Heavy-Ion Excitation of Autoionization States in Helium*

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The autoionization spectrum of He produced by 3.0-MeV Cl^{2+} ions is compared with results from other heavy-ion collisions to indicate the relative importance of collision velocity and projectile nuclear charge on the double excitation mechanism.

In a recent Letter[1] we reported the excitation of autoionization states in He by 30-MeV oxygen ions. The spectra were unique relative to previously used means of excitation in that the $(2pnp)^1D$ series was strongly excited, and no triplet excitation was observed. The spectra were independent of the incident oxygen-ion charge state. It was argued that these features and the relative intensities observed were a result of the high nuclear charge of the projectile together with the high velocity of the projectile relative to the average velocity of the He electrons [$V_{\rm rel}$ = (projectile velocity)/(He electron velocity)].

Here we report the same He autoionization spectrum produced by 3-MeV Cl^{2+} ions—in this collision $V_{\rm rel}$ is much lower and the incident nuclear charge much higher. The resulting spectrum is quite different; this difference and a comparison with other heavy-ion–excited spectra give some insight into the relative importance of the nuclear and atomic charges versus the relative velocity in a general description of the excitation mechanism. The spectrum is shown in Fig. 1 in comparison with the results of Ref. 1. The widths of the individual lines are broader in this collision because of the larger energy transfer and subsequently larger kinematic (Doppler) broadening.

For the Cl^{2+} collision ($V_{\rm rel}=1.4$), the ^3P series is strongly excited, in contrast to the O^{5+} collision ($V_{\rm rel}=6.4$) where no triplet excitation was observed. The relative amount of triplet to singlet excitation is a measure of the importance of electron-exhange excitation. Thus the amount of electron exchange decreases with increasing velocity—a result which might be expected from rather general arguments.

Less obvious, however, is the dependence of electron exchange upon the projectile nuclear charge. The relative intensities of all the lines

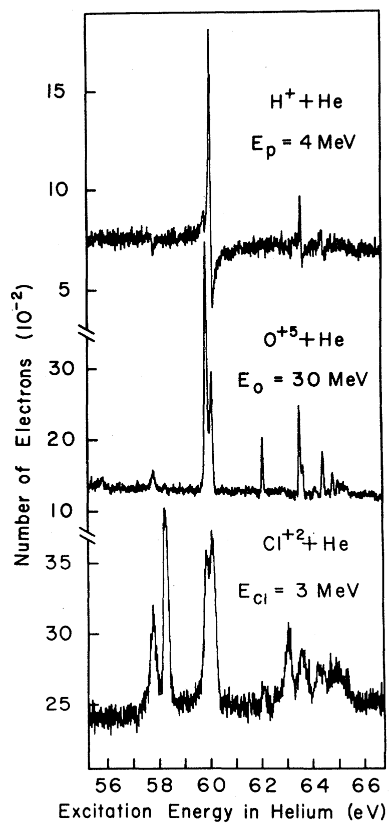

FIG. 1. Electron emission spectra at 90° from hydrogen-, oxygen-, and chlorine-ion collisions with helium. The experimental apparatus is the same as in Ref. 1. The indicated excitation energy scale corresponds to the ejected electron energy plus the first ionization energy of helium (24.59 eV). The lines referred to in the text are identified from the compilation of W. C. Martin, J. Phys. Chem. Ref. Data 2, 257 (1973) (energies in eV): $(2s^2)^1S$, 57.87; $(2s2p)^3P$, 58.31; $(2p^2)^1D$, 59.88; $(2s2p)^1P$, 60.13; $(2p^2)^1S$, 62.14; and $(2s3p)^3P$, 63.10.

in the Cl^{2+} spectrum are nearly identical to the 75-keV H_2^+ + He ($V_{rel}=0.92$) spectra measured by Rudd.[2] In this comparison V_{rel} is comparable, but the projectile nuclear charges are vastly different. Using the amount of triplet excitation as a measure of electron exchange, we might conclude that this means of excitation is independent of the projectile nuclear charge and depends primarily upon the projectile velocity—provided, of course, that there is at least one weakly bound electron present.

In comparison of the O^{5+} and Cl^{2+} excitation, the intensity ratio $(2p^2)^1S/(2s^2)^1S$ is reversed. Thus the argument presented in Ref. 1 for an independent two-step Coulomb excitation of the He electrons does not appear to hold for the slow Cl^{2+} collision. It was supposed in Ref. 1 that this second-order process was dominant primarily because of the high nuclear charge of the oxygen ion, i.e. that the collision velocity was not the important factor. The present result for the Cl collision does not rule out the previous interpretation of the high-energy collision, but it does point out that the direct excitation mechanisms present are definitely velocity dependent and are not determined by the magnitude of the nuclear charge alone.

Also in the Cl^{2+}-O^{5+} comparison of Fig. 1, the relative intensities of the $(2s2p)^1P$ and $(2p^2)^1D$ states are quite different. It is difficult to infer a nuclear charge dependence of this ratio since it is the same in the Cl^{2+} excitation as it is in the precited H_2^+ collision. For low-energy proton collisions, Rudd[3] has shown that the relative excitation of these two states reverses in going from 65- to 200-keV proton energies; at the same V_{rel} the proton and the Cl^{2+} collisions yield the same relative intensities for these two states.

To our knowledge there is no available theoretical work generally applicable to double excitation in heavy-ion collisions. At very low velocities, $V_{rel}\lesssim 0.5$, a molecular promotion model provides a qualitative description of the interaction in some collisions. Gerber, Morgenstern, and Niehaus[4] have investigated this region for He^+ + He at $V_{rel} \leq 0.24$ (0.5 to 10 keV). Cross sections for the excitation of the $^1D+{}^1P$ states have been measured by Benoit-Cattin *et al.*[5] for He^+ + He at 5 to 70 keV. Except for the collision systems mentioned here[6] there appears to be no other work on heavy-ion excitation of autoionization states in He.

Very fast heavy-ion collisions with He should provide an interesting test area for theoretical work on both single and double excitation. The high velocities might indicate the applicability of the Born approximation, but the high ratio of nuclear charges may quickly invalidate a perturbation approach. Recent developments in heavy-ion sources for tandem Van de Graaff accelerators can now yield an essentially continuous variation of projectiles at a fixed high velocity. Theoretical developments obtained from the analysis of a relatively simple system, like a bare heavy nucleus plus He, may be applicable to the vast amount of atomic collision data now being acquired for very complicated collisions of heavy atoms in the MeV energy range.[7]

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[1]D. Burch, J. Bolger, and C. F. Moore, Phys. Rev. Lett. 34, 1067 (1975).

[2]M. E. Rudd, Phys. Rev. Lett. 13, 503 (1964); M. E. Rudd and D. V. Lang, *in Proceedings of the Fourth International Conference on the Physics of Electronic and Atomic Collisions. Abstracts* (Science Bookcrafters, Inc., Hastings-on-Hudson, N. Y., 1965), p. 153.

[3]M. E. Rudd, private communication of unpublished work.

[4]G. Gerber, R. Morgenstern, and A. Niehaus, J. Phys. B 6, 493 (1973).

[5]P. Benoit-Cattin, A. Bordenave-Montesquieu, A. Gleizes, and H. Merchez, in *Proceedings of the Ninth International Conference on the Physics of Electronic and Atomic Collisions. Abstracts* (Univ. of Washington Press, Seattle, Wash., 1975), p. 861.

[6]For a more detailed list of references, see Ref. 1.

[7]See the several review papers from the Symposium on Inner-Shell Ionization contained in *Proceedings of the Ninth International Conference on the Physics of Electronic and Atomic Collisions. Invited Lectures and Progress Reports* (Univ. of Washington Press, Seattle, Wash., to be published).