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Double-electron capture from helium by ions of helium, lithium, carbon, and oxygen

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Cross sections for double-electron capture from helium atoms by fully stripped ions of lithium, carbon, and oxygen are calculated in the framework of the continuum distorted-wave (CDW) and continuum intermediate-state (CIS) approximations in the energy range of 0.125—2.5 MeV/amu. Cross sections are also calculated for α particles as the projectile in the CIS approximation. The results are compared with existing experimental findings. The present calculated results for symmetric and near-symmetric cases show good agreement with the experimental findings. The discrepancies between the calculated and observed values for the asymmetric cases are discussed.

In case of heavy-ion—atom collisions the production mechanism of the structures formed by the x-ray satellite lines of the projectiles become much more complicated due to the occurrence of multiple-electron transfer. This may be one of the reasons that multiple-electron capture by partially or fully stripped heavy ions from neutral atoms have a high degree of intrinsic interest both experimentally as well as theoretically. Again, with the advent of multiply charged ion sources, theoretical interest has been focused on the investigation of multicharged ion-atom collisions. In addition, these processes have wide applications in astrophysics, cosmic-ray studies, and also in the design of heavy-ion accelerators. These data are also needed for the diagnostics of fusion plasma. In the last few years a good number of experimental works[1–6] have been carried out to determine single- and double-electron-capture processes by fully stripped heavy ions from inert gases. Sasao *et al.*[7] have measured both single and double charge-transfer cross sections for $He^{2+}+Li$ collisions at high energy. Most of the theoretical calculations for such processes are centered around the determination of single-capture cross sections. Only very recently have attempts[8–10] been made to calculate double-electron-capture cross sections.

The object of the present report is to calculate, in the high-energy region, double-electron-capture cross sections for the following processes:

$$X^{Z+}+\mathrm{He}\rightarrow X^{(Z-2)+}({}^1S)+\mathrm{He}^{2+} ,$$

where X^{Z+} indicates He^{2+}, Li^{3+}, C^{6+}, and O^{8+}.

Experimental determination of double-electron-capture cross sections in collisions of highly charged ions with neutral atoms includes the following possibilities: (i) capture of both electrons into the ground state, and (ii) capture into excited states which are radiatively stabilized with the consequence of some percentage of fluorescence yield. Capture into those excited states escape detection, which leads to autoionization. Due to the limitations of the theoretical model, we have considered only the double-electron capture into the ground state in the framework of the independent-particle model. Since accounting for correlations between electrons[8,9] is very important in describing the double-electron-capture process, we have considered the Hartree-Fock orbital[11] for each individual electron both in the initial and the final ground state. As the intermediate continuum states are supposed to play quite an important role in the description of charge-transfer events, we propose to study the cross sections in the framework of both continuum distorted-wave (CDW) and continuum intermediate-state (CIS) approximations. The theoretical method and the numerical procedure we follow here have already been discussed in connection with our earlier investigation.[9]

Calculations of the double-electron-capture cross sections from He by He^{2+}, Li^{3+}, C^{6+}, and O^{8+} ions have been performed in the energy regions 0.5—2 MeV, 1.12—2.8 MeV, 12—25 MeV, and 32—42 MeV, respectively. The choices of the lower limits of the projectile energies have been made using the validity condition[12] for single-electron capture. The continuum intermediate-state

TABLE I. Double-electron-capture cross sections in $He^{2+}+He\rightarrow He+He^{2+}$ collisions.

Projectile energy (keV)	Double-electron-capture cross sections (10^{-16} cm^2) CDWA	CISA	Experimental results (10^{-16} cm^2)
500	1.3×10^{-1}	2.28×10^{-1}	5.1×10^{-2}
750	1.1×10^{-1}	2.36×10^{-2}	9.5×10^{-3}
1000	1.7×10^{-3}	4.07×10^{-3}	2.6×10^{-3}
1400	1.7×10^{-4}	4.42×10^{-4}	3.6×10^{-4}
2000		3.49×10^{-5}	

TABLE II. Double-electron-capture cross sections in $Li^{3+}+He \rightarrow Li^{+}+He^{2+}$ collisions.

Projectile energy (keV)	Double-electron-capture cross sections (10^{-16} cm^{-2}) CDWA	CISA	Experimental results (10^{-16} cm^{2})
1120	8.37×10^{-2}	1.17×10^{-1}	$(5.04\pm0.16)\times10^{-2}$
1400	2.97×10^{-2}	4.04×10^{-2}	$(2.31\pm0.15)\times10^{-2}$
1750	9.54×10^{-3}	1.34×10^{-2}	$(8.9\pm0.8)\times10^{-3}$
2191	2.75×10^{-3}	4.12×10^{-3}	$(3.1\pm0.6)\times10^{-3}$
2800	6.35×10^{-4}	1.05×10^{-3}	

(CIS) approximation has been used for all systems but the continuum distorted-wave (CDW) approximation has only been used for the collisions of Li^{3+}, C^{6+}, and O^{8+} ions with helium since the cross sections for $He^{2+}+He$ collisions in the CDW approximation have already been calculated by Gayet *et al.*[8] The data on double-electron-capture cross sections, for $He^{2+}+He$, $Li^{3+}+He$, $C^{6+}+He$, and $O^{8+}+He$ collisions in both CDW and CIS approximations, is presented in Tables I, II, III, and IV, respectively. In Figs. 1 and 2 we have plotted double-electron-capture cross sections versus projectile energies.

From Fig. 1 it appears that the curve for the double-electron-capture cross sections in He^{2+}-He collisions obtained by Gayet *et al.*[8] in the CDW approximation shows a trend similar in nature with that of the CIS curve obtained by the present calculation. However, in the low-energy region the cross-section values obtained with the CDW approximation are found to give somewhat better agreement with the observed results by McDaniel *et al.*[3] as compared to the values obtained by the CIS approximation. From Table II and Fig. 2 it is seen that the results obtained in the CIS approximation overestimate the present calculated results in the CDW approximation over the entire energy region. However, CDW results agree very well with experimental results of Shah and Gilbody[6] for near-symmetric collisions of the Li^{3+} ion with helium. From Table IV it is seen that our calculated results at 32 MeV for double-electron capture in collisions of the O^{8+} ion with helium are less than 2 orders of magnitude in comparison with the experimental results of Hippler *et al.*[5] This may be due to the fact that we have calculated double-electron-capture cross sections into ground state only. For highly asymmetric collisions, double-electron capture into excited levels may be a dominant contribution since the binding energies both in the initial and final states of the captured electrons play a significant role in the determination of the cross sections.[2] In the case of heavy-ion—atom collisions, Andriamonje *et al.*[13] have shown that the single-electron capture from a particular shell of a many-electron atom to a particular level of the projectile is determined by the momentum distribution in the initial and the final state. Since in the present theoretical model, the double-electron-capture probability has been expressed in terms of a single-electron-capture probability, we have applied the procedure of Andriamonje *et al.*[13] with suitable modifications to have a qualitative idea about the contribution of transition into excited levels in case of double-electron capture. We have verified numerically that for the case of double-electron capture in $He^{2+}+He$ and $Li^{3+}+He$ collisions, the transition to the ground state of the projectile ion is the dominant contribution. However, in the case of $C^{6+}+He$ and $O^{8+}+He$ collisions, transitions to excited states may be significant contributions. Due to limitations in the existing theoretical model, the double-electron capture into excited states cannot be properly calculated. This may explain the discrepancy between our calculated results and the experimental results for the $O^{8+}+He$ collision. However, MacDonald and Martin[1] have suggested the possibility of electron capture into the K shell of the bare oxygen ion. Another interesting feature of our calculated results is that the discrepancy between the results obtained in the CDW and CIS approximations reduces as the asymmetry between the collision partners increases. To have a systematic observation of this effect, we have calculated the double-electron-capture cross sections for $C^{6+}+He$ collision and the results are listed in Table III. Unfortunately, no comparison could be made due to the nonavailability of any theoretical or experimental results for this reaction.

TABLE III. Double-electron-capture cross sections in $C^{6+}+He \rightarrow C^{4+}+He^{2+}$ collisions.

Projectile energy (keV)	Double-electron-capture cross sections (10^{-16} cm^{2}) CDWA	CISA
12 000	1.07×10^{-5}	1.15×10^{-5}
15 000	3.39×10^{-6}	3.40×10^{-6}
18 000	1.18×10^{-6}	1.23×10^{-6}
21 000	4.53×10^{-7}	5.06×10^{-7}
25 000	1.42×10^{-7}	1.78×10^{-7}

TABLE IV. Double-electron-capture cross sections in $O^{8+}+He \rightarrow O^{6+}+He^{2+}$ collisions.

Projectile energy (keV)	Double-electron-capture cross sections (10^{-16} cm^{2}) CDWA	CISA
30 000	3.48×10^{-7}	3.66×10^{-7}
32 000	2.53×10^{-7}	2.55×10^{-7}
35 000	1.58×10^{-7}	1.54×10^{-7}
38 000	1.01×10^{-7}	9.63×10^{-8}
42 000	5.63×10^{-8}	5.44×10^{-8}

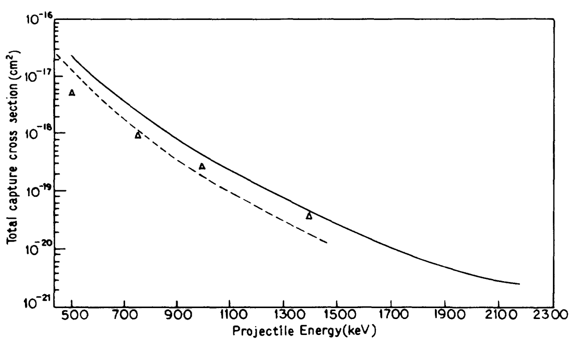

FIG. 1. Double-electron-capture cross section ($Q^{(K)}$) for the projectile He^{2+} incident on a helium atom. Theory: ——, present results in CIS approximation; — — —, CDWA results of Gayet *et al.* (Ref. 8). Experiment: △, McDaniel *et al.* (Ref. 2).

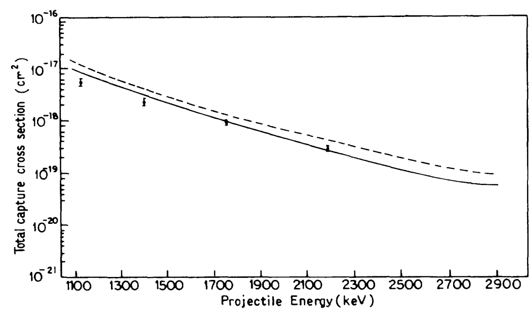

FIG. 2. Double-electron-capture cross section ($Q^{(K)}$) for the projectile Li^{3+} incident on a He atom. Theory: ——, present results in CDW approximation; — — —, present results in CIS approximation. Experiment: ⫯, Shah and Gilbody (Ref. 6).

In the case of collisions of heavy ions with heavy atoms, the present model of calculation for double-electron capture may be reliable when the transition of both the electrons into the ground state is dominant. So, for collisions of heavy ions with helium atoms, this model of calculation is reliable for symmetric or near-symmetric cases. However, for highly asymmetric collisions, it suffers from serious limitations. Under the present situation, the experimental investigations for such collision processes should be extensively carried out and further attempts should be made for the refinement of the existing theoretical models for the study of such highly complicated problems of multiple-electron-capture processes.

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