Excitation of helium by proton and multicharged ions at intermediate and high impact energies

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Total cross sections for proton and multicharged ions ($Z_p=1-8$) impact excitation of helium ($1\,^1S\to 2\,^1P$, $3\,^1P$) have been calculated in the framework of the semiclassical sudden Born (SSB) approximation. The cross sections for multicharged ion impact show a good agreement with the experimental data for $\eta=Z_p/v_p<1.5$. No other theoretical results for $Z_p>2$ are available.

Collisional processes between heavy particles and helium atoms resulting in target excitation are of fundamental and practical interest. Recently considerable experimental [1–4] and theoretical [5–16] efforts have been devoted to the proton excitation of helium and only few papers [6,17] have dealt with multicharged ion–helium collisions being of particular importance for various fields (nuclear fusion, plasma diagnostics, lasers, astrophysics etc.).

Among theoretical studies of helium excitation by proton impact beyond the first Born approximation one can point out the calculations based on the various distorted wave approximations [5–9], the coupled states method [10], the second order perturbation theory [11,12], the second order diagonalization [13], the Glauber approximation [14–16]. Apart from the calculations of the excitation by α-particle impact within the distortion approximation [6], we are not aware of other calculations going beyond the first Born approximation for multicharged ion impact.

In this Letter we present the cross sections of helium excitation ($1\,^1S\to 2\,^1P$, $3\,^1P$) by proton and multicharged ions which have been calculated using the semiclassical sudden Born (SSB) approximation suggested earlier by one of the authors [18–21].

The SSB approximation is based on joining the probabilities obtained for a small and a large impact parameter using different theoretical grounds. The transition probability in the first order of the ordinary semiclassical theory (SCA) (cf. ref. [18]) is

$$W_{\mathrm{fi}}^{\mathrm{SCA}}(\boldsymbol{b})=\left|-\frac{\mathrm{i}\eta}{\pi}\int\frac{\mathrm{d}^3q}{q^2}\,\delta\!\left(\frac{\boldsymbol{q}\cdot\boldsymbol{v}_\mathrm{p}-\Omega_\mathrm{fi}}{v_\mathrm{p}}\right)\exp(-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{b})\right.$$
$$\left.\times\langle \mathrm{f}|\exp(\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}_1+\exp(\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}_2)|\mathrm{i}\rangle\right|^2, \tag{1}$$

where $\Omega_\mathrm{fi}=\omega_\mathrm{f}-\omega_\mathrm{i}$ is the transition frequency, $\eta=Z_p/v_p$, Z_p and v_p are the projectile charge and its velocity, $\boldsymbol{r}_1$, $\boldsymbol{r}_2$ are the radius-vectors of the target electrons. In the dipole area a measure of the interaction strength is $\eta a/b$ ($a=\hbar^2/Z_t me^2$ is the characteristic target atom size), therefore the use of eq. (1) is correct for $b\gg\eta a$. For $b\sim a$ the interaction strength is of the order of η which is not small for multicharged ions in most particular cases. In this area the transition probability is defined by the exponential amplitude [21],

$$W_{\mathrm{fi}}^{\Omega}(\boldsymbol{b})=\left|\langle \mathrm{f}|\exp\left[\mathrm{i}\int\mathrm{d}t\begin{pmatrix}\cos\Omega_\mathrm{fi}t\\ \sin\Omega_\mathrm{fi}t\end{pmatrix}V(t)\right]|\mathrm{i}\rangle\right|^2, \tag{2}$$

where

$$V(t)=\frac{Z_p}{|\boldsymbol{R}(t)-\boldsymbol{r}_1|}+\frac{Z_p}{|\boldsymbol{R}(t)-\boldsymbol{r}_2|}, \tag{3}$$

and $\boldsymbol{R}(t)=\boldsymbol{b}+\boldsymbol{v}t$ is the internuclear distance. One should take $\cos\Omega_\mathrm{fi}$ in eq. (2) for even $l_\mathrm{i}+m_\mathrm{i}+l_\mathrm{f}+m_\mathrm{f}$

and sin Ω_{fi} otherwise, where l_i, m_i and l_f, m_f are the orbital and magnetic quantum numbers of the initial and final eigenstates respectively.

The exponential probability (2) is an improvement over the sudden one [21,22] by retaining the transition frequency Ω_{fi}. For $b \lesssim a$ the explicit account of Ω_{fi} in eq. (2) allows one to combine automatically the probability originating from the sudden perturbation theory [22] for small internuclear distances with the semiclassical probability in outgoing legs of the trajectory where the interaction strength is small enough. As the impact parameter increases the exponential probability (2) turns into with the semiclassical one (1) according to the interpolation formula,

$$W_{fi}(\boldsymbol{b}) = \frac{W_{fi}^{SCA}(\boldsymbol{b})}{1+g(\boldsymbol{b})\,W_{fi}^{SCA}(\boldsymbol{b})}, \tag{4}$$

where

$$g(\boldsymbol{b}) = \frac{1}{W_{fi}^{\Omega}(b\ll a)} - \frac{1}{W_{fi}^{SCA}(b\ll a)}. \tag{5}$$

The use of the exponential probability requires the "suddenness" conditions to hold:

$$\xi = Z_t/v_p \ll 1, \tag{6}$$

where ξ is a measure of the collisional time. Since the semiclassical theory is employed for $R \gg a$ the renormalized probability (4) is expected to be more correct the better the following inequality is satisfied.

$$\eta = Z_p/v_p \lesssim 1. \tag{7}$$

Conditions (6) and (7) provide together the applicability of the stated approach. The cross section is given by

$$\sigma_{fi} = 2\pi \int \mathrm{d}b\, bW_{fi}(b). \tag{8}$$

Throughout the formulae atomic units have been used.

In this calculation the analytic wave functions of van den Bos [10] have been taken for the helium eigenstates. The use of the diverse initial state wave functions [23,24] involving two exponents does not affect the cross sections drastically but if one employs the single exponent wave function of Morse et al. [25] for the initial eigenstate the results would be different even in the Born limit.

The calculated SSB cross sections of helium excitation by proton impact are compared with the SCA ones and experimental data [1,2,4] in fig. 1 for the $1\,^1S \to 2\,^1P$ transition and in fig. 2 for the $1\,^1S \to 3\,^1P$

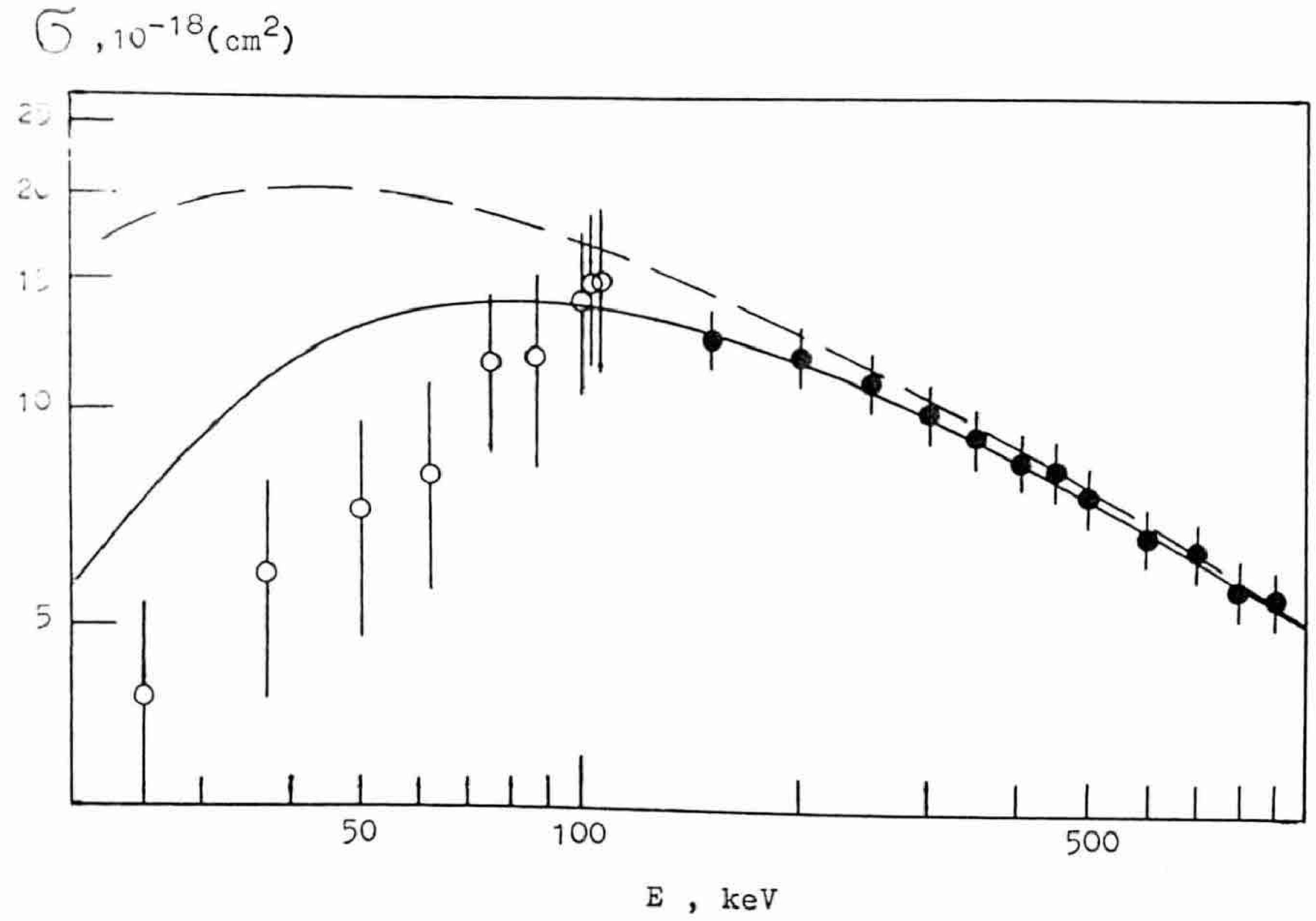

Fig. 1. Excitation cross section of helium $1\,^1S$–$2\,^1P$ by proton impact. Theory: (——) SSB, (– – –) SCA. Full circles and open ones are from the experiments of Hippler and Schartner [4] and Park and Schowengerdt [2] respectively.

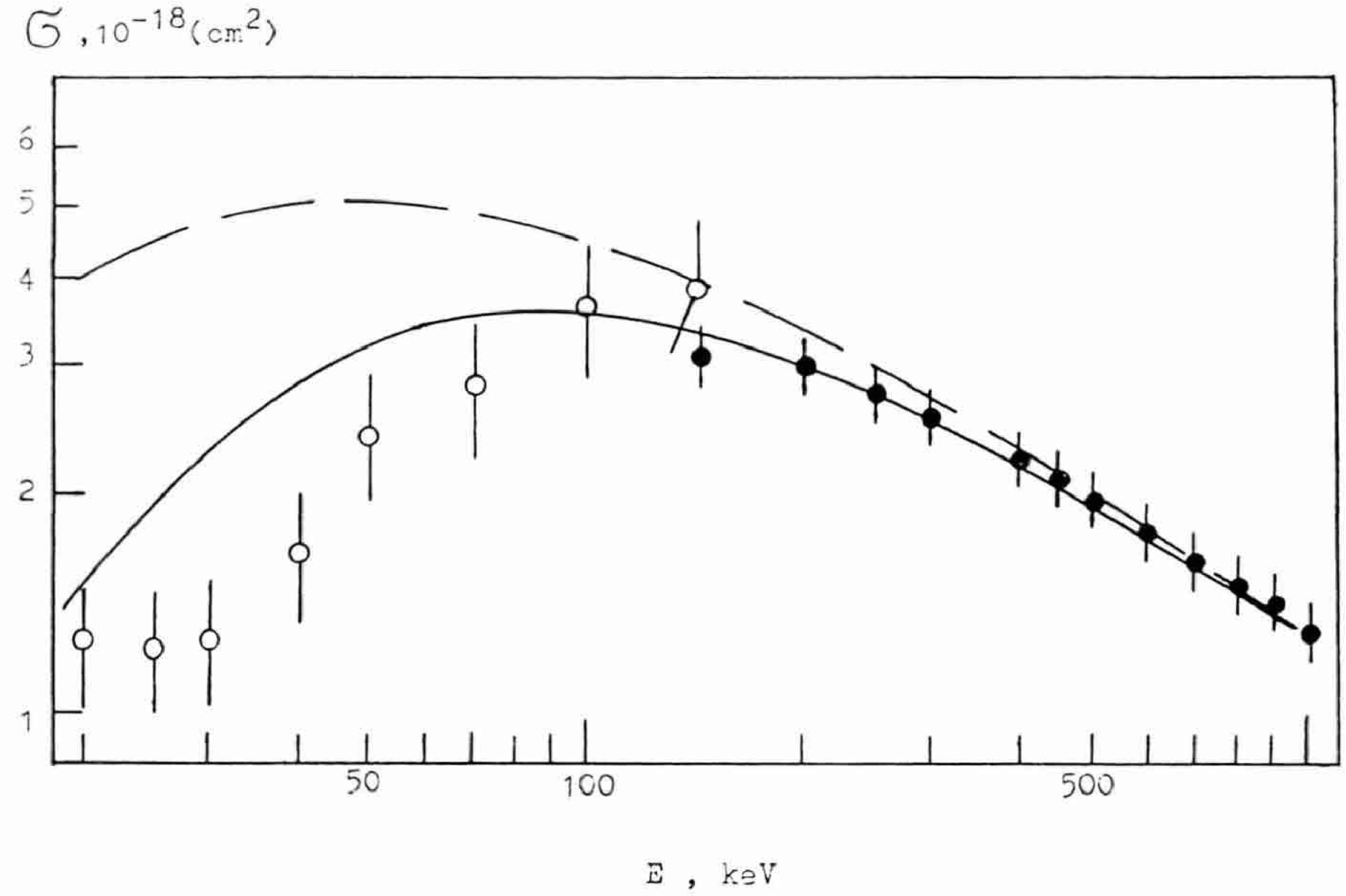

Fig. 2. Excitation cross section of helium 1 ^{1}S-3 ^{1}P by proton impact. Theory: (——) SSB, (- - -) SCA. Full circles and open ones are from the experiments of Hippler and Schartner [4] and Bos et al. [1] respectively.

Table 1
Excitation cross section of A^{q+} + He (1 ^{1}S→3 ^{1}P). σ^{exp} is from ref. [17]

E (keV/amu)	Projectile	$\eta = Z_p/v_p$	σ^{SCA} (10^{-18} cm^2)	σ^{SSB} (10^{-18} cm^2)	σ^{exp} (10^{-18} cm^2)
500	Si^{3+}	0.67	18	13	10.7
500	Si^{4+}	0.89	34	18	15.4
500	Si^{8+}	1.8	130	73	28.2
365	Cu^{5+}	1.3	62	14	17.9
318	Cu^{5+}	1.4	67	12	17.2
191	Cu^{5+}	1.8	87	3.6	17.2
444	Cu^{6+}	1.4	78	14	20.6
444	Cu^{8+}	1.9	140	4.6	23.7
1400	O^{6+}	0.80	36	25	15.6
1400	Ne^{7+}	0.94	48	28	24.4

transition. Agreement with experiment is good for $E > 75$ keV (the data of ref. [3] are very close to the data of ref. [4] and are not displayed in figs. 1, 2). As the energy is lower, the theoretical curve overestimates the experimental data by 30–50%, which is because, for projectile velocities of the order of the Bohr one, the collisional process ceases to be sudden and the exponential approximation (2) is inadequate. This is not the case the SSB approximation has been developed for. Proton–helium excitation cross sections are quite successfully estimated by means of the Glauber method, coupled states calculations, distorted wave approximation, etc. In the case of collision involving multicharged ions a correct account of the strong interaction between the target atom and the moving force centre requires additional efforts. In the SSB approximation even for a strong interaction rate ($\eta \sim 1$) does the "suddenness" condition (6) allow us to describe close collisions ($b \lesssim a$), while the combined probability gives a correct curve in the whole impact parameter range.

The calculated cross sections for collisions A^{q+} + He (1 ^{1}S→3 ^{1}P) are compared with the experimental data of ref. [17] in table 1. We only pres-

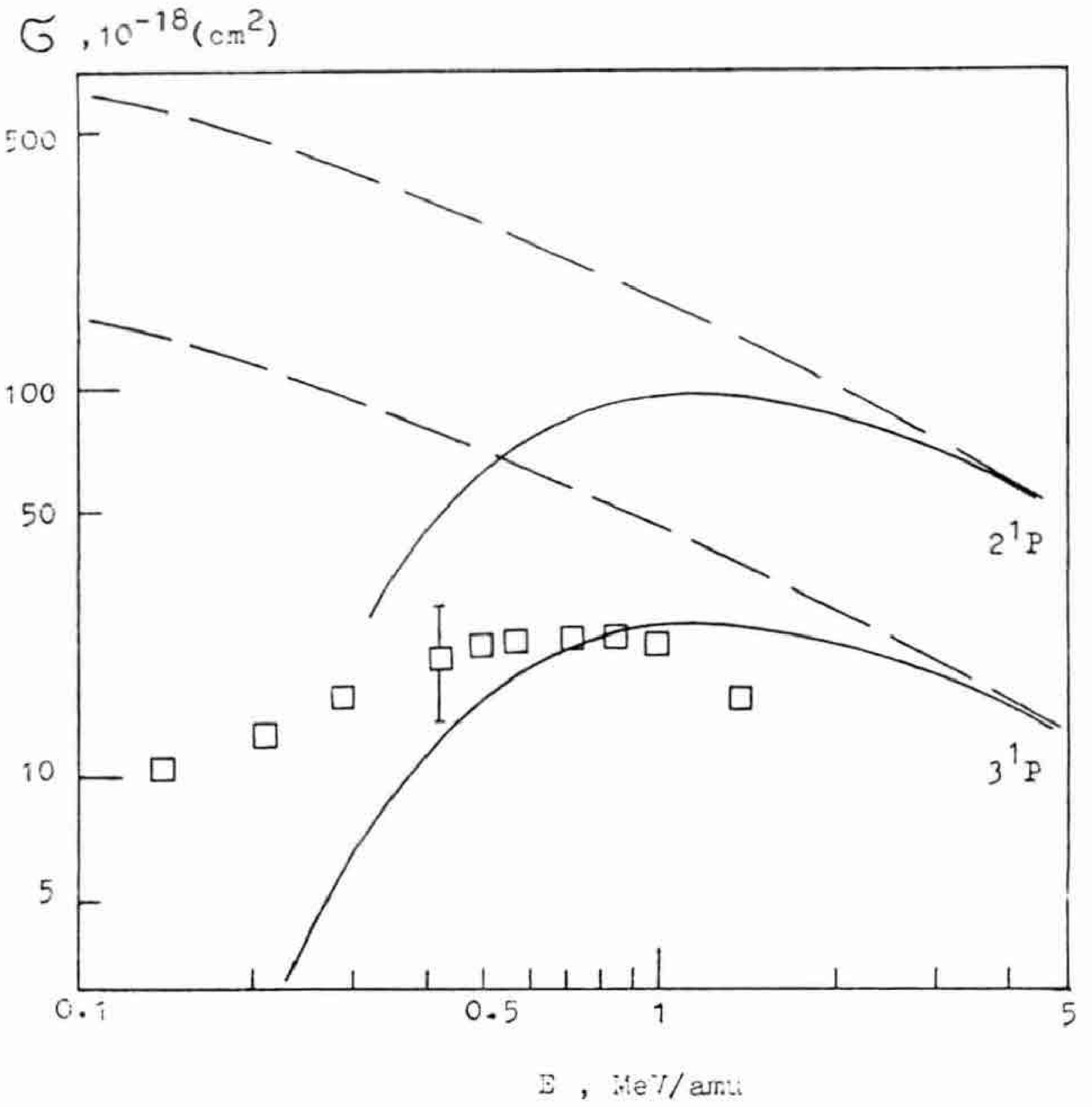

Fig. 3. Excitation cross sections of helium 1 ^{1}S–2 ^{1}P, 3 ^{1}P by impact of bare carbon nuclei, theory: (——) SSB, (- - -) SCA. The experimental points for Si^{6+} impact are from ref. [17].

ent the results for which $\eta < 2$. It is seen that for $\eta < 1.5$ the theoretical values lie within the experimental error bars ($\pm 50\%$). For $\eta > 1.5$ the SSB cross sections give rise to values of the same order as the experimental ones but which tend to exceed the data for $E > 500$ keV/amu and to underestimate them for $E < 500$ keV/amu. One also sees from table 1 that the SCA cross sections drastically overestimate the data for every collisional parameter pair (Z_p, v_p).

The calculated cross sections for helium excitation 1 ^{1}S→2 ^{1}P, 3 ^{1}P by impact of bare carbon nuclei as well as the corresponding data from ref. [17] are shown in fig. 3. It is noted that though the theory and the experiment give nearly equal magnitudes of the cross section maximum for the 1 ^{1}S→3 ^{1}P transition, $\sigma_{max} \sim 0.9 a_0^2$, the position of the experimental maximum is shifted to lower energy. A lack of experimental data at energies higher than 1.4 MeV/amu does not allow us to test the Born limit.

In summary, the total cross sections for excitation of atomic helium to the 2 ^{1}P, 3 ^{1}P levels by protons and multicharged ions have been calculated in the SSB approximation. For $Z_p/v_p < 1.5$ theoretical results show in most cases a good agreement with the data [17]. This limitation conforms to the basis applicability conditions which were laid in the theory at its development.

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