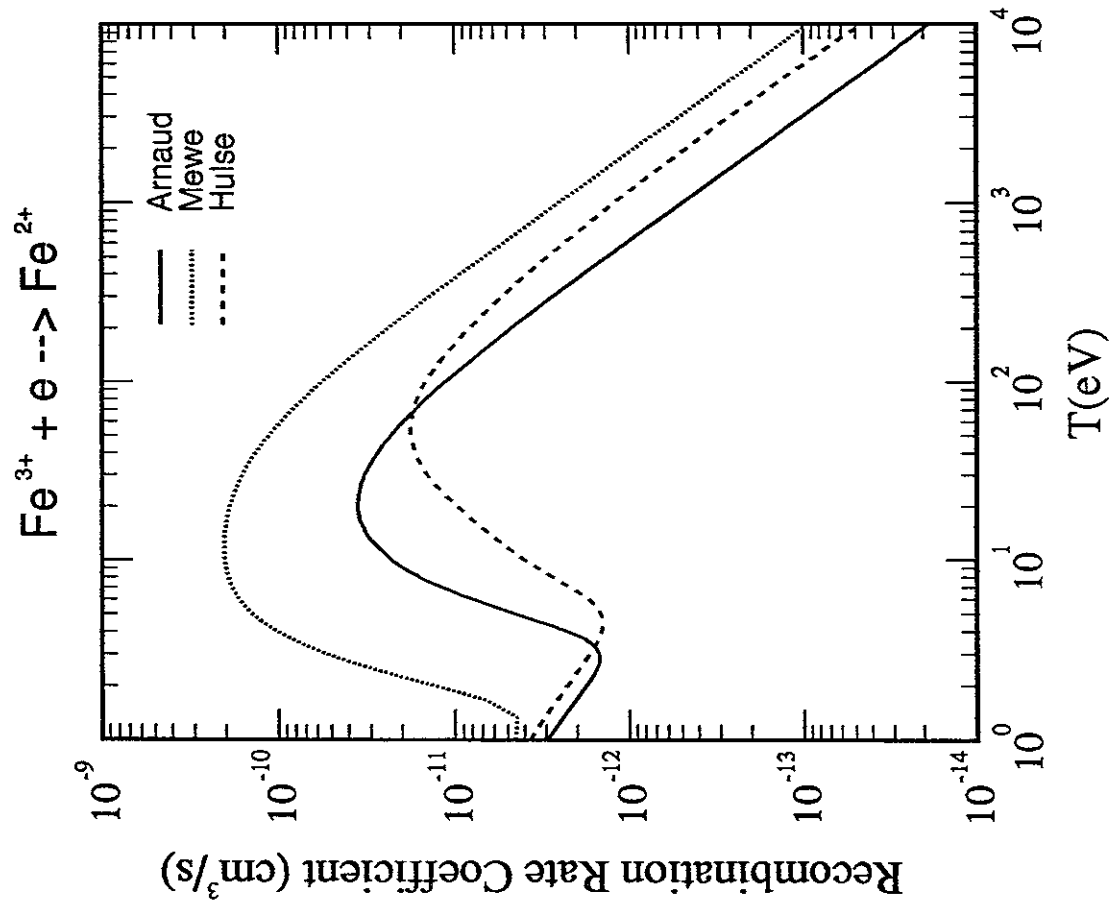
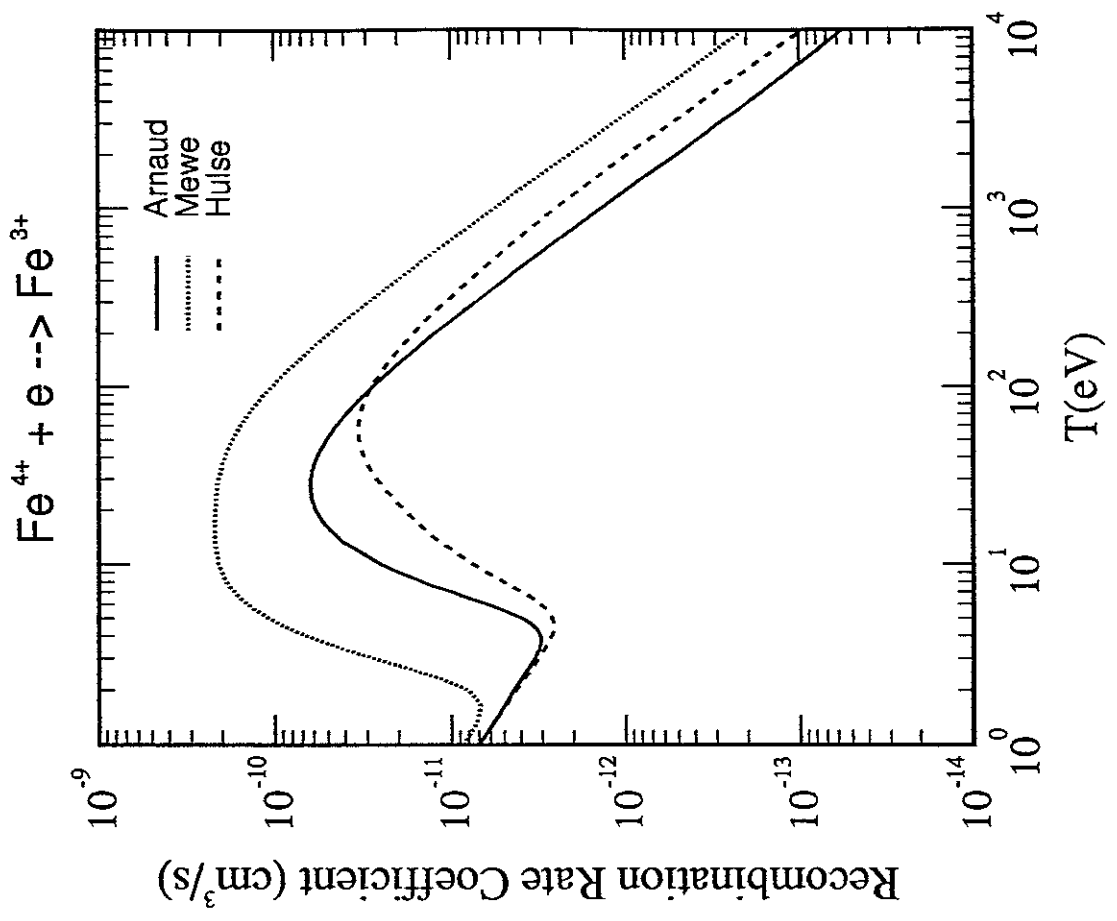


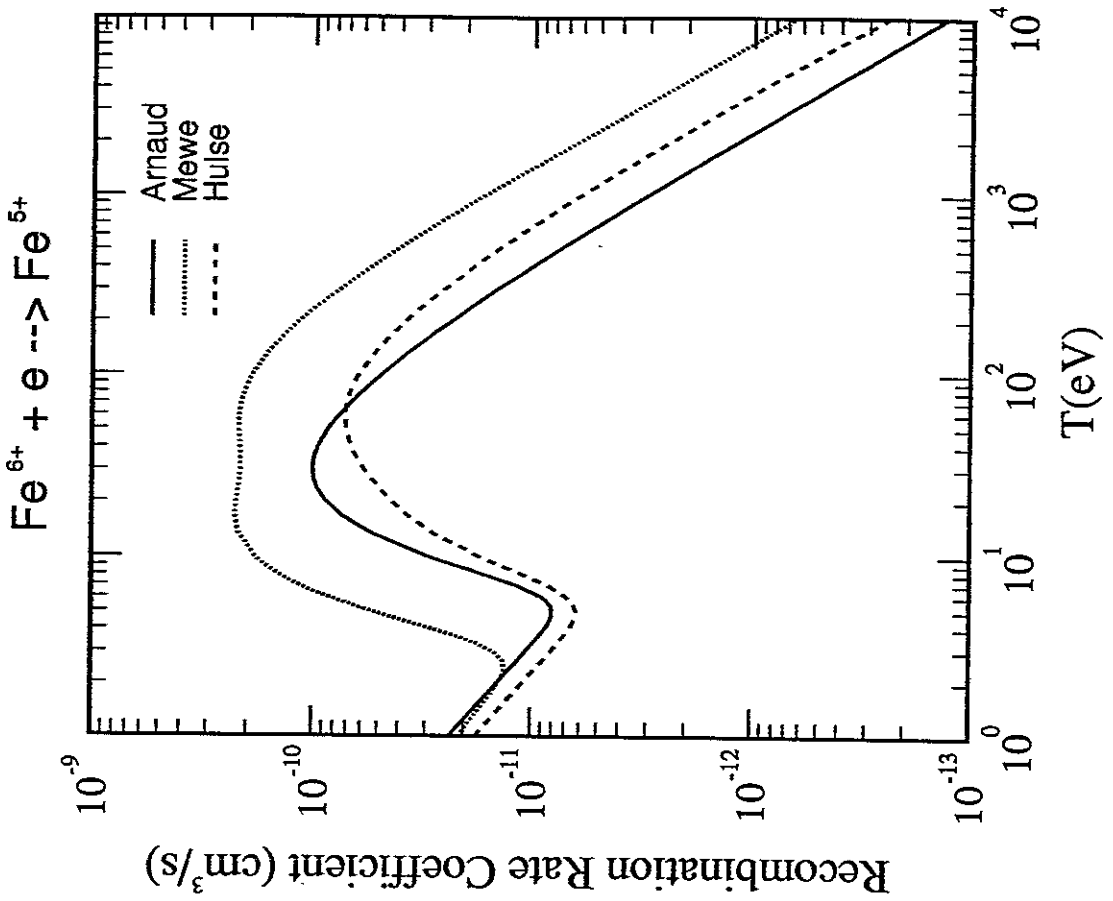
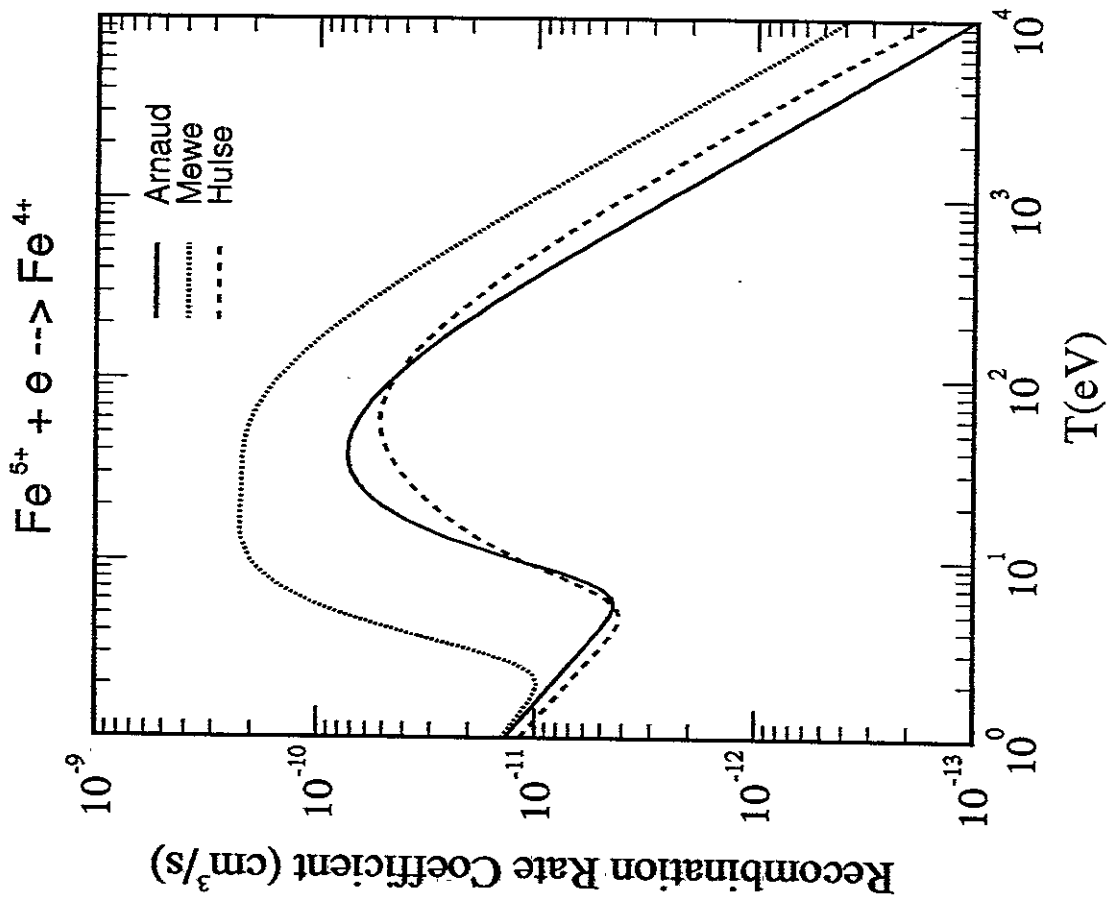


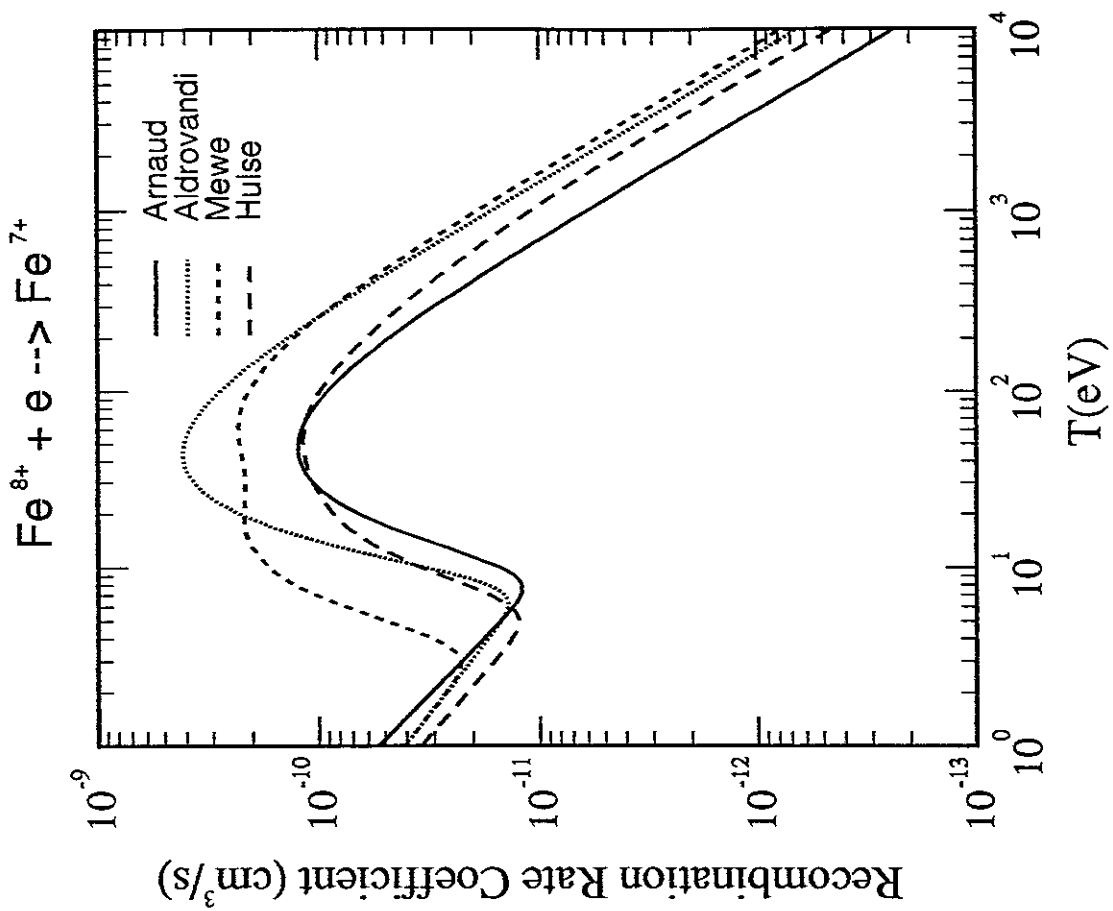
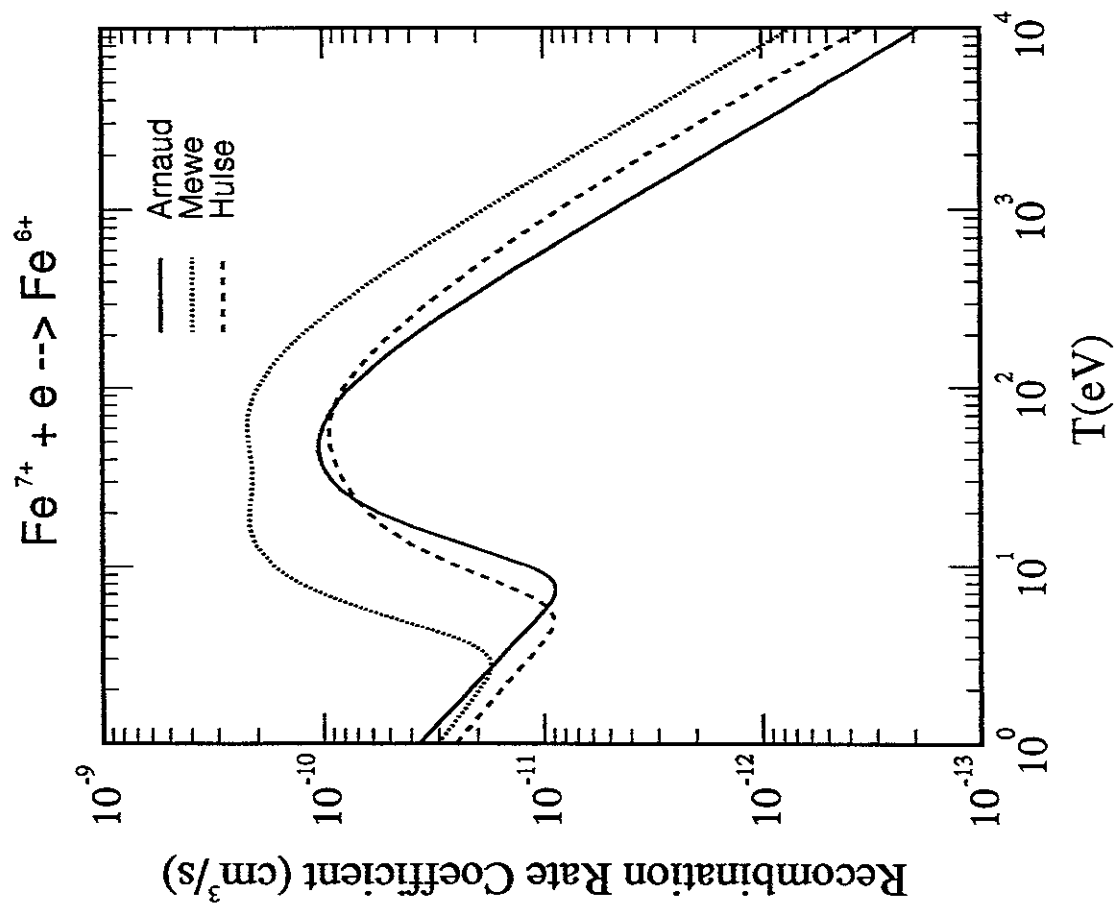


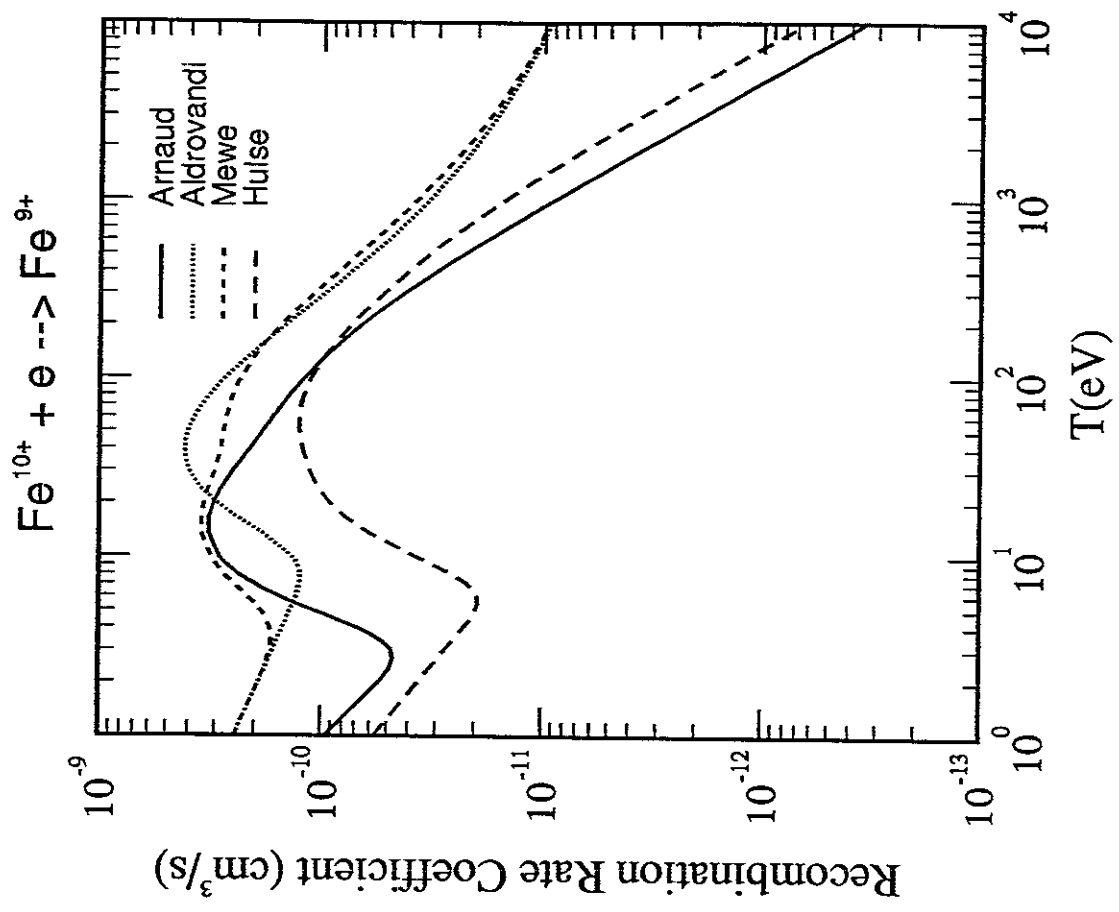
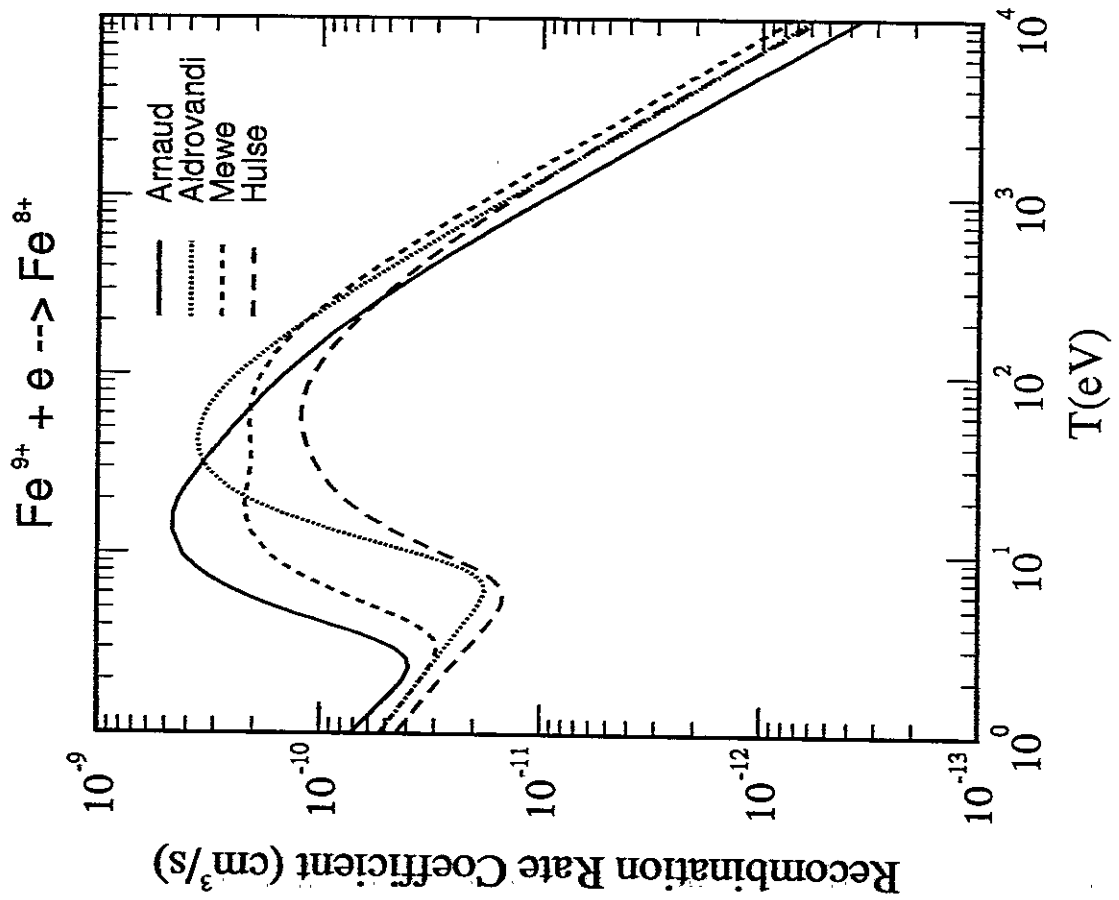


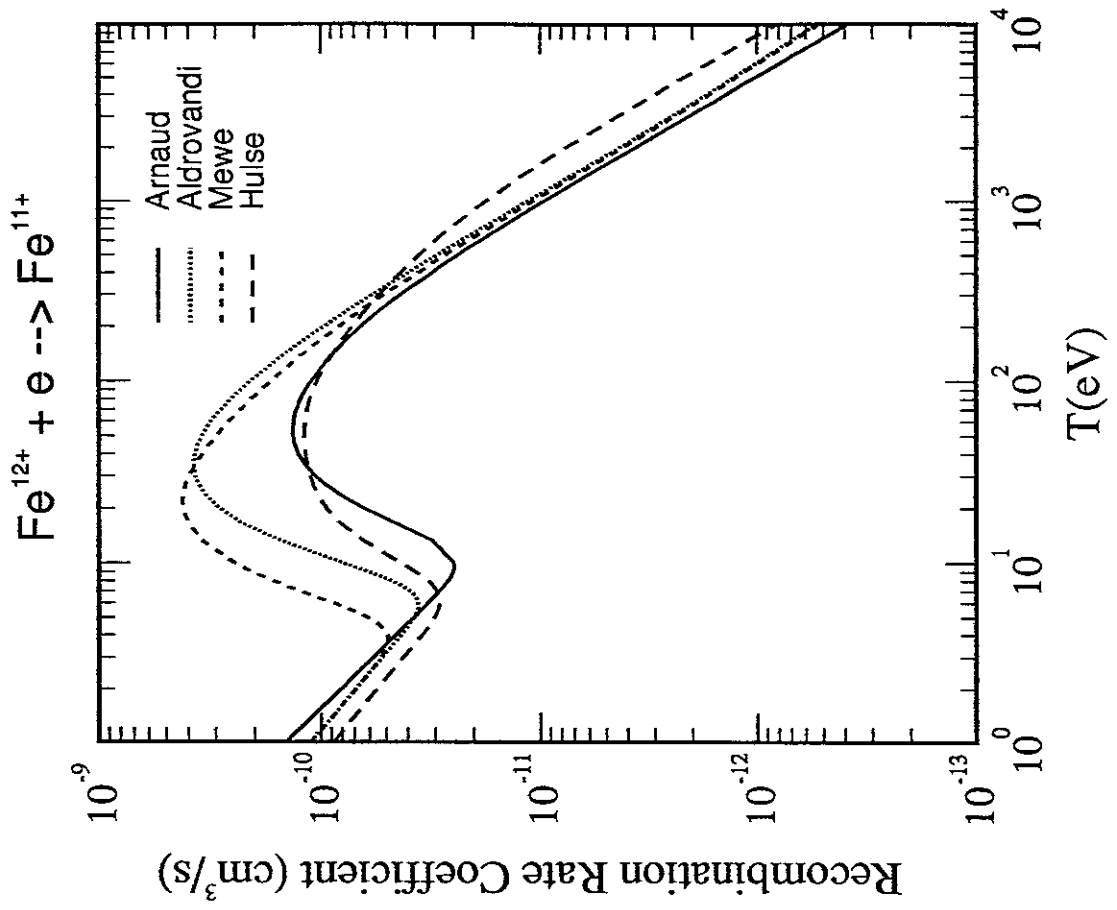
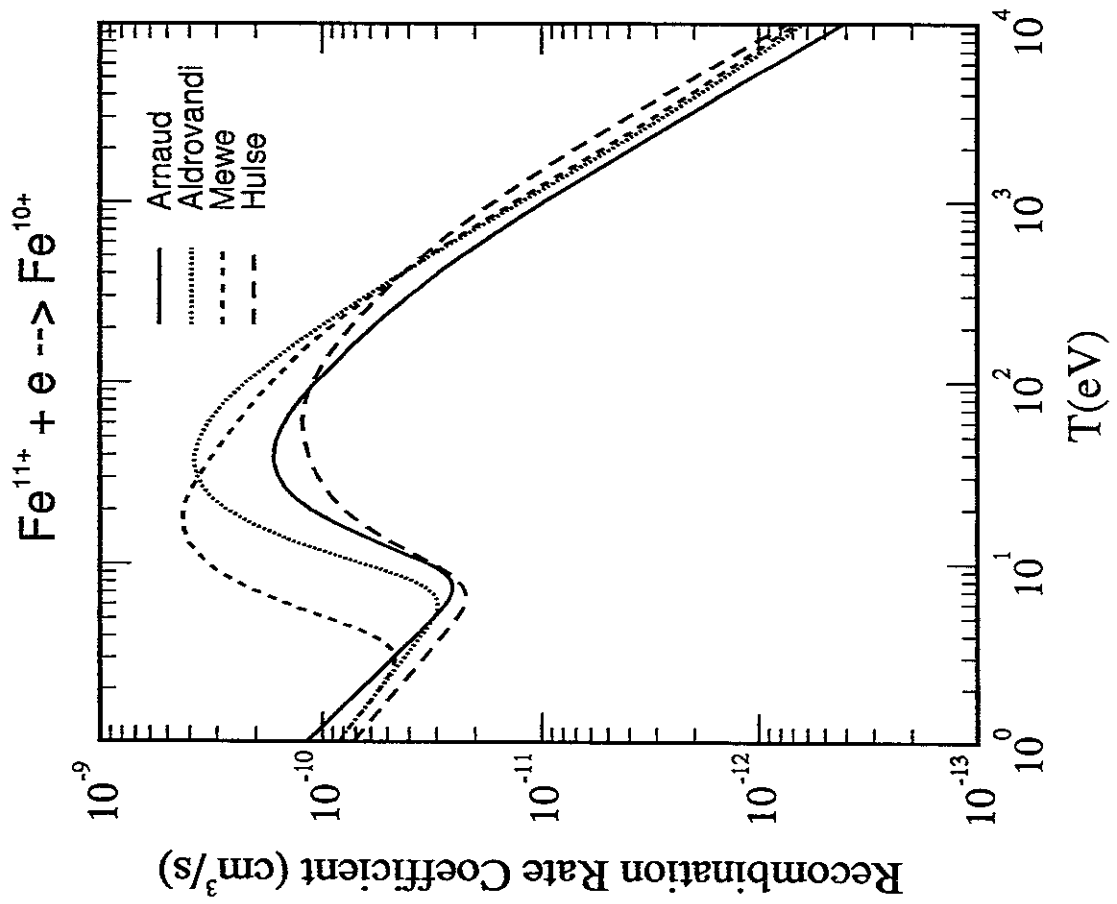


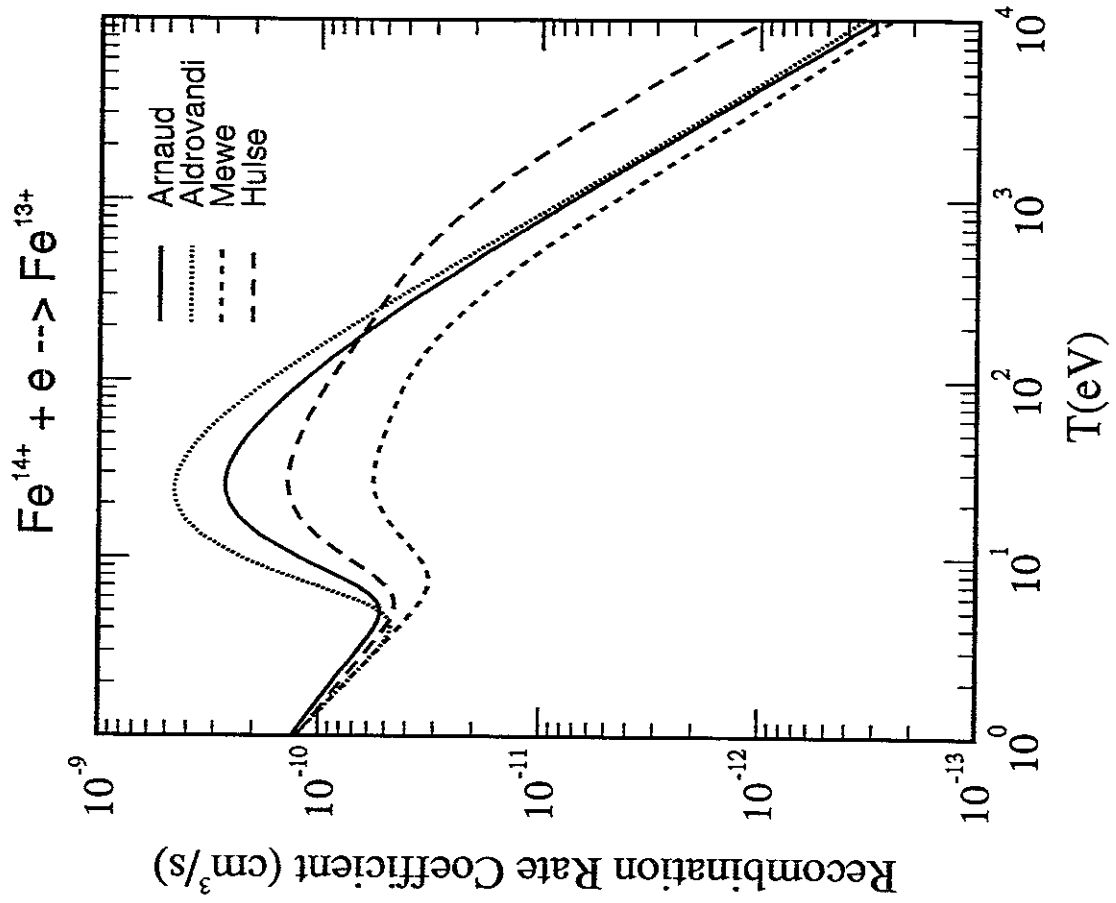
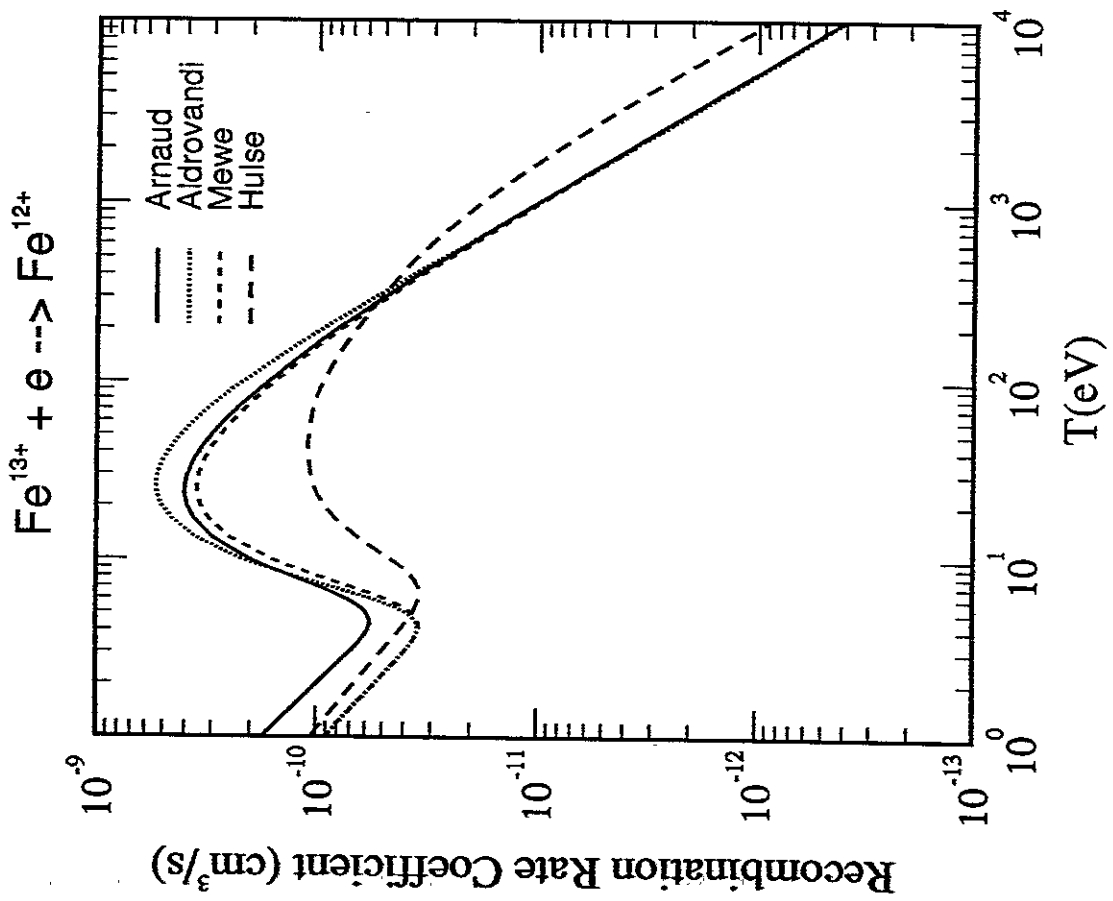


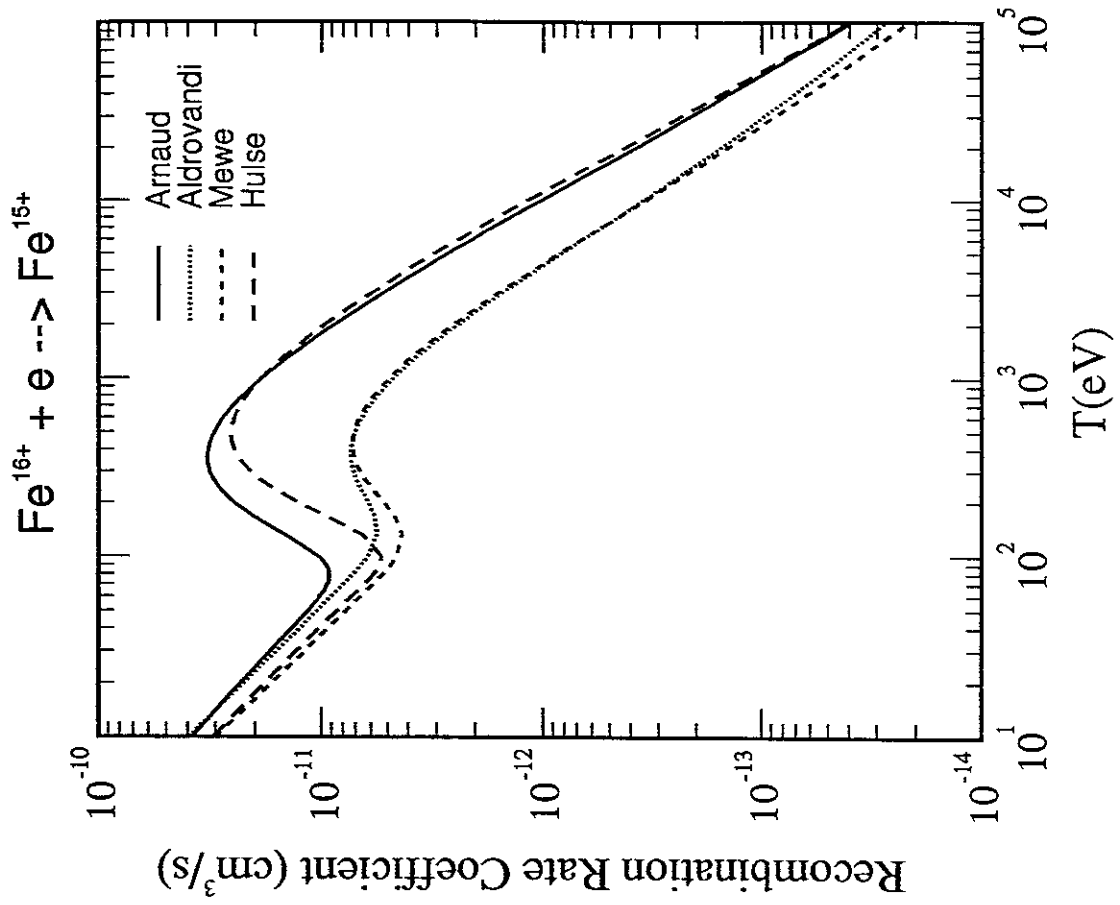
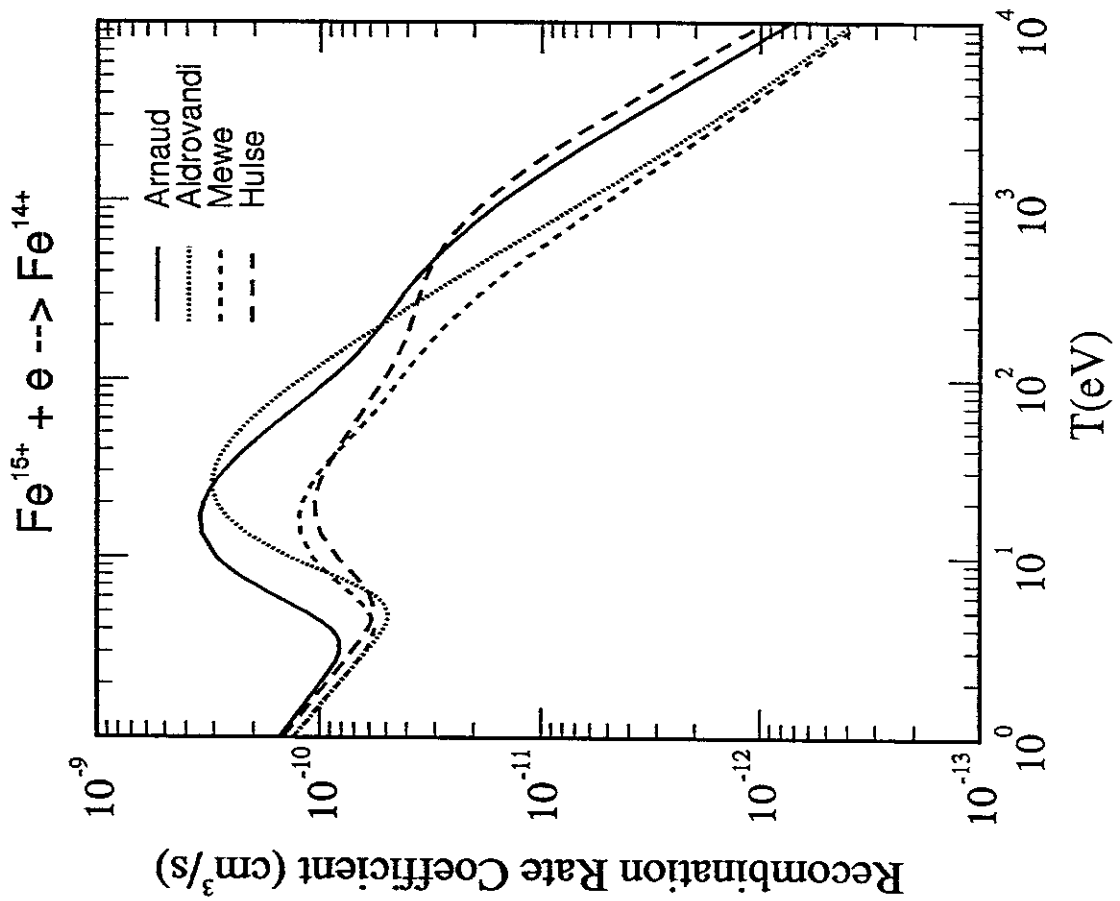


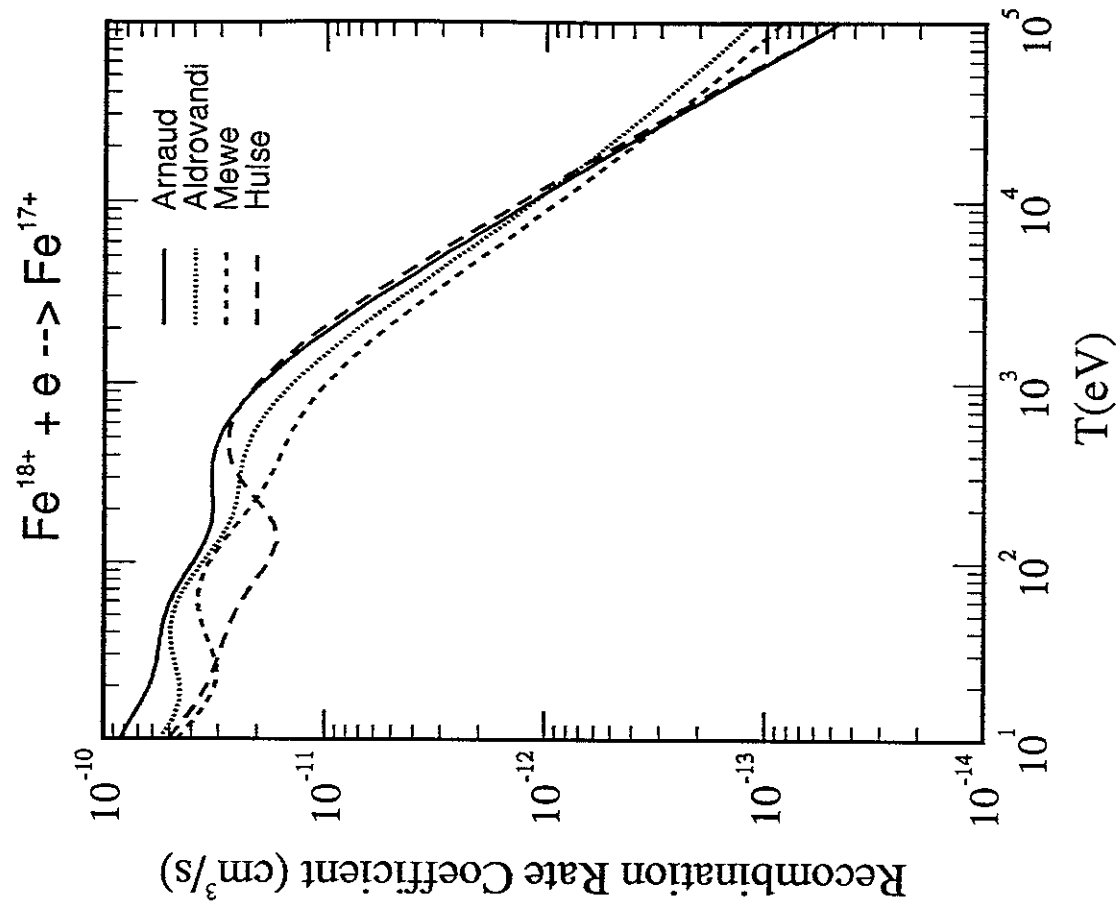
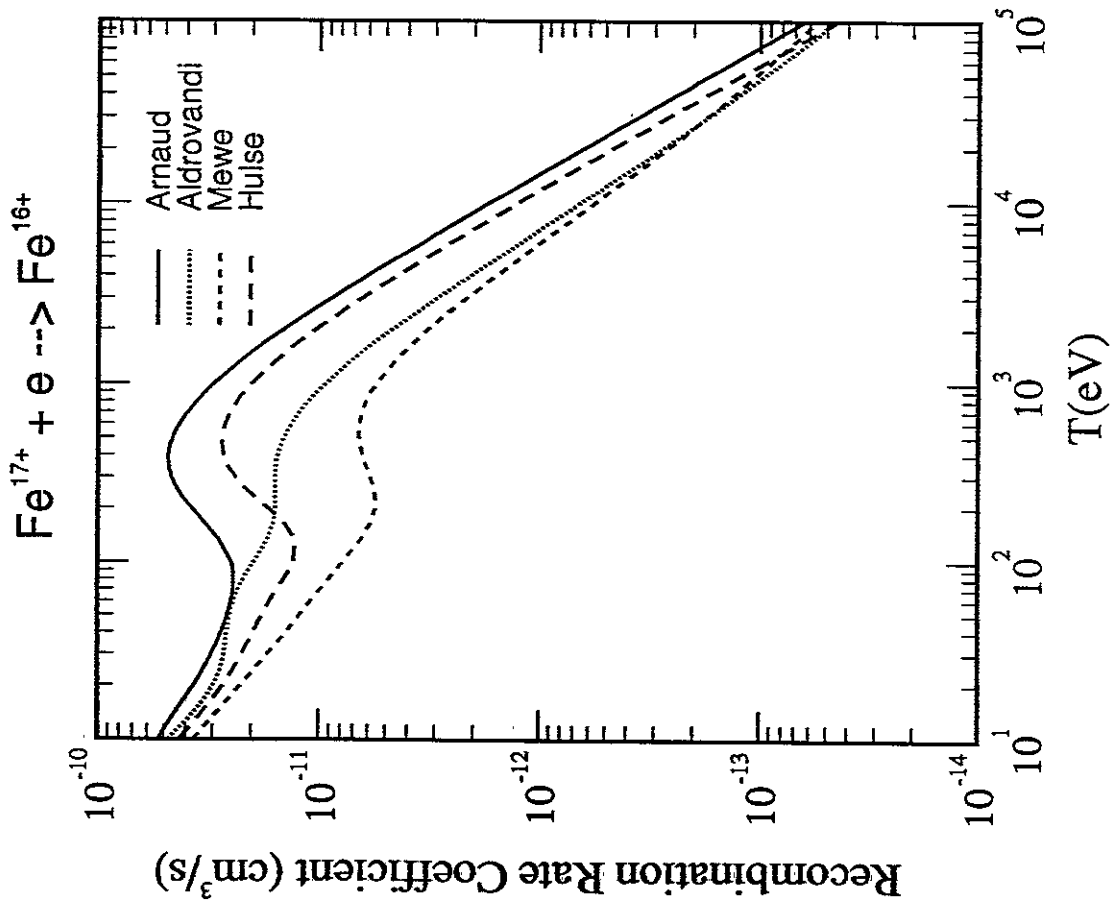


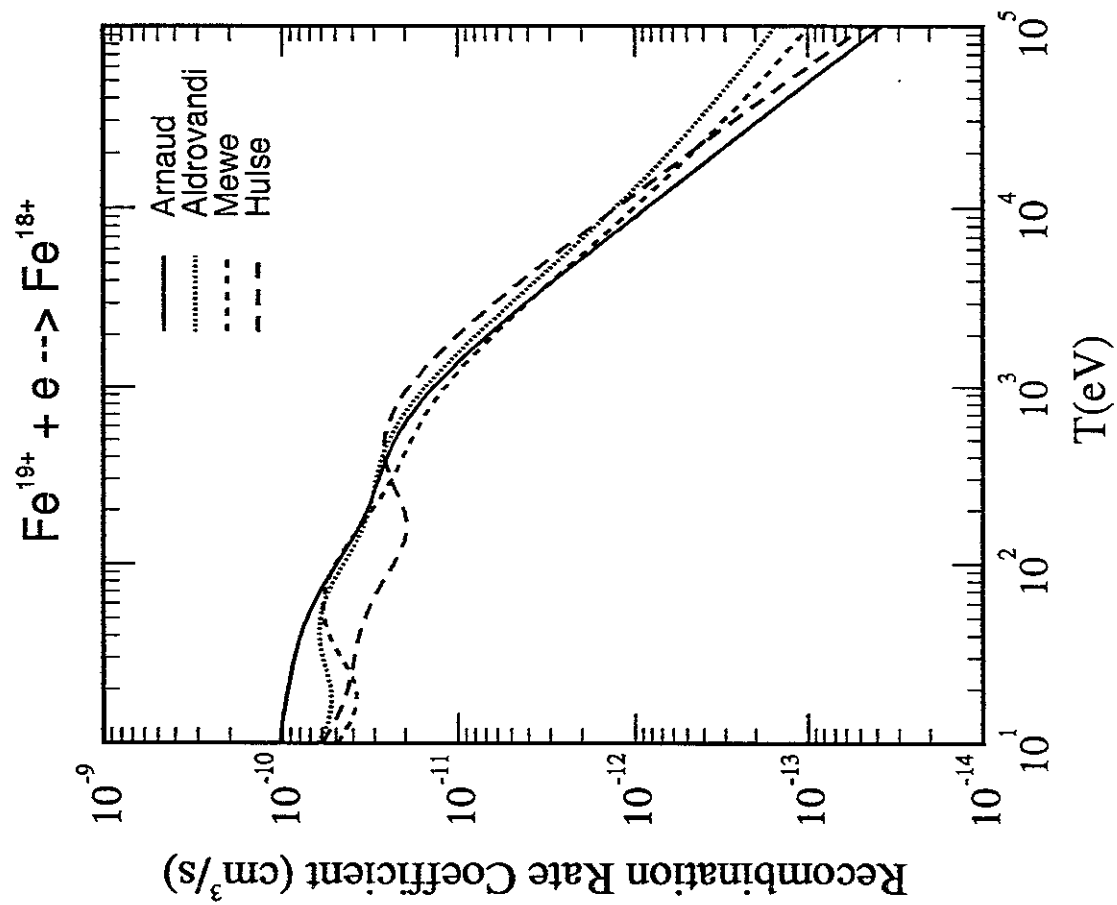
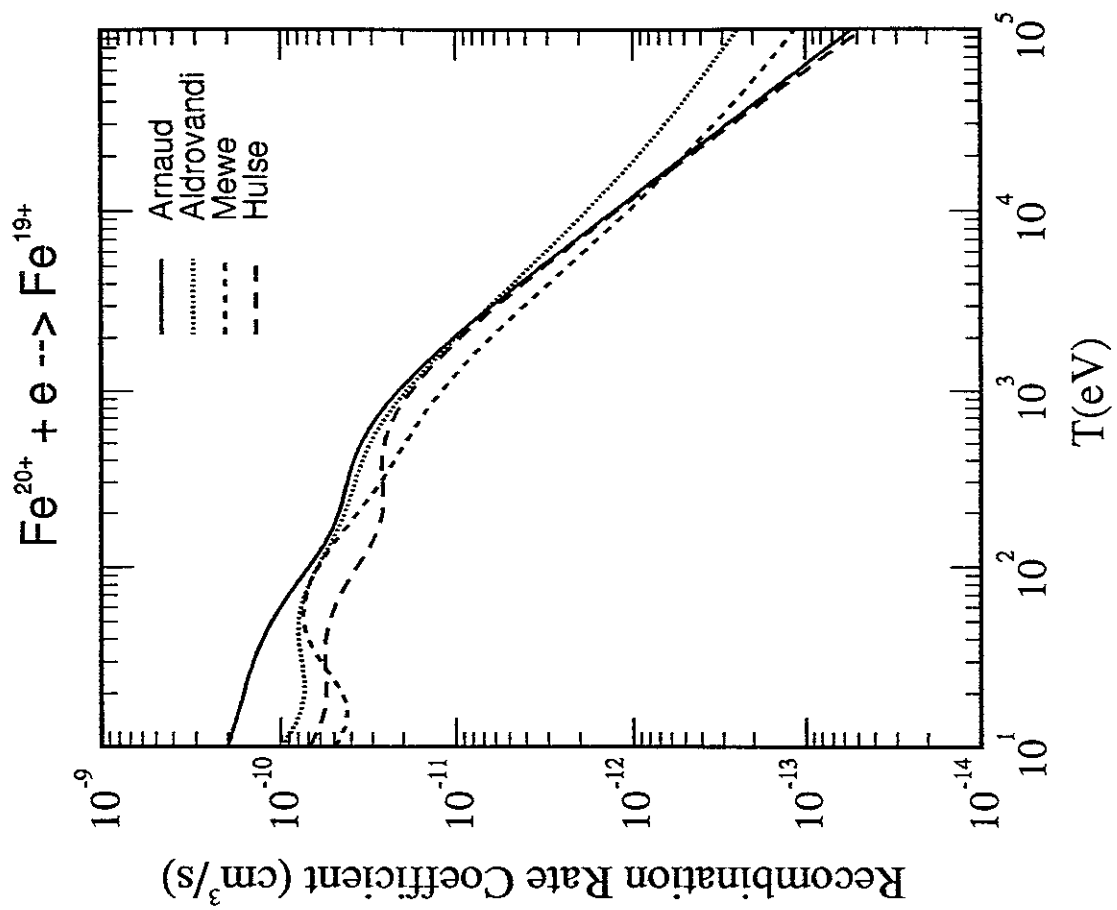


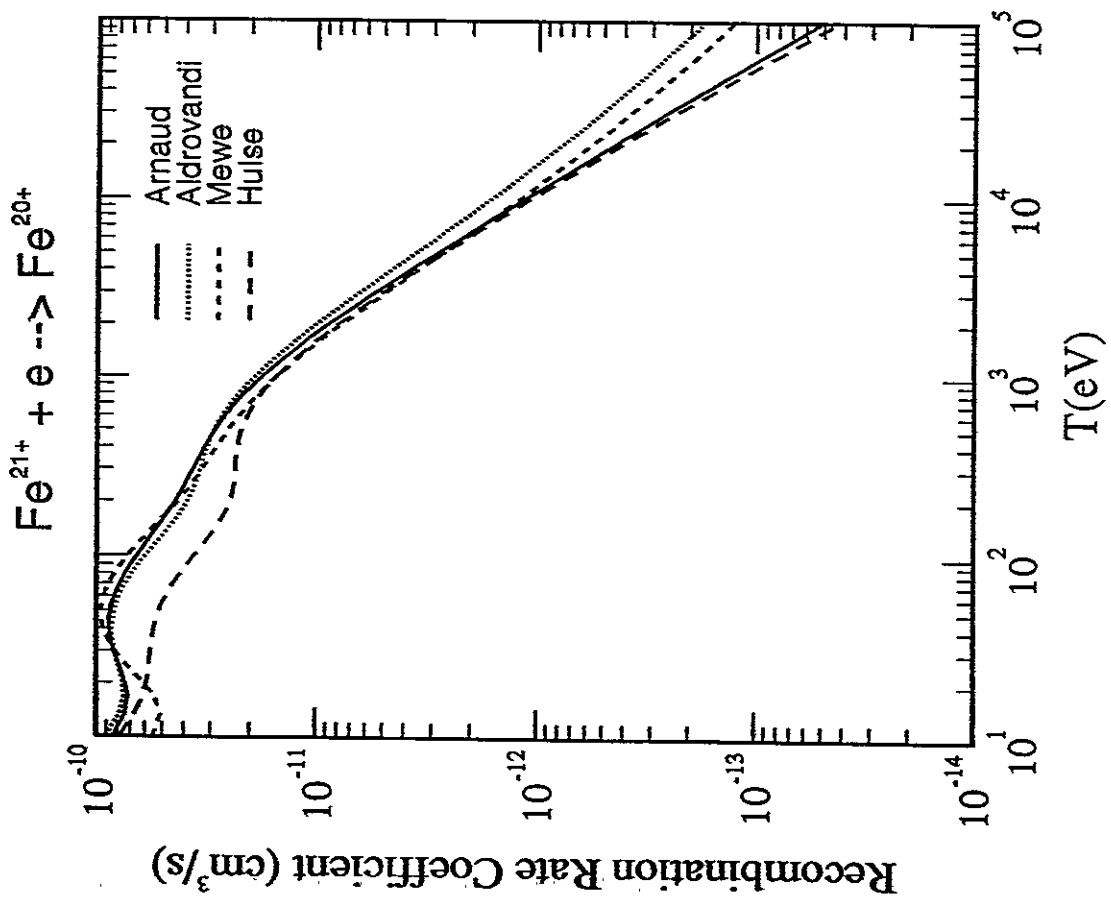
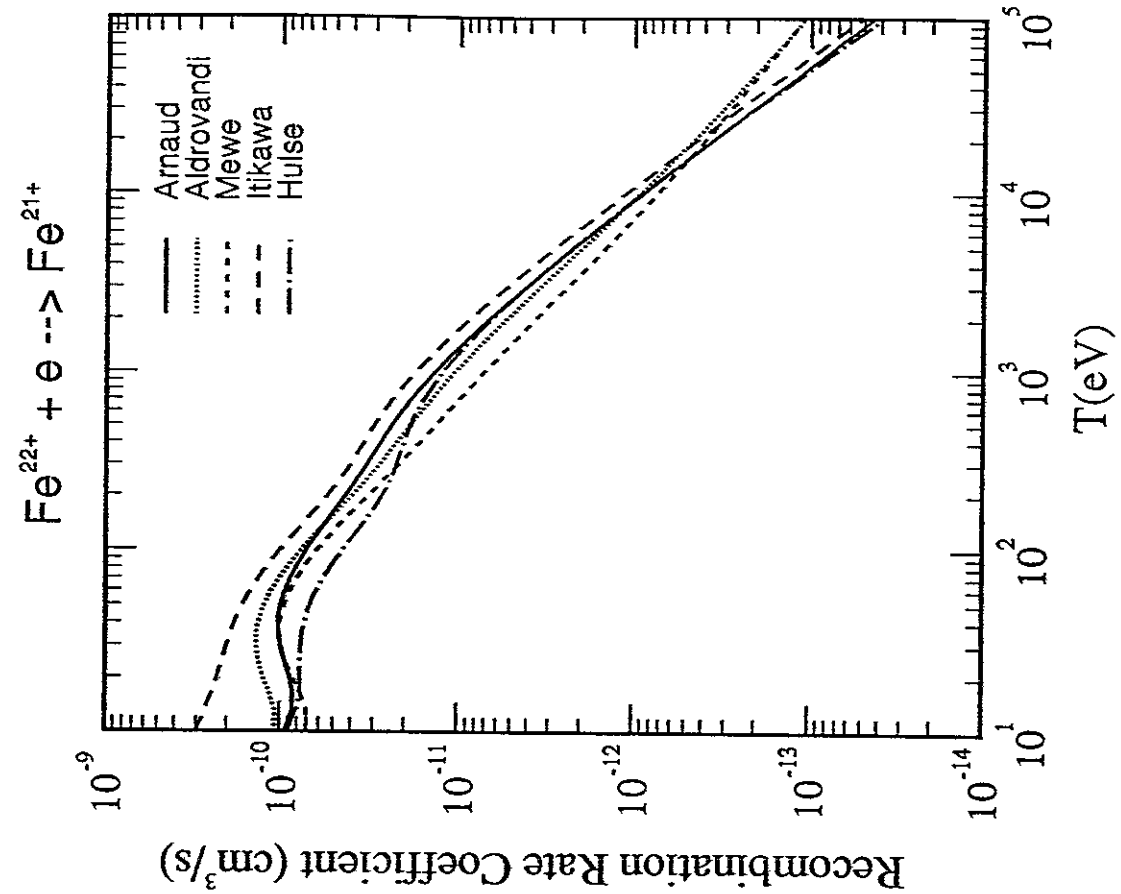


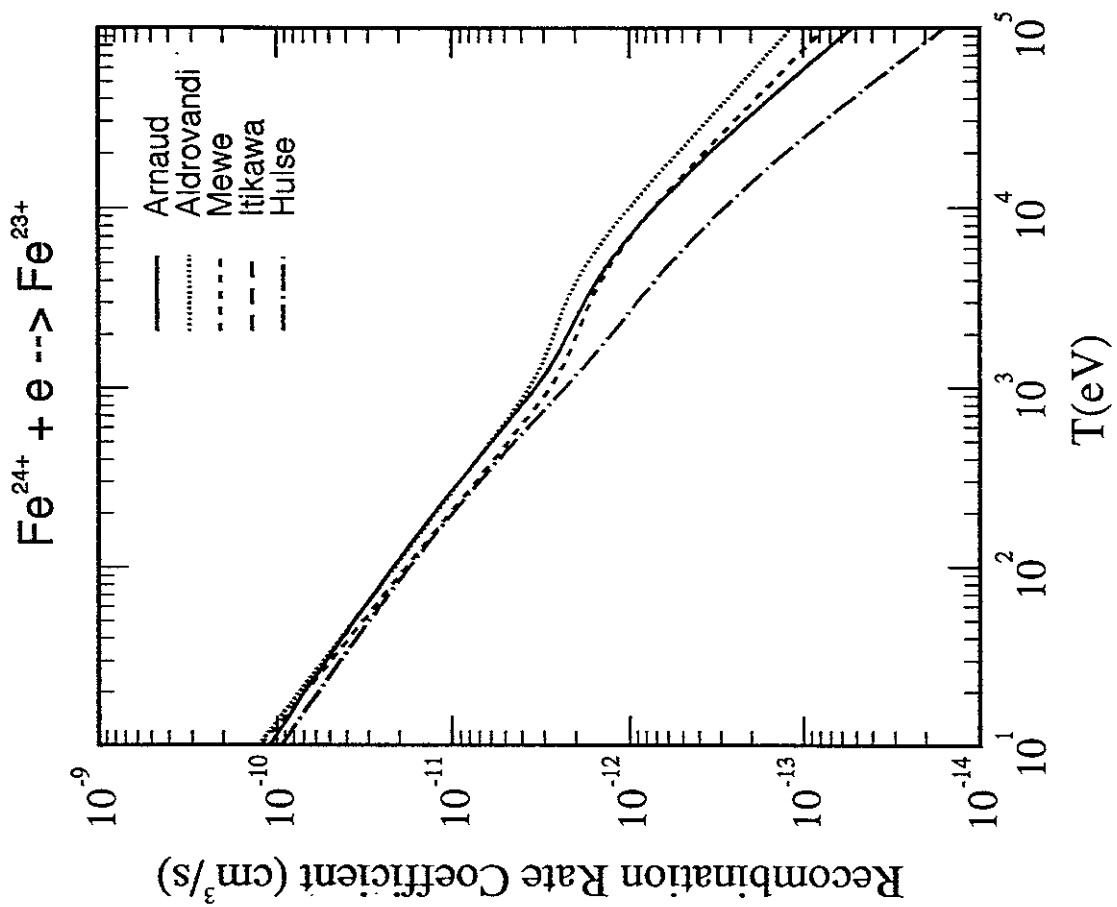
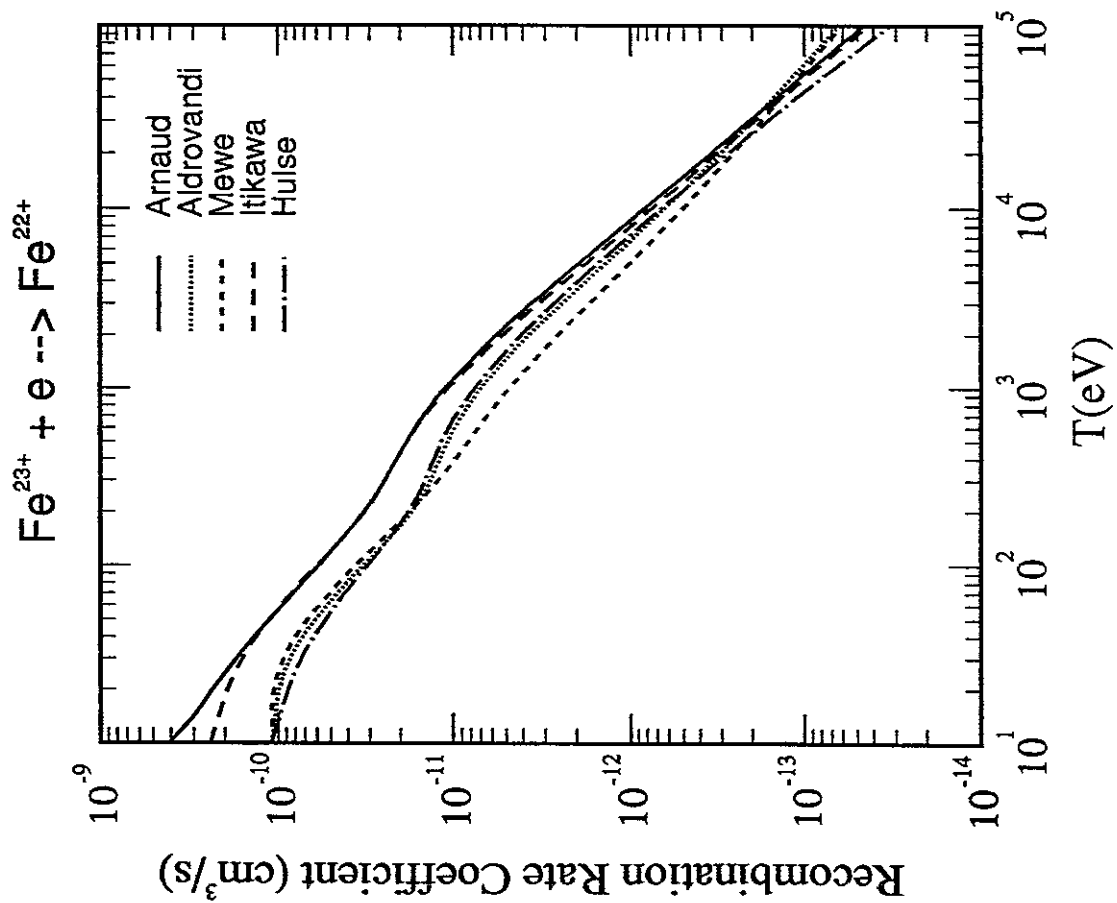


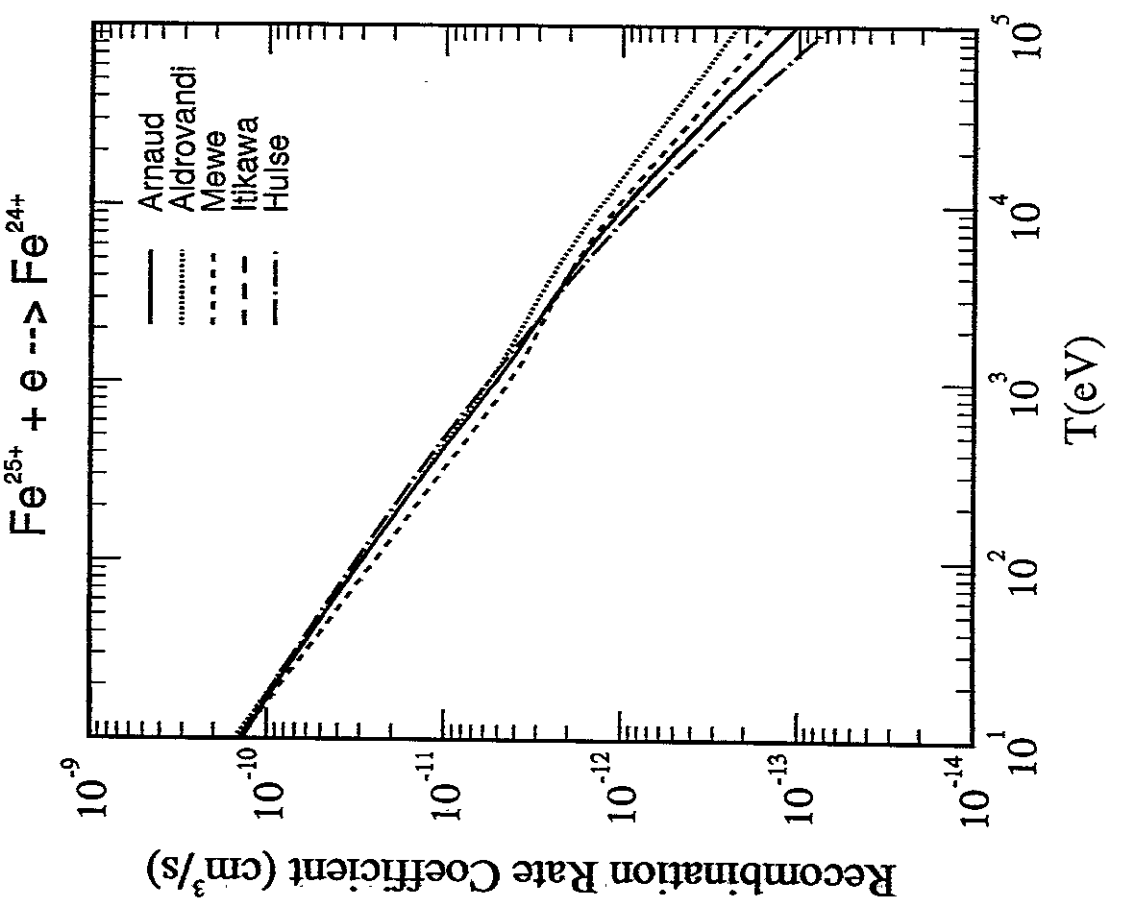
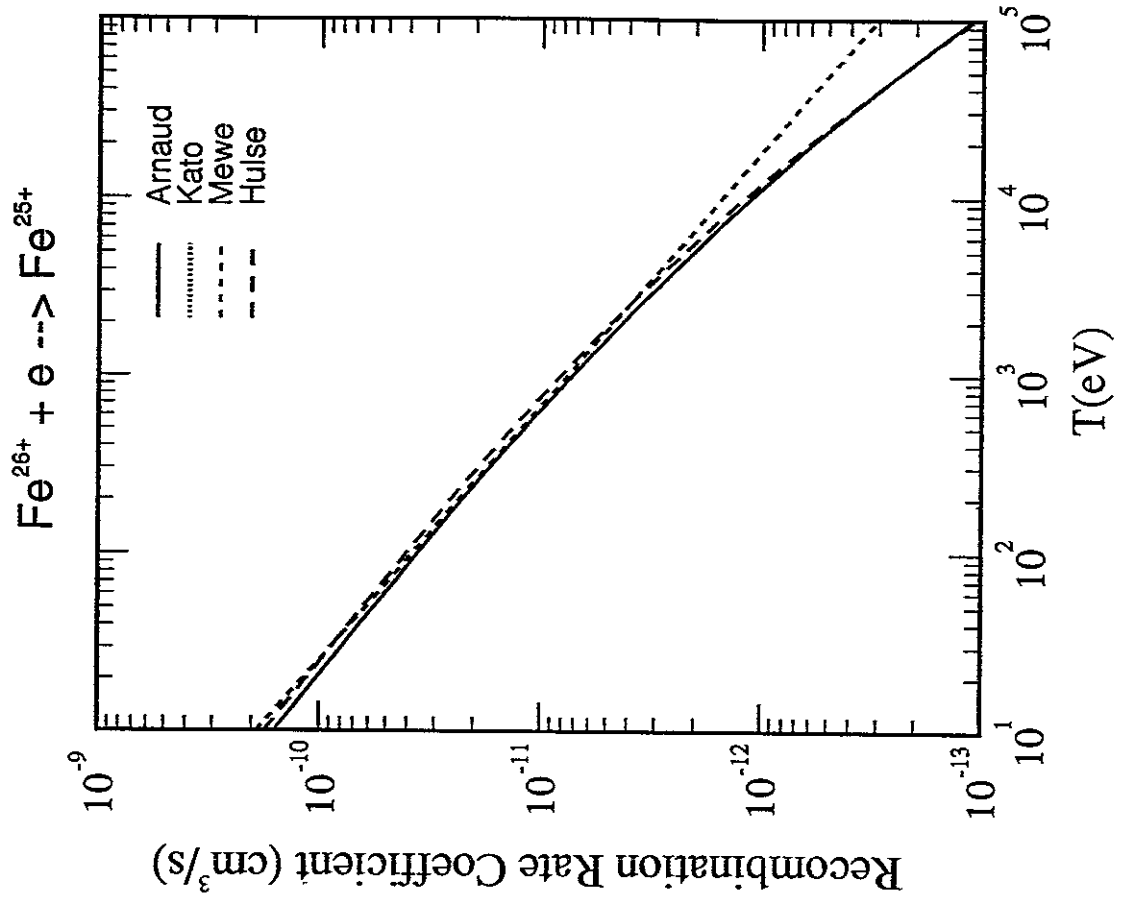


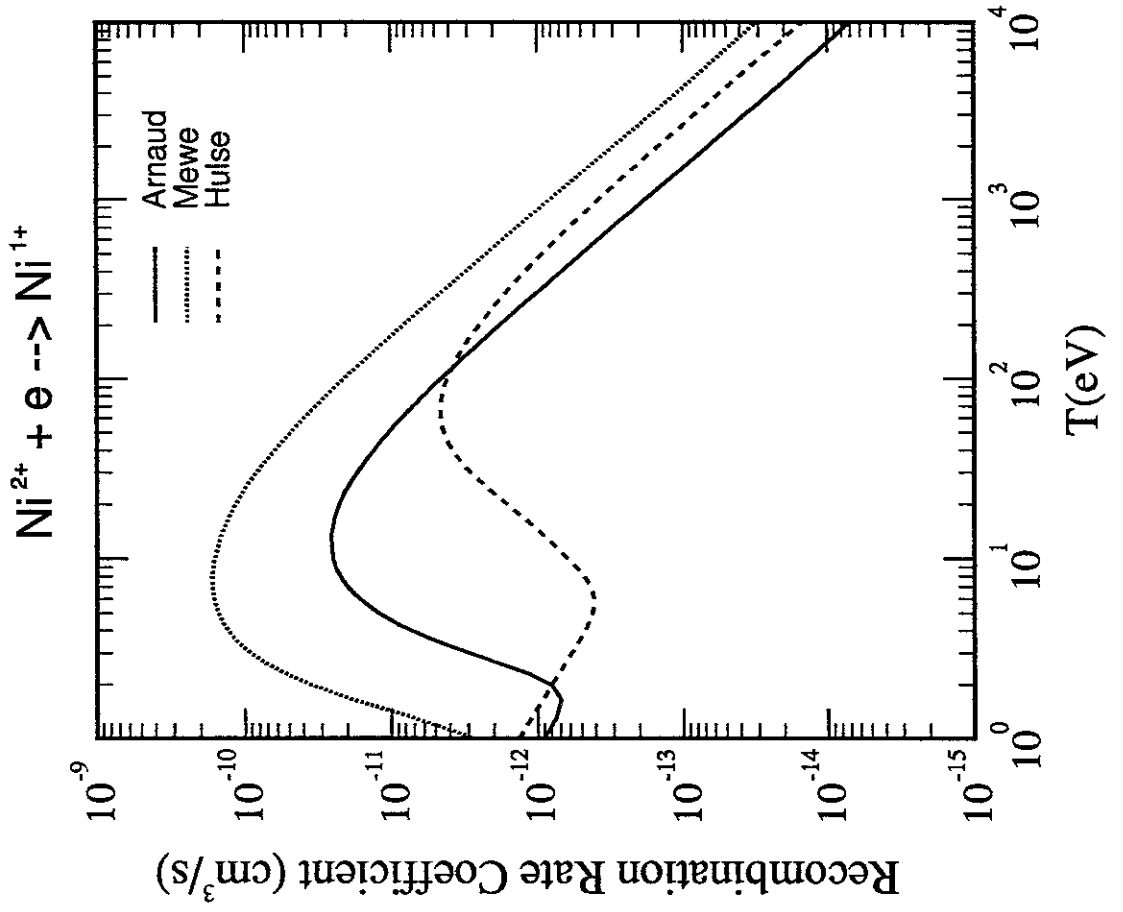
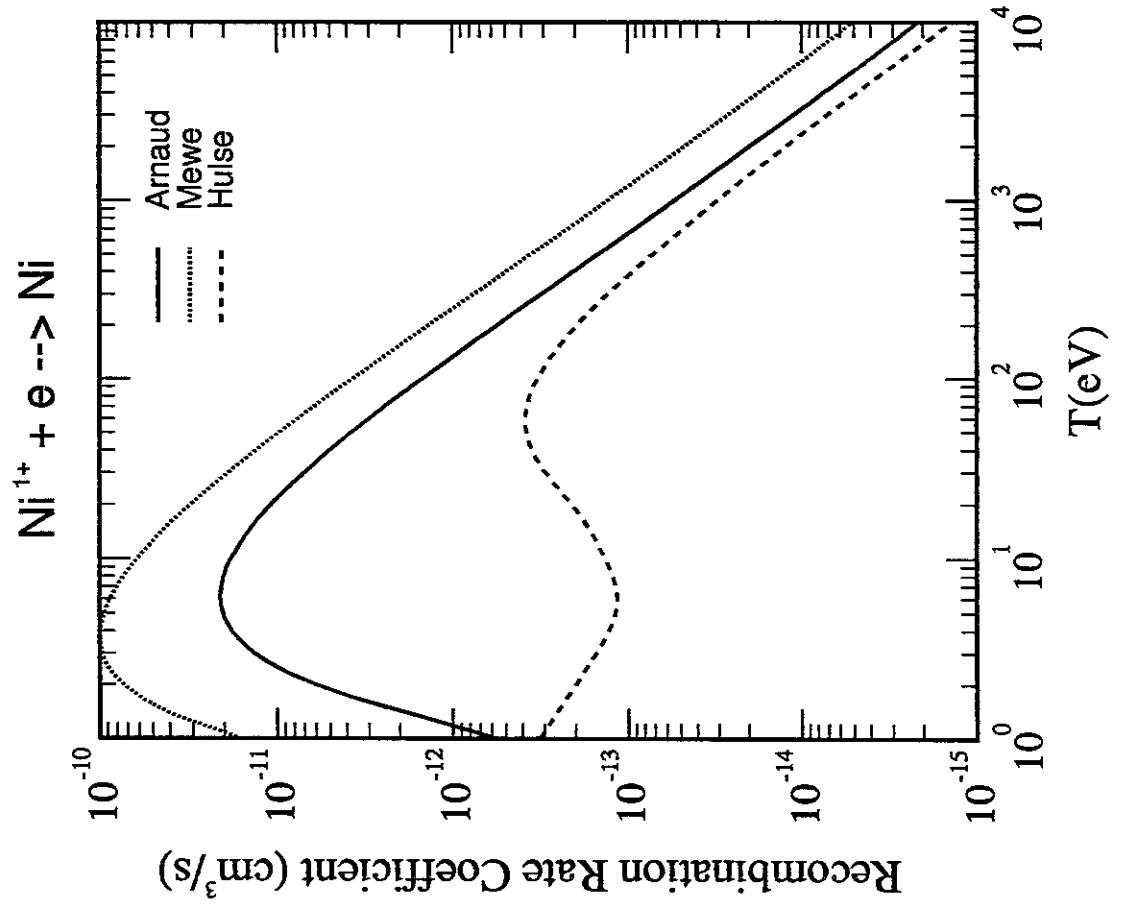


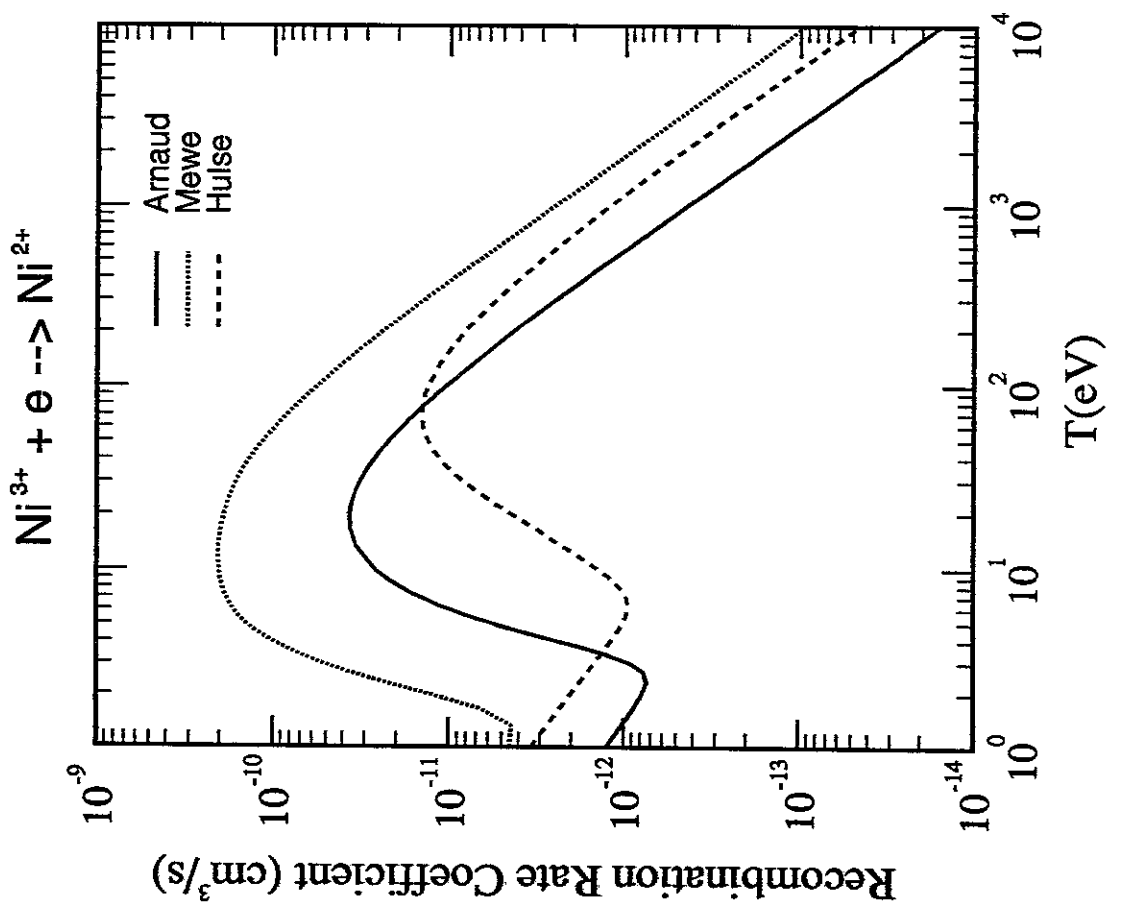
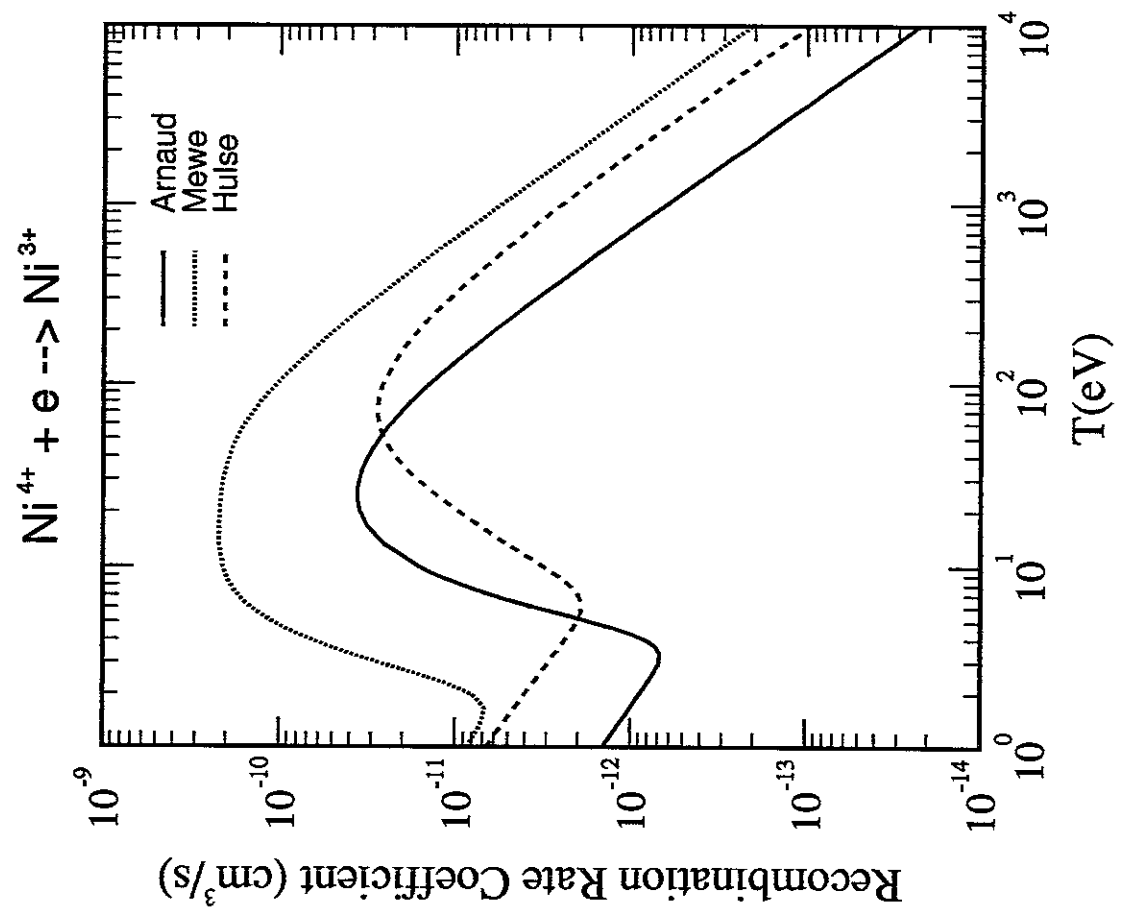


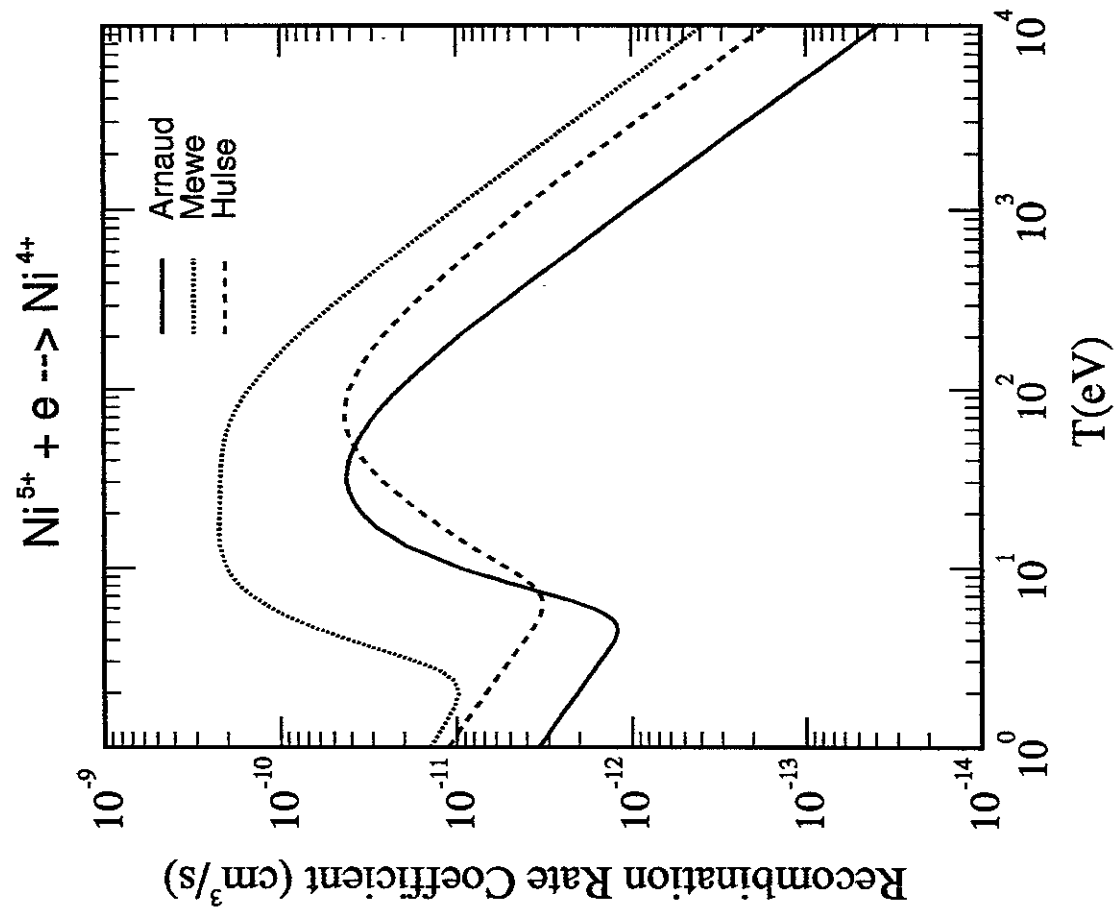
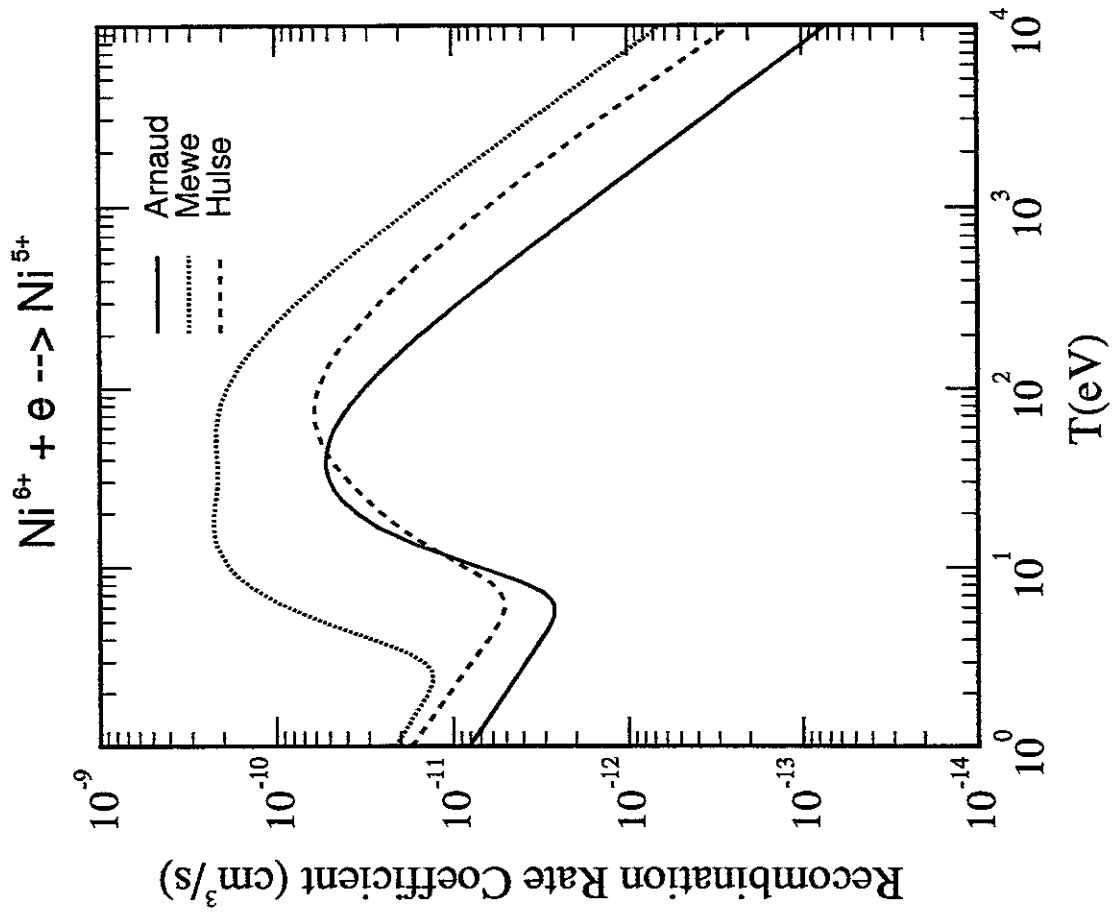


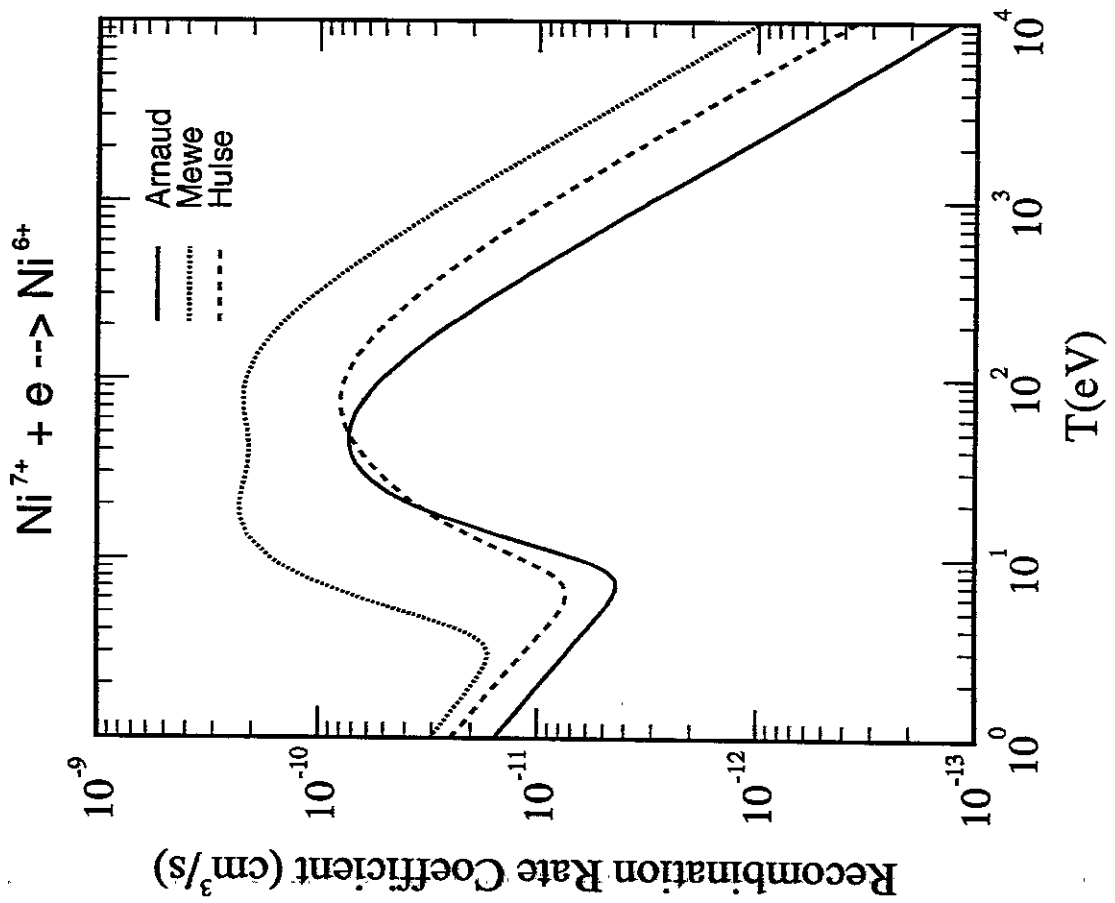
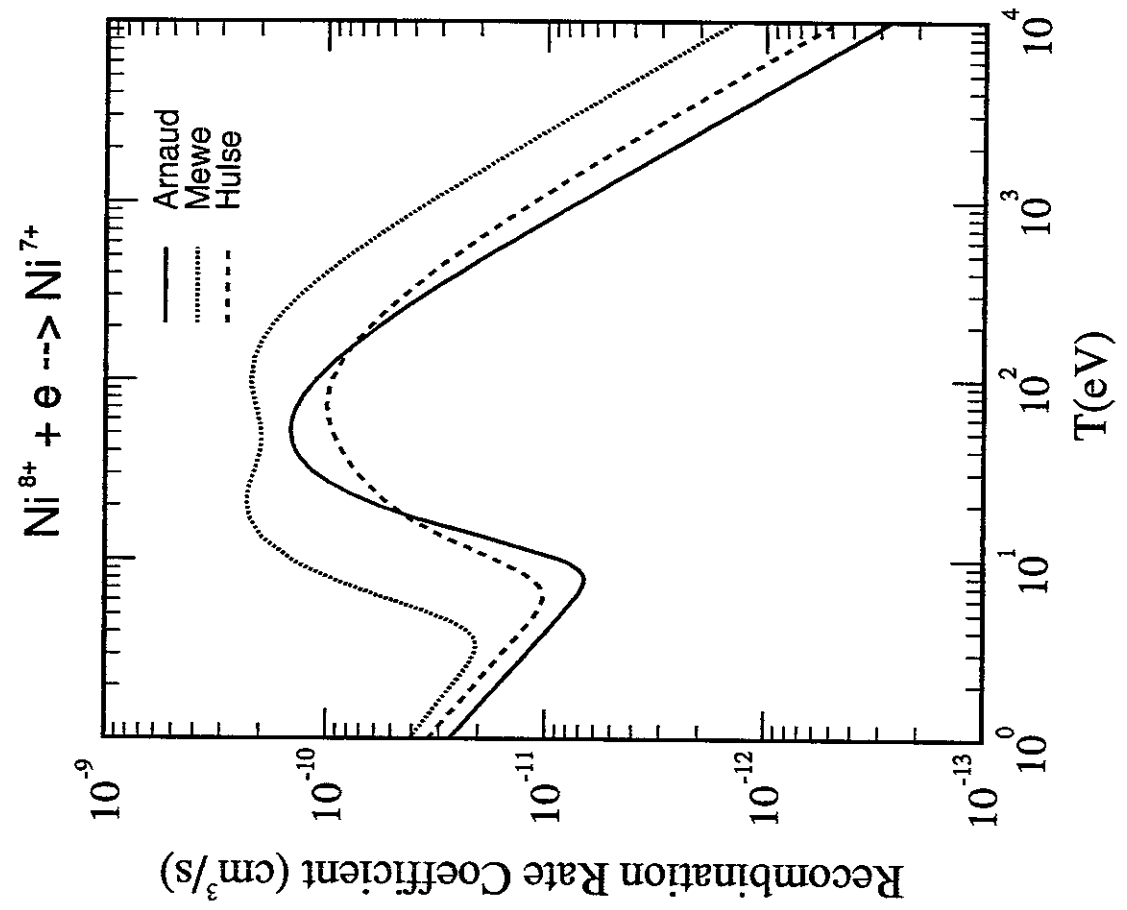


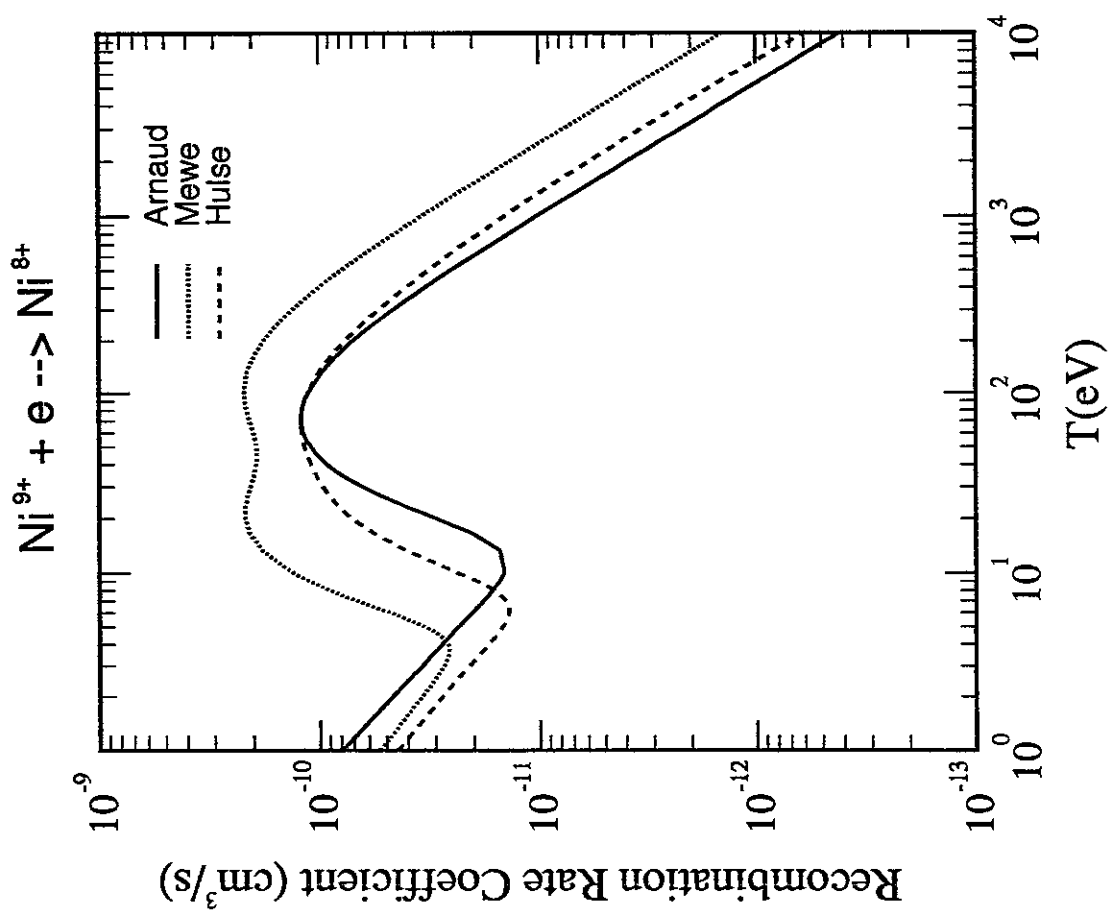
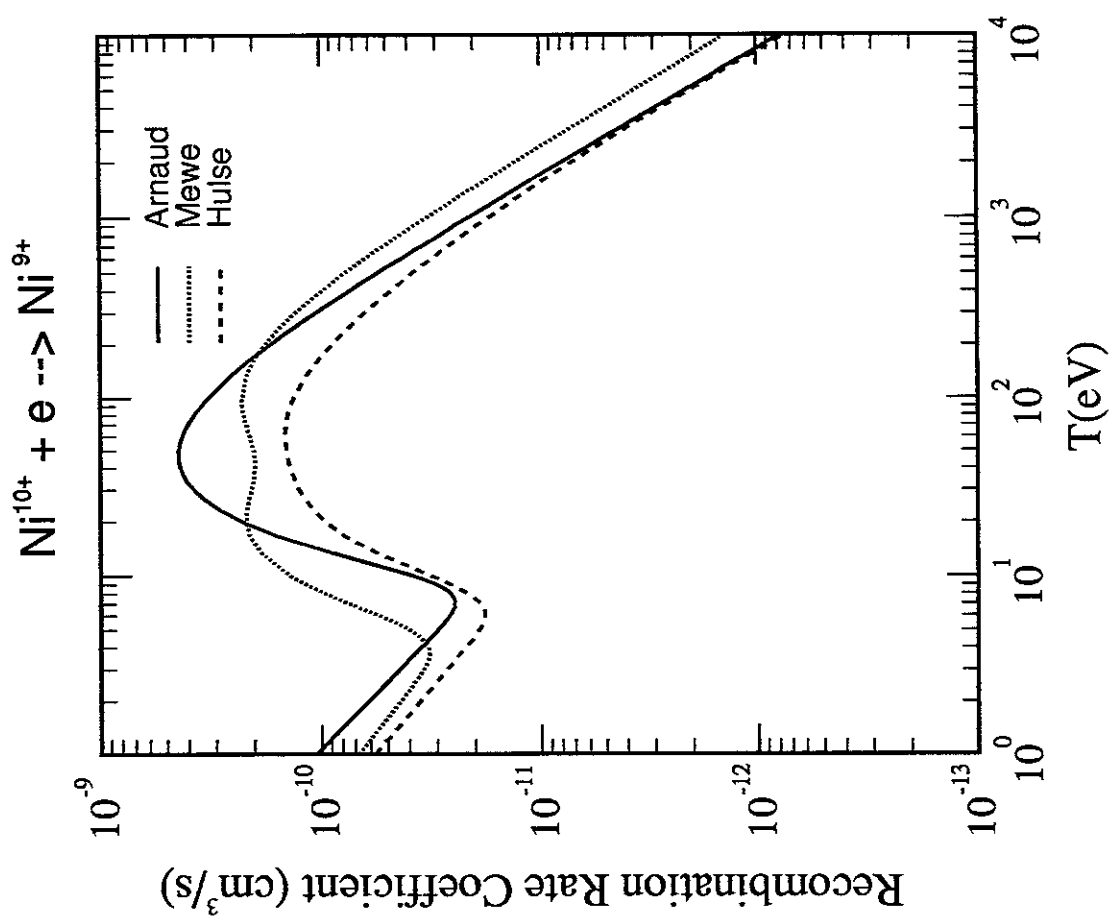


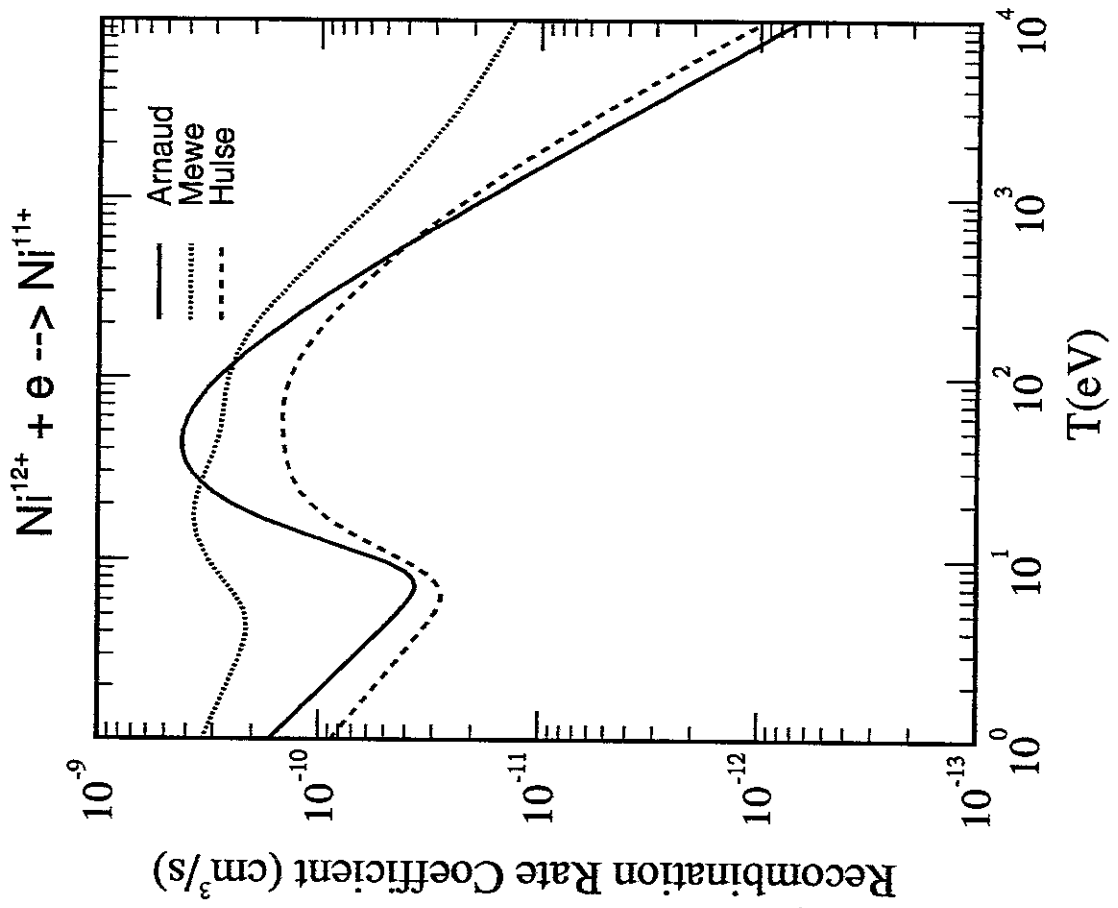
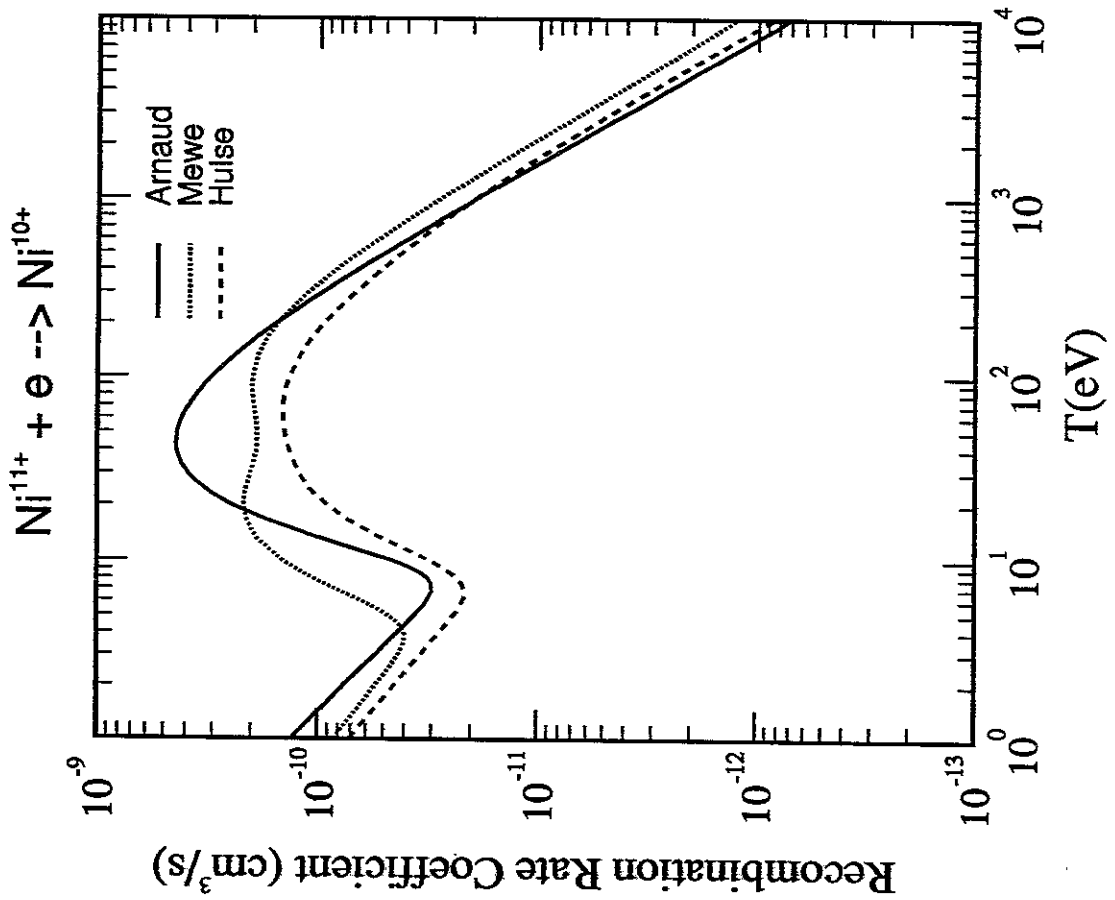


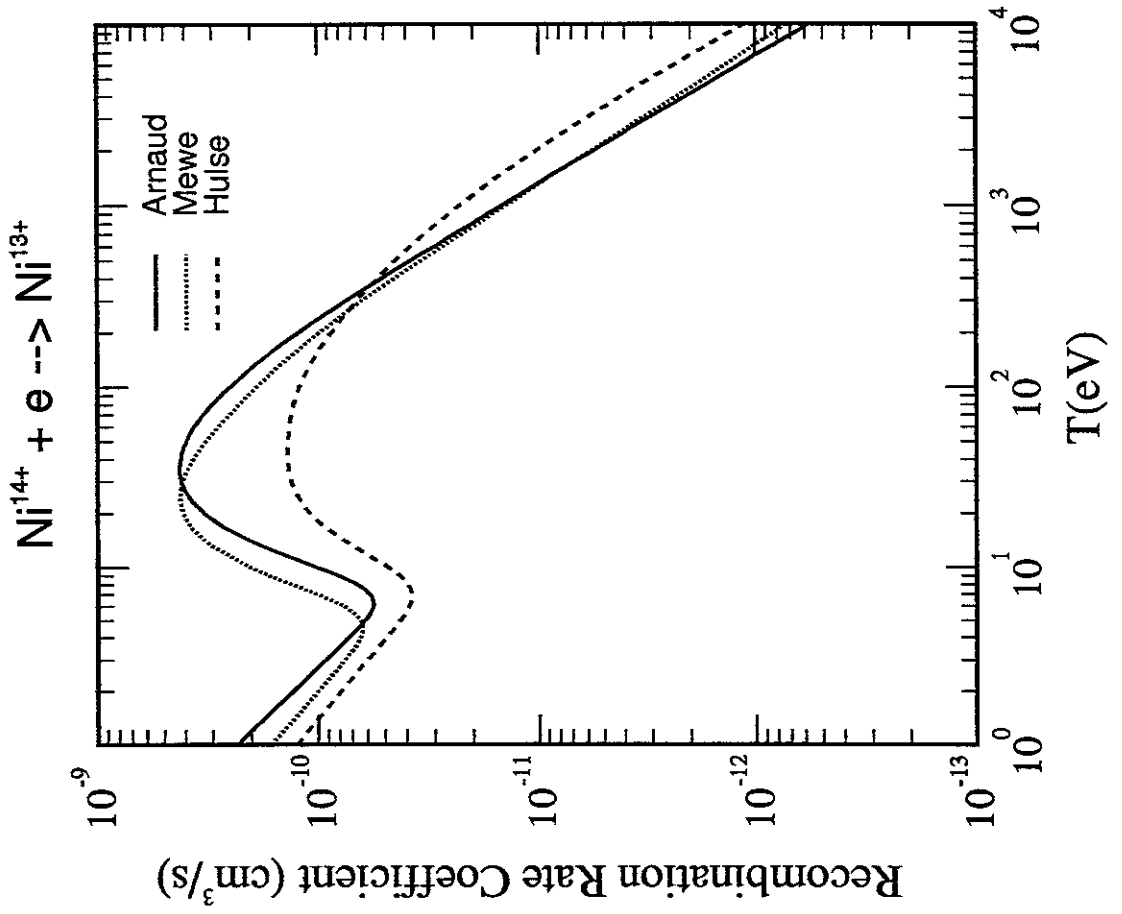
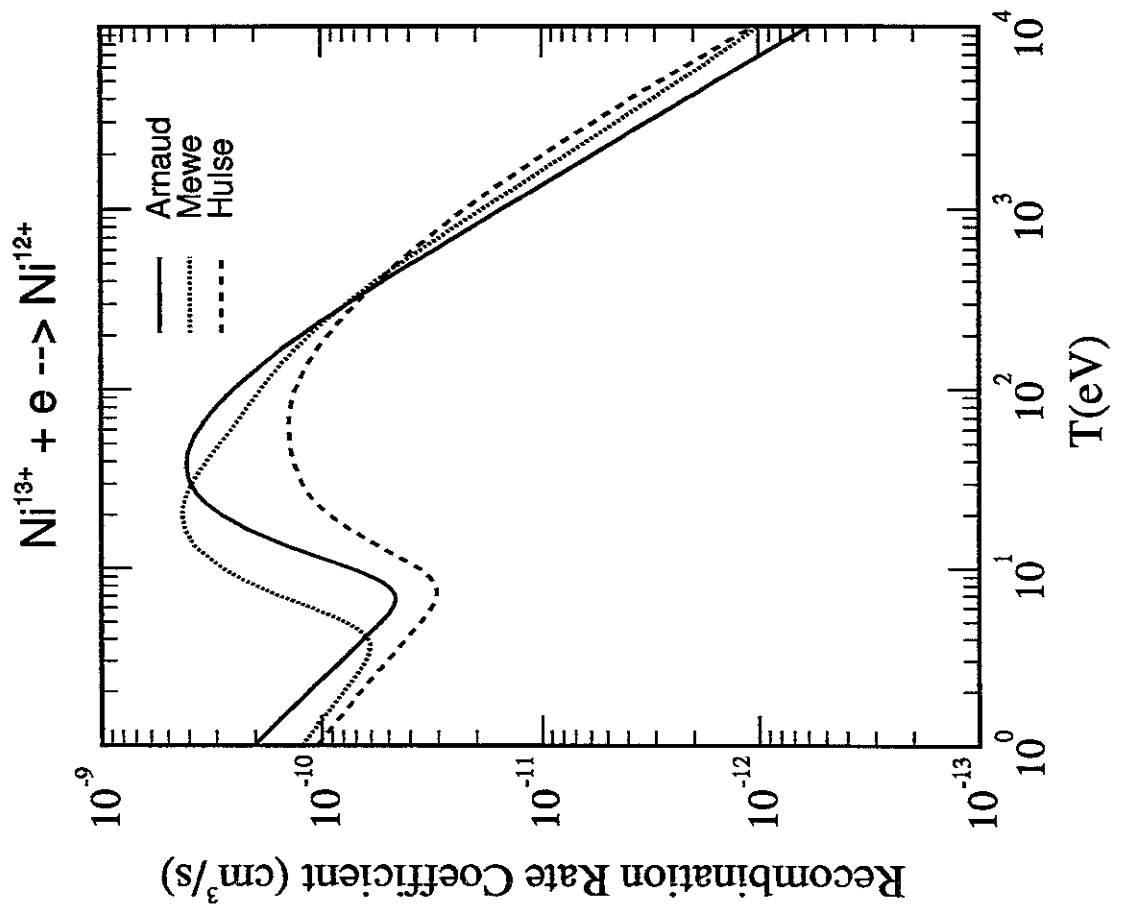


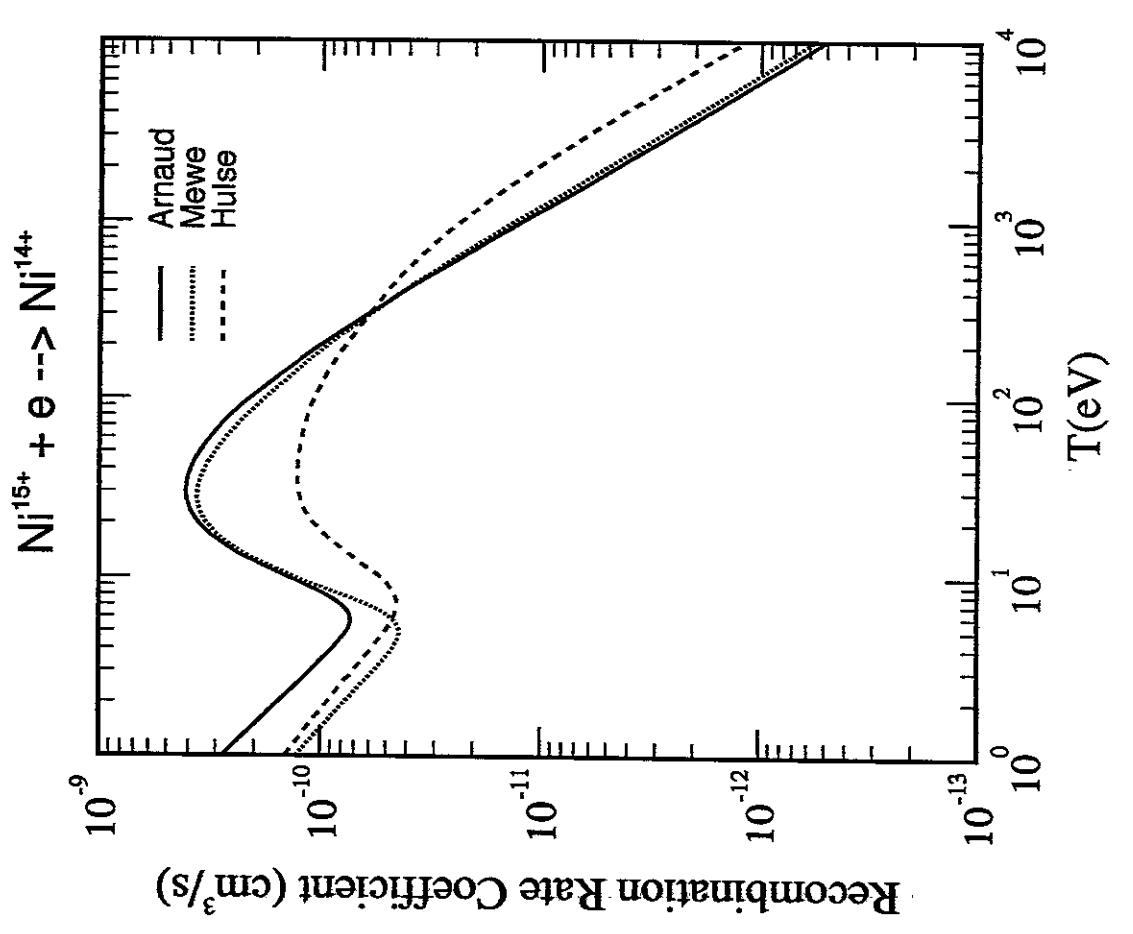
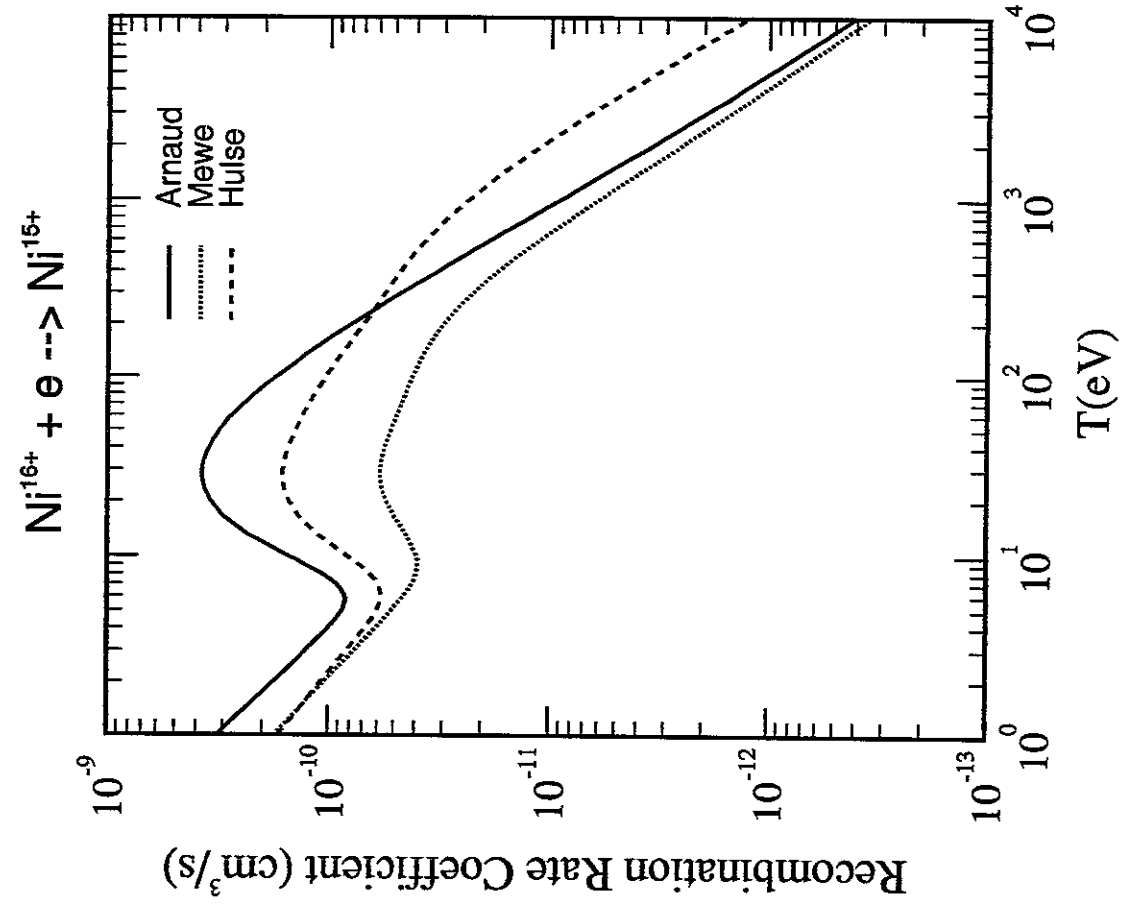


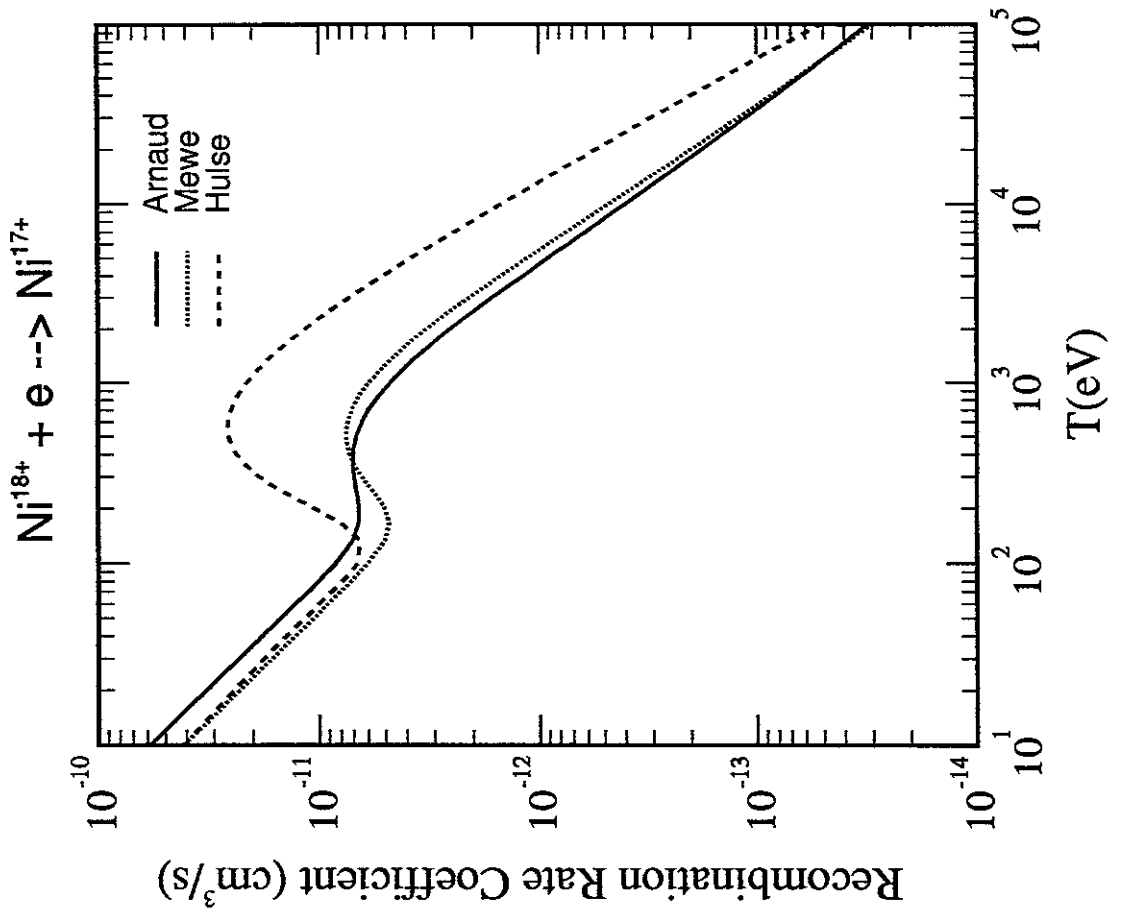
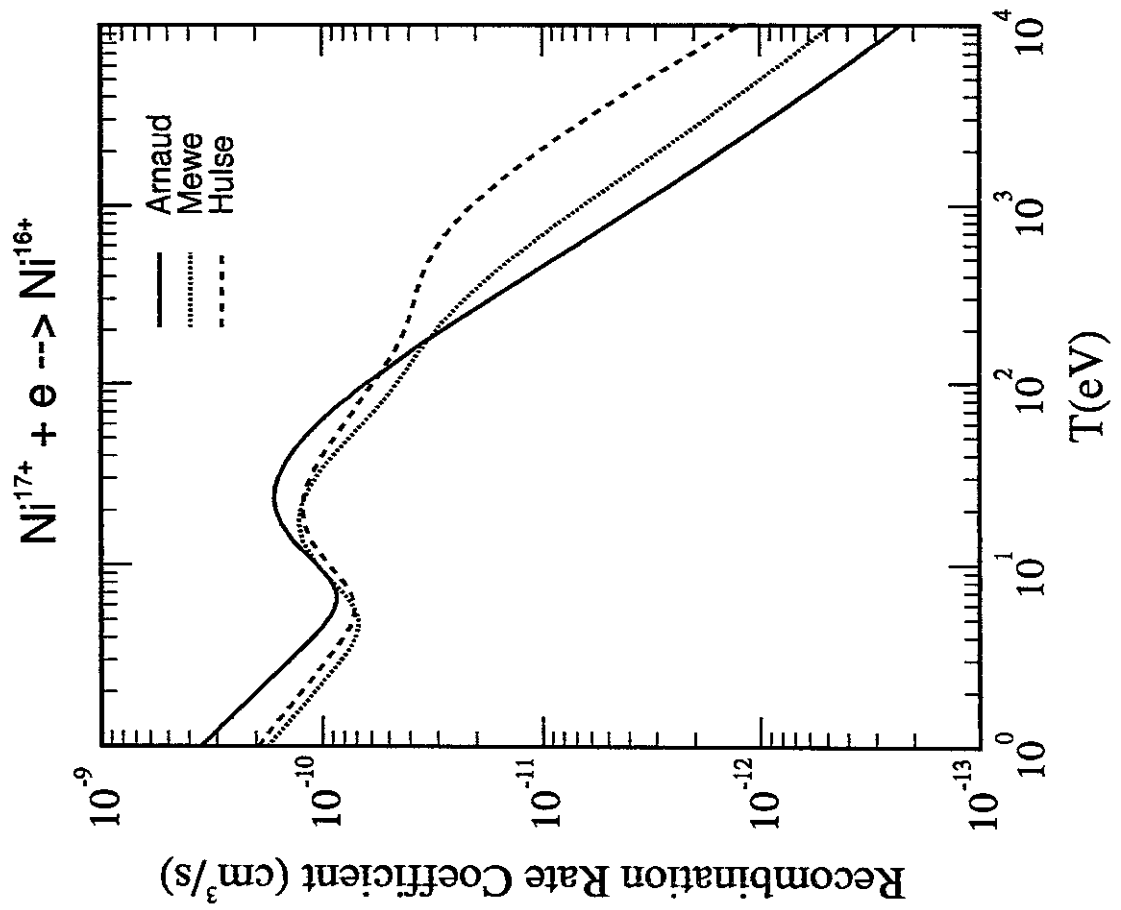


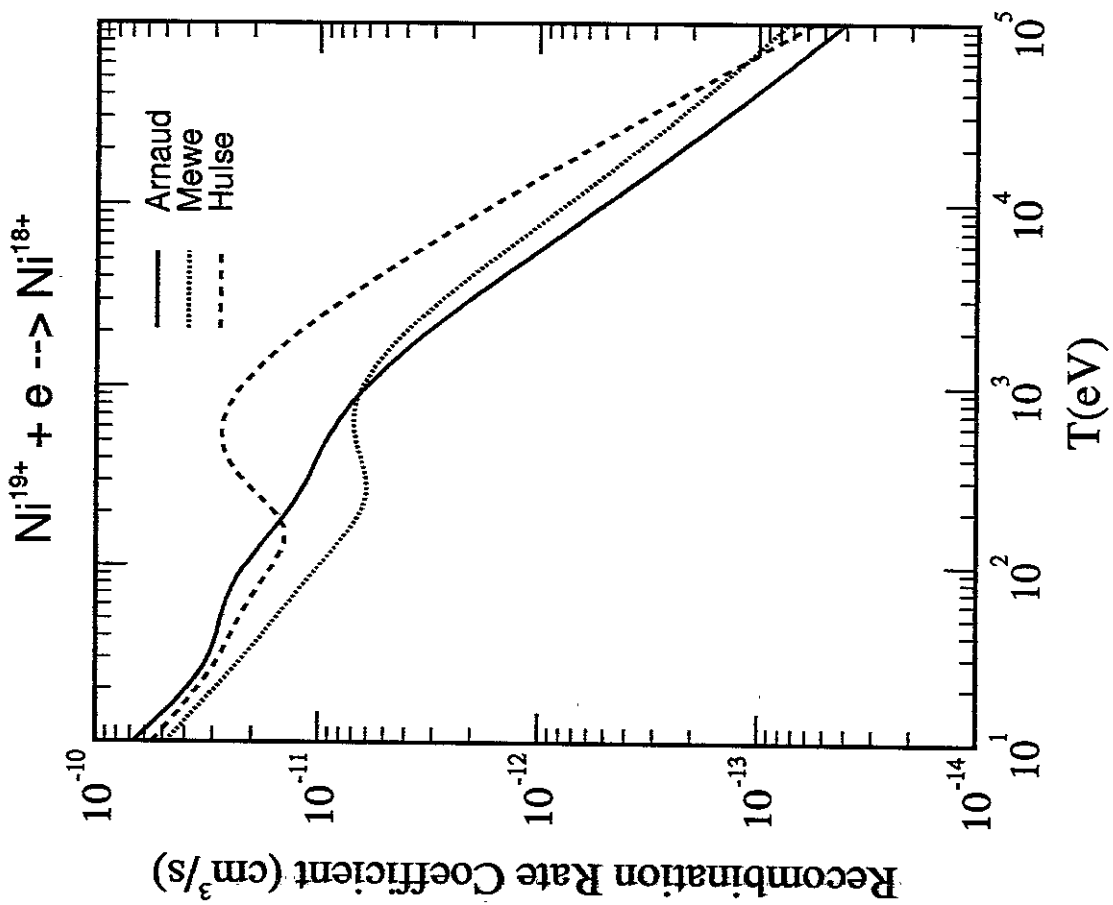
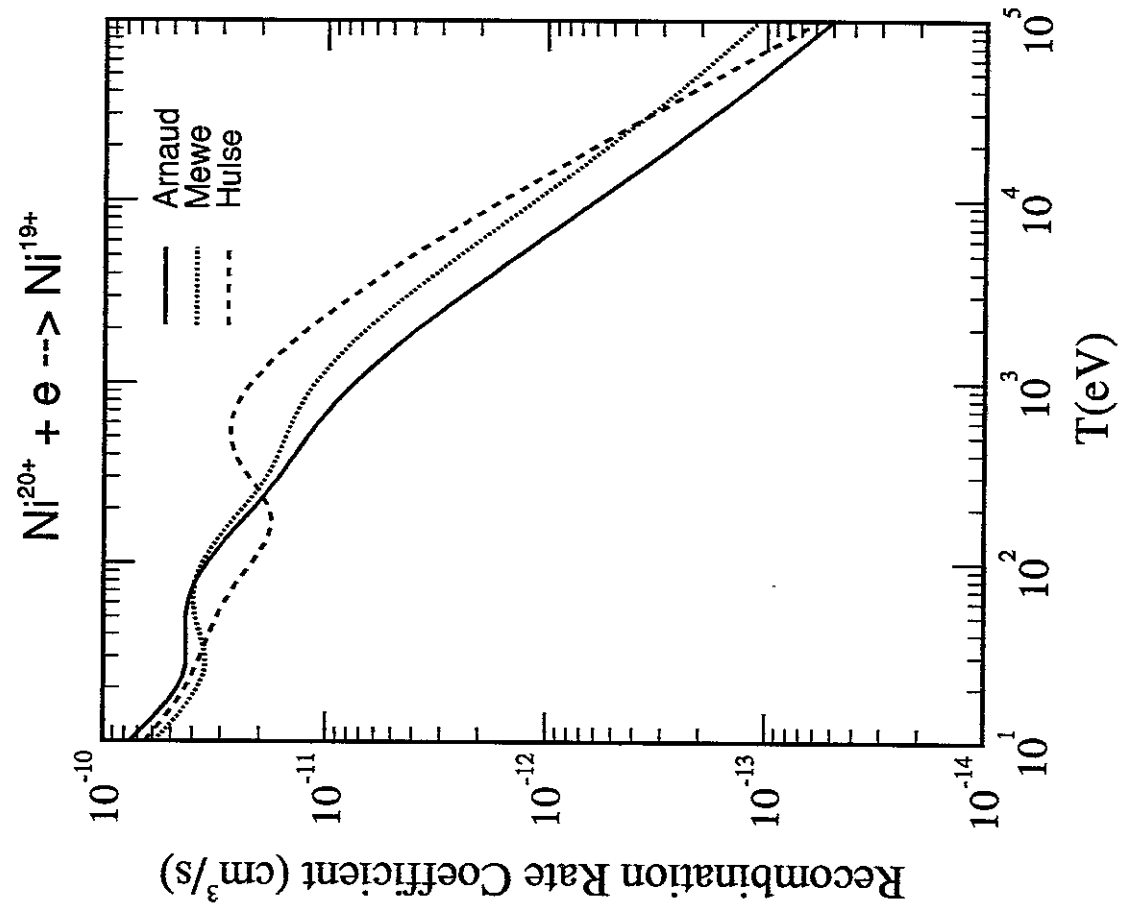


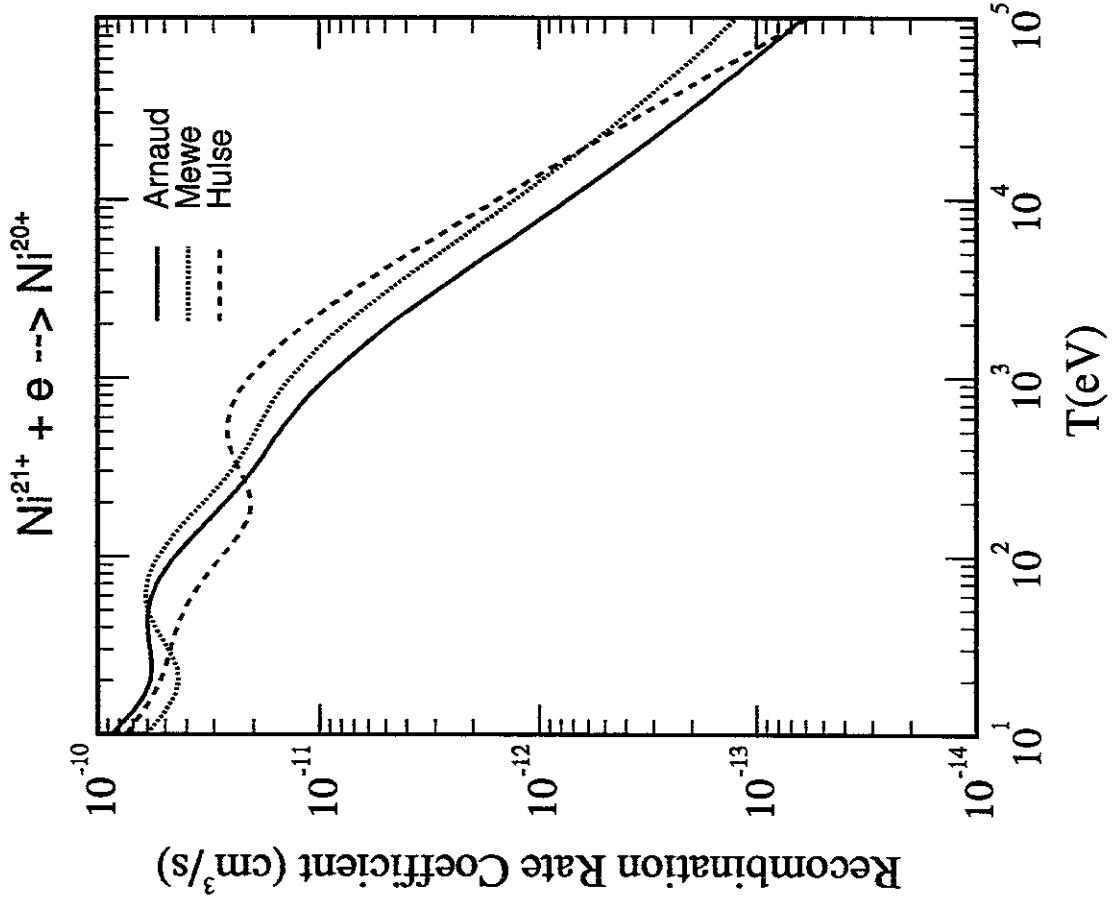
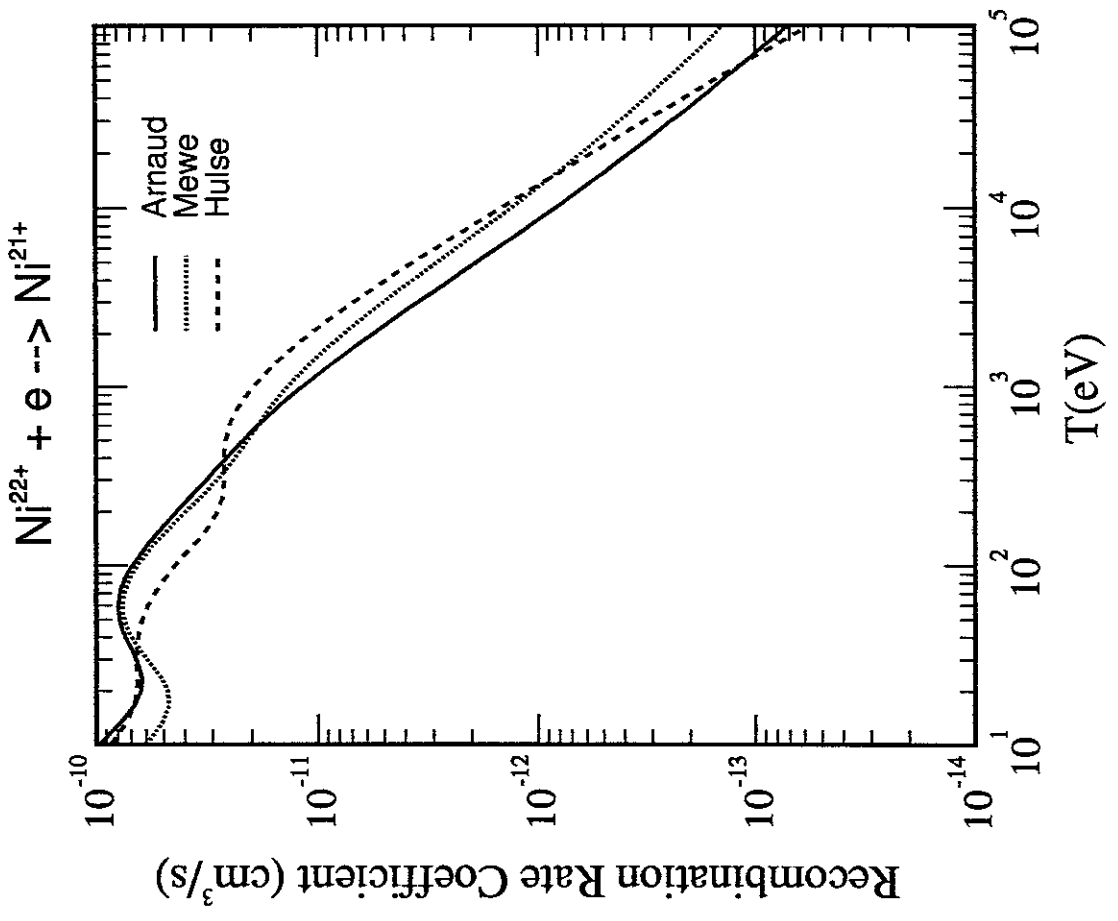


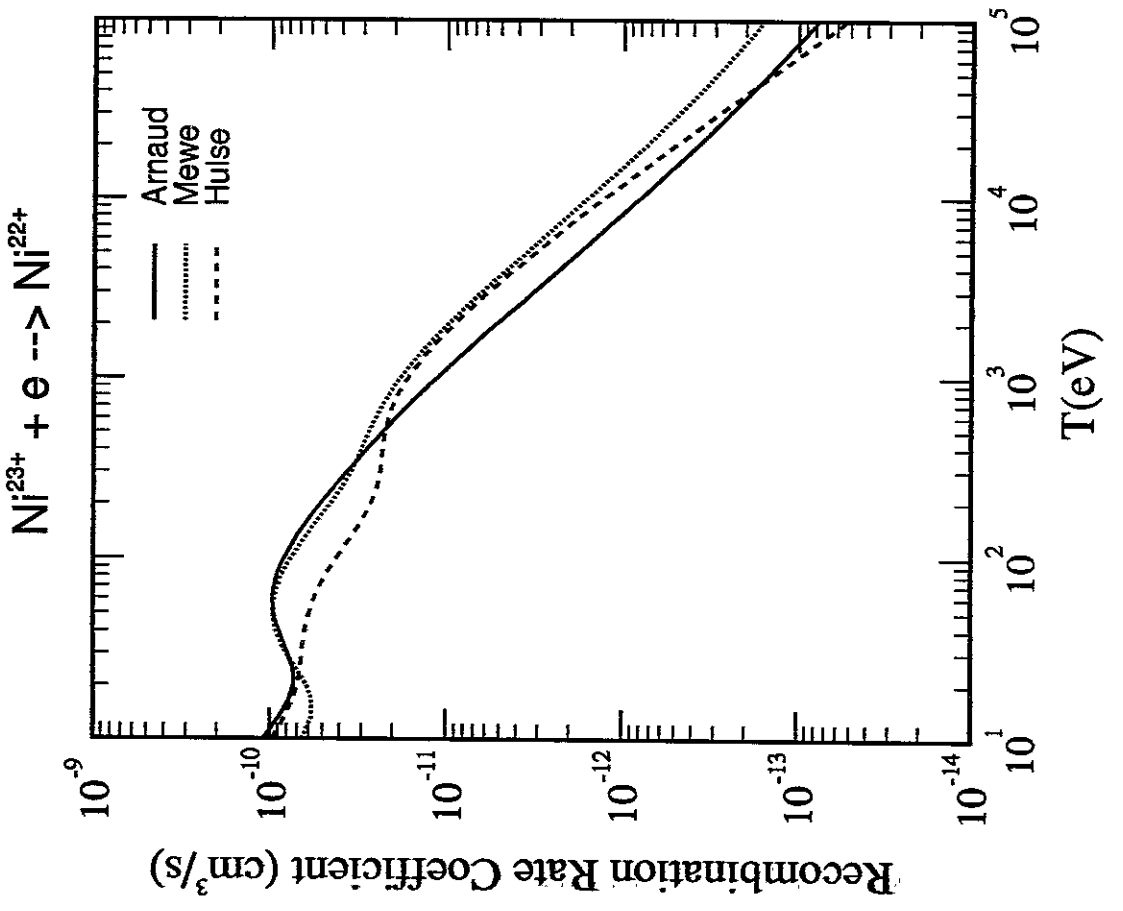
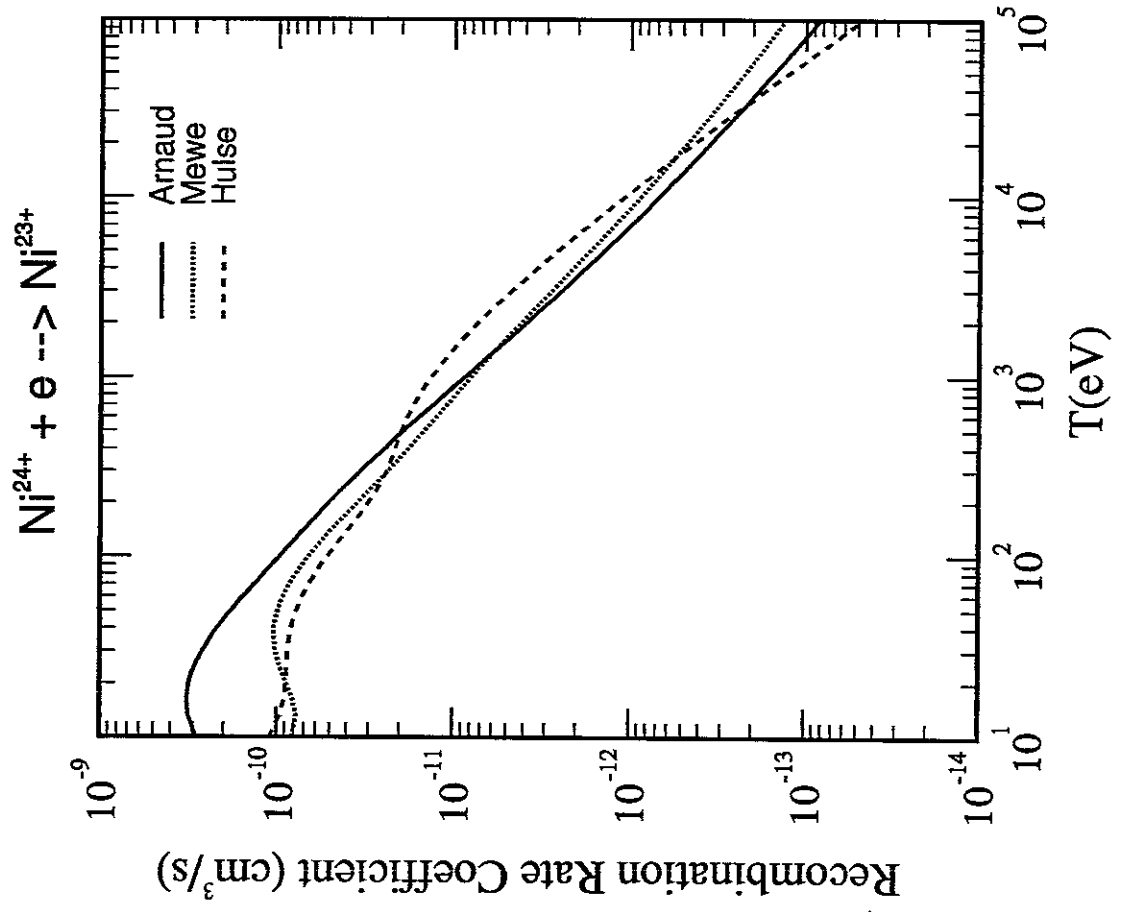


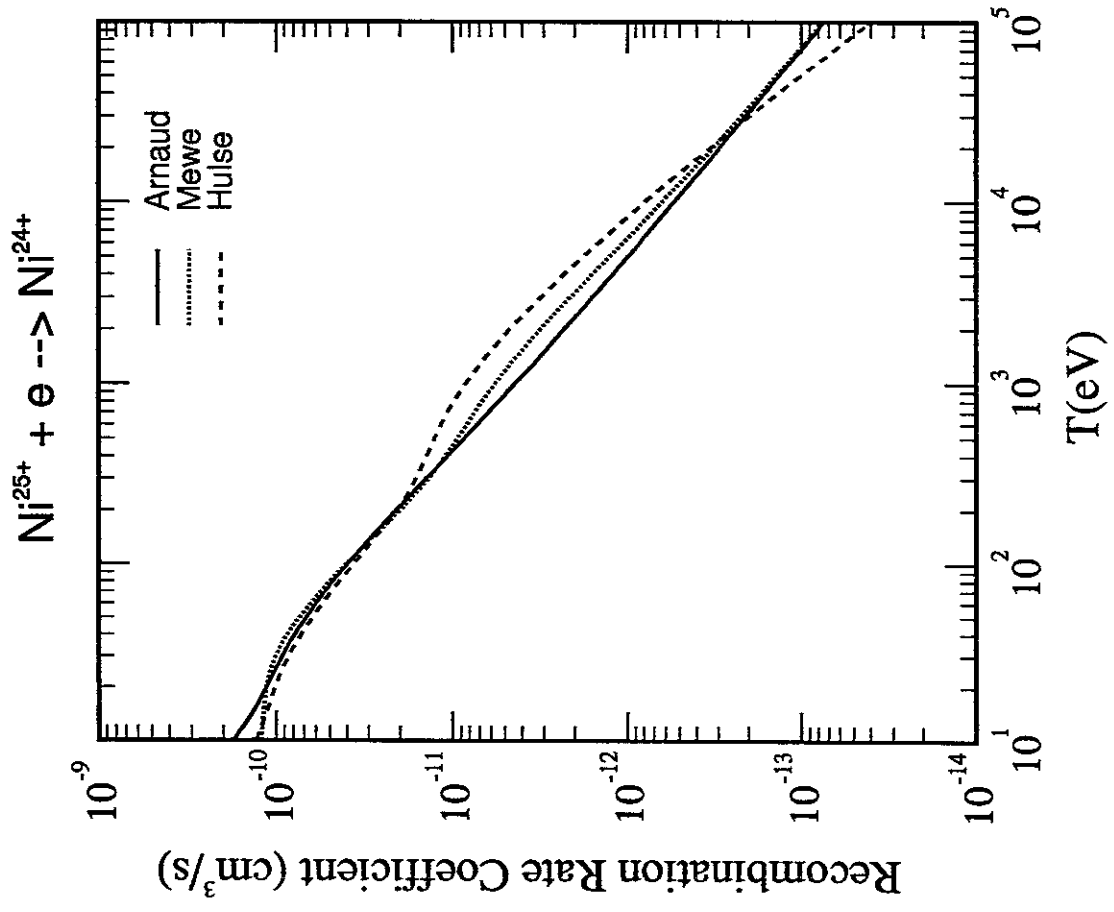
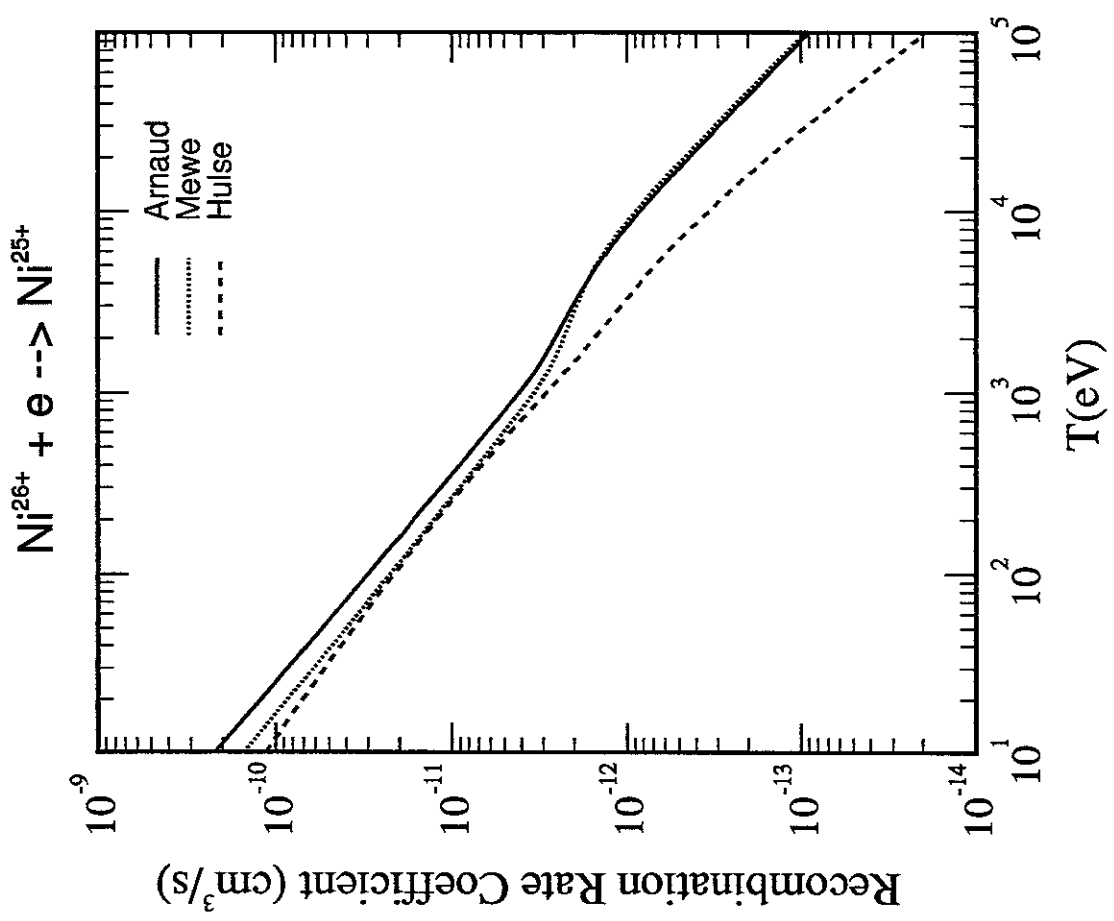


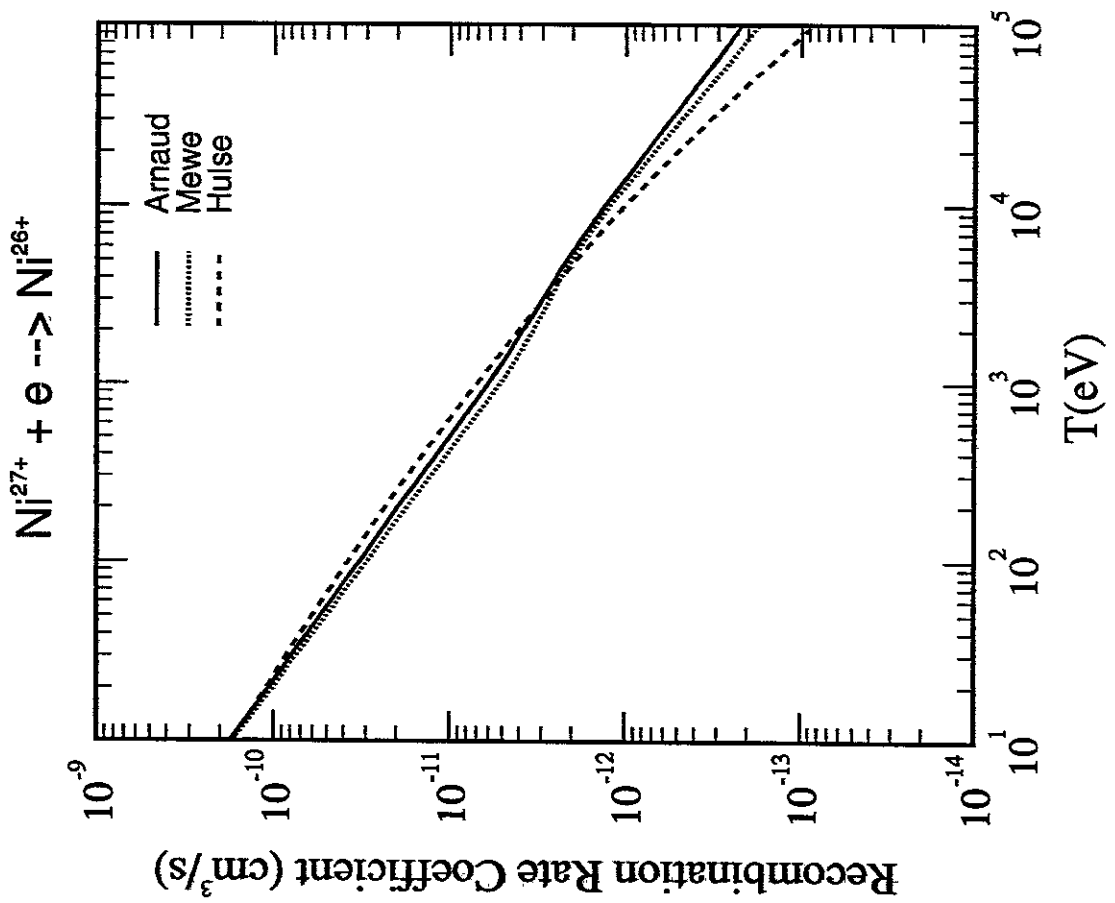
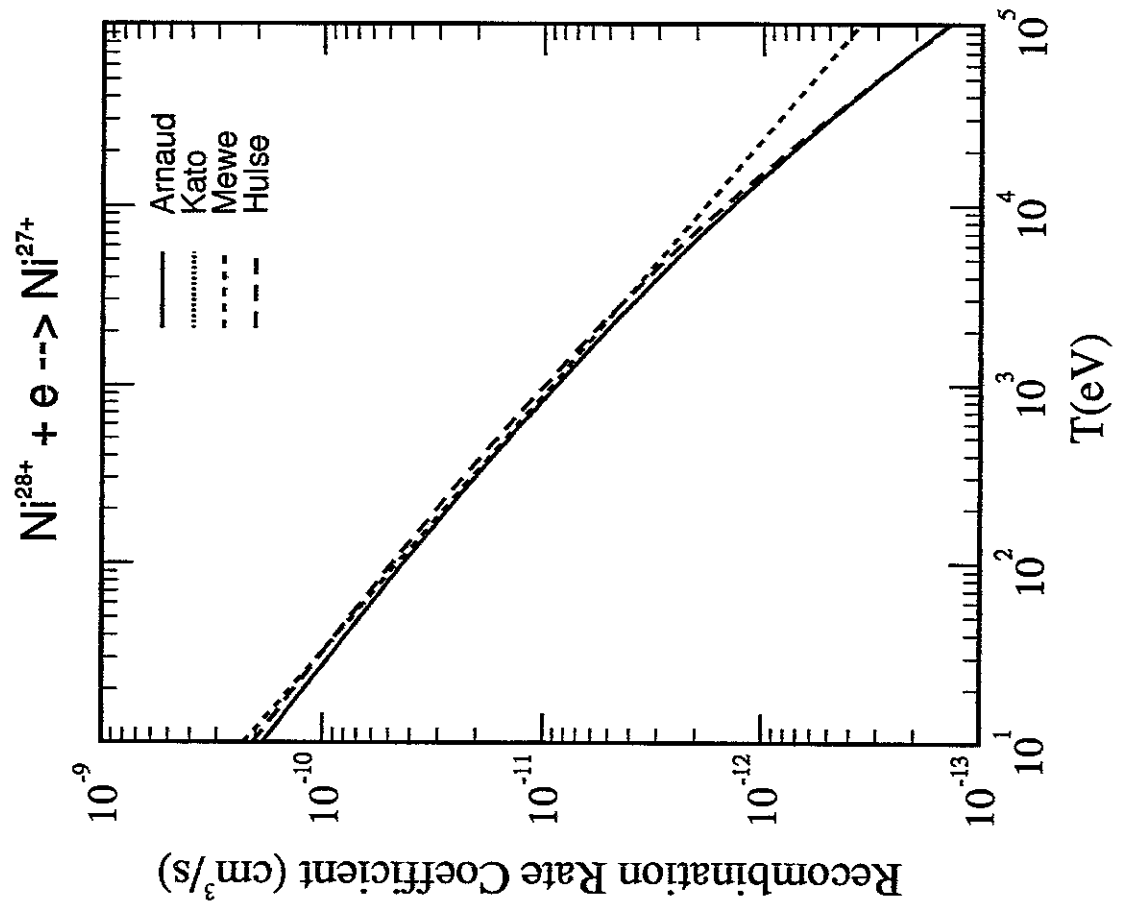












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- NIFS-DATA-3 T. Kaneko,
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- NIFS-DATA-4 T. Fujimoto, K. Sawada and K. Takahata,
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- NIFS-DATA-6 H Tawara, Y. Itikawa, H. Nishimura, H Tanaka and Y. Nakamura,
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Partial and Total Electronic Stopping Cross Sections of Atoms for a Singly Charged Helium Ion: Part I: Mar. 1991
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