Excitation of Ne, Ar, and Kr Induced by H^+ and He^+ Impact (5–35 keV)*

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Impact radiation from H^+ and He^+ in noble gases is studied in the wavelength region below 1250 Å. A vacuum spectrograph has been built and absolutely calibrated for this purpose, so that the measurements provided absolute excitation or emission cross sections. We observe strong maxima in the light intensities of some atom and ion lines of noble gases. These maxima appear at remarkably low energies of the impinging particles, and moreover, correspond with large absolute cross sections ($\sim 10^{-17}$ cm^2/atom). For instance, the excitation of the $np^6\,{}^2S_{1/2}$ states of Ar II ($n=3$) and Kr II ($n=4$) induced by the He^+ impact on Ar and Kr show maxima at 9 and 7 KeV, respectively. This can be predicted by the adiabatic criterion of Massey. However, for the $(n+1)s'\,{}^2D_{5/2}$ states of Ar II ($n=3$) and Kr II ($n=4$) the maxima lie below 5 keV, though more energy is needed for the excitation of these states than there is for the ${}^2S_{1/2}$ ones. Also for the excitation of the $2p^5\,3s$ state of Ne I induced by He^+ impact on Ne, the maximum lies below 5 keV. There are indications that intermediate molecular states occur which contribute to the formation of these low-energy maxima.

UNTIL now, only a few determinations have been made of absolute emission cross sections for atomic and ionic noble gas spectra induced by bombardment with fast ions. They were limited to transitions giving rise to the emission of photons in the wavelength region of 2000 to 7000 Å. The study of the lower lying radiating states of atoms and ions is much more important, however, as only then theoretical approaches are available. Transitions to the ground state mostly lead to the emission of photons with a wavelength below 1250 Å. We have succeeded in building and calibrating equipment for this purpose, and we want to report here on the first remarkable results. We observe strong maxima in the light intensities of some atom and ion lines of noble gases, induced by bombardment with fast H^+ or He^+ particles. These maxima appear at remarkably low energies of the impinging particles, and moreover correspond with very large absolute cross sections ($\sim 10^{-17}$ cm^2/atom). There are indications that intermediate molecular states occur like those observed in mass spectrometrical research by Pahl and Kaul.[1]

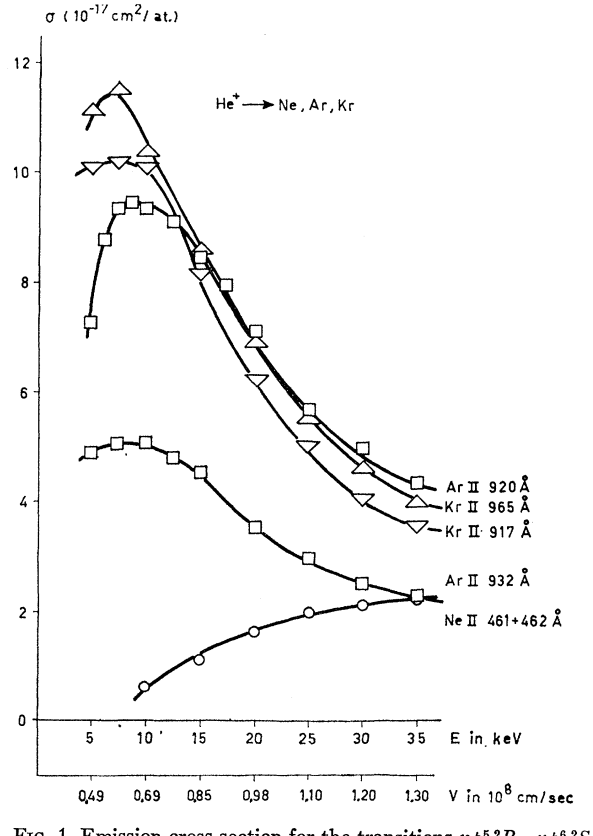

FIG. 1. Emission cross section for the transitions $np^5\,{}^2P-np^6\,{}^2S$ in the ion spectra of Ne, Ar, and Kr excited by He^+ ions as a function of energy.

The processes considered in this paper are:

(a) simultaneous ionization and excitation of the target atom, either direct or by charge exchange:

$$A^+ + B \rightarrow A^+ + B^{+*} + e + \Delta E;$$
$$A^+ + B \rightarrow A + B^{+*} + \Delta E;$$

(b) excitation of the target atom

$$A^+ + B \rightarrow A^+ + B^* + \Delta E.$$

ΔE is the change of internal energy.

The experimental procedure in the wavelength region of 2000 to 6000 Å has already been described in a recent article by the authors.[2] A grazing incidence vacuum monochromator is used to analyze the light emitted in the spectral range of 200–1250 Å. The monochromator is provided with an EMI particle multiplier for the detection of the ultraviolet radiation.

In order to determine absolute cross sections, the quantum yield of the vacuum monochromator defined as the current registrated per incident photon per second, was determined at 537 Å. The method was

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[1] M. Pahl and U. Weimer, Z. Naturforsch. **12a**, 926 (1957); W. Kaul and R. Taubert, *ibid.* **17a**, 88 (1962).
[2] J. van Eck, F. J. de Heer, and J. Kistemaker, Physica **28**, 1184 (1962).

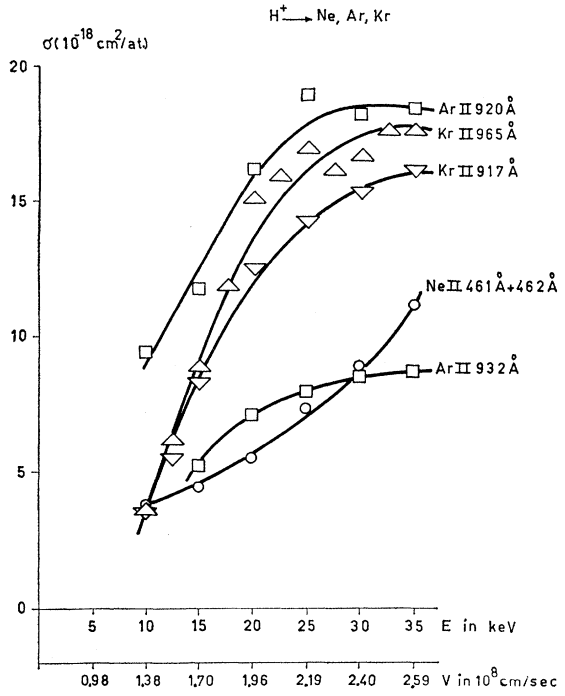

FIG. 2. Emission cross section for the transitions $np^5\,{}^2P-np^6\,{}^2S$ in the ion spectra of Ne, Ar, and Kr excited by protons as a function of energy.

based on the observation of the intensities of two spectral lines of helium involving the transition from a common upper level ($3\,{}^1P$) to the $2\,{}^1S$, respectively, $1\,{}^1S$ state, the former of which lies in the visible region ($\lambda=5016$ Å), whereas the latter one lies in the far ultraviolet ($\lambda=537$ Å). The intensity of the visible line was measured by means of another monochromator (2000–6000 Å), which was absolutely calibrated by means of a tungsten band-lamp. By comparison of the measured signals at 537 and 5016 Å, combined with theoretical knowledge about the transition probabilities corresponding to these lines, the quantum yield of the vacuum monochromator at 537 Å could be calculated.

The two spectral lines were induced by a beam of fast helium ions (30 keV) passing through the collision chamber filled with neon or hydrogen gas. The ion can capture an electron from the target atom or molecule into the He I $3\,{}^1P$ state. Decay of this state gives rise to the emission of the considered radiation. By the choice of neon and hydrogen as target gases, absorption of the He I radiation from the beam particles was avoided and the He I lines could be easily distinguished from the emitted lines of the target atoms. In this way we determined the quantum yield of our vacuum monochromator to be 3.8×10^{-16} A sec/quant, at 537 Å (possible error about 40%). The quantum efficiency at other wavelengths was obtained by a comparison of the open particle multiplier and a photomultiplier covered with a fluorescent screen of sodium salicylate. It has been shown[3] that the sodium salicylate has a constant quantum yield down to about 584 Å. The reflectivity of the grating and the astigmatism of the monochromator depended on the wavelength and were taken into account.

TABLE I. Summary of the considered emission lines of the ion spectra.

Ground state:	Excited state:	Ne II ($n=2$) (Å)	Ar II ($n=3$) (Å)	Kr II ($n=4$) (Å)
$np^5\,{}^2P_{3/2}{}^0$	$np^6\,{}^2S_{1/2}$	461	920	917
$np^5\,{}^2P_{1/2}{}^0$	$np^6\,{}^2S_{1/2}$	462	932	965
$np^5\,{}^2P_{3/2}{}^0$	$(n+1)s'\,{}^2D_{5/2}$	406	672	782
$np^5\,{}^2P_{1/2}{}^0$	$(n+1)s'\,{}^2D_{3/2}$	407	679	
$np^5\,{}^2P_{3/2}{}^0$	$(n+1)s'\,{}^2D_{3/2}$		673	783

Additional measurements are planned in order to consider the effect of polarization of the radiation.

Table I summaries the considered emission lines of the ion spectra.

The emission cross sections of the $^2S-{}^2P$ transitions in Ne, Ar, and Kr target atoms induced by fast helium ions or fast protons, are shown in Figs. 1 and 2.

The behavior of these curves is in agreement with the adiabatic criterion of Massey,[4] if it is assumed that the maxima in the cross sections arise from the charge exchange process already mentioned. For ^2D-^2P transi-

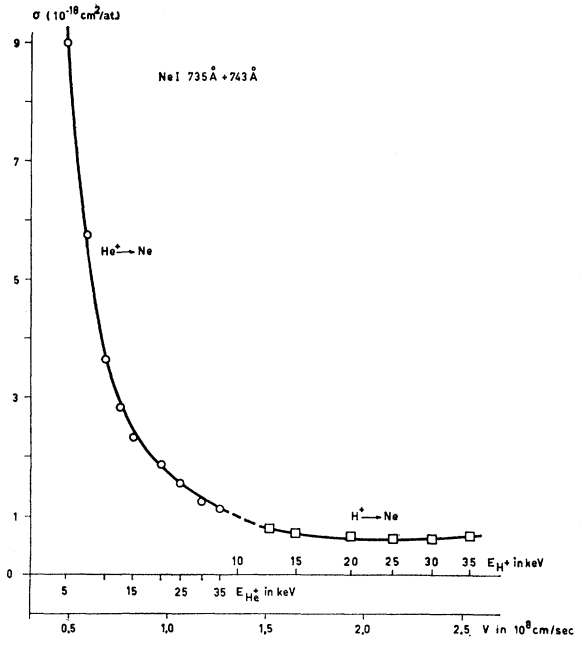

FIG. 3. Emission cross section for the transitions $2p^6\,{}^1S-3s$ in the atom spectrum of neon excited by protons and He^+ ions, and plotted as a function of energy and velocity.

[3] K. Watanabe and Edward C. Y. Inn, J. Opt. Soc. Am. **43**, 32 (1953).

[4] H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Clarendon Press, Oxford, England, 1952), 513/37.

tions the curves (not shown here) are slightly different; the most striking feature is that in the combinations He^+, Ar and He^+, Kr the emission cross sections are still rising with decreasing energy at 5 keV, and will reach maxima below this energy. However, in case of ^2D excitation the change of internal energy ΔE is larger than with ^2S excitation, so that the emission maxima of the $^2D-^2P$ transitions should be expected at higher energies, in contradiction to our results.

The results for H^+ and He^+ shot into neon gas are given in Fig. 3, for the excitation of the Ne I $2p^6\,{}^1S$ level giving rise to the emission of the Ne I lines $2p^6\,{}^1S-3s[1\frac{1}{2}]^0$ and $2p^6\,{}^1S-3s'[\frac{1}{2}]^0$, which could not be separated. Ar I and Kr I lines were observed only at high pressures (15–50 μ), partly because the sensitivity of the particle multiplier is lower in this spectral region (1000–1250 Å). The cross section for the He^+, Ne combination rises very sharply at lower energy. However, the adiabatic criterion predicts a maximum around 60 keV.

A theory explaining the rise in the emission cross sections at very low energy cannot be given at present. An approach towards the problem is under study, in which we assume that for low velocities the colliding particles may form intermediate molecular states. Such intermediate states may show lower changes of internal energy than the atomic states giving rise to maxima in the emission cross sections at correspondingly lower energies.[5]

[5] See also E. S. Solov'ev, R. N. Ill'in, V. A. Oparin, and N. V. Fedorenko, Soviet Phys.—JETP **15**, 459 (1962).

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Model for the Scattering of Slow Electrons by Cesium Atoms*

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The computation of the total cross section for the elastic scattering of slow electrons from cesium atoms was investigated. The model adopted consisted of a combination of the Biermann and Harting polarization potential with the Hartree potential of a cesium atom. The cross section was computed by the phase shift method. Using the reported values of the polarizability of cesium and a value of 6.13 a_0 for the cutoff parameter, fr_0, in the polarization potential, it was found that this model yields values of the cross section in agreement with current experimental results. A method is proposed for the choice of the cutoff parameter.

I. INTRODUCTION

EXACT calculations of electron scattering by alkali atoms are not possible at present because of the computational difficulties involved. Calculations using the Hartree or Hartree-Fock atomic potential functions give unsatisfactory results at low incident energies because of large contributions to the interaction potential due to the polarization of the target atom. Some method for calculating scattering cross sections for the alkali atoms is desirable which includes this polarization effect. Robinson[1] has recently given results of calculations made for electron-cesium atom cross sections where the potential function used was constructed from one-electron Slater type wave functions plus a polarization term of the form:

$$V_p(x)=-\frac{\epsilon^2}{2a_0}\frac{\alpha}{(x_p^2+x^2)^2}. \quad (1)$$

Here α is the polarizability, ϵ the energy, and x_p the "screening constant." His results are not completely in accord with the experimental data.

We attempt to build a model of the alkali atom which includes the rather large polarization contribution to the interaction potential in such a way that calculated cross sections can be made to fit experimental data in a satisfactory manner. In the present calculations the Hartree potential for the neutral cesium atom was obtained. To this was added a polarization term of the Biermann-Harting[2] type which has been used previously in calculations of excited state wave functions of alkali atoms.[3,4] It might be argued that such a representation of the potential function is not well founded, especially if the velocity of the incident particle is comparable with the orbital velocities of the bound electrons. Here we consider incident velocities much less than those of the orbital electrons.

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† National Science Foundation Cooperative Graduate Fellow.
[1] L. B. Robinson, Phys. Rev. **127**, 2076 (1962).
[2] L. Biermann and H. Harting, Z. Astrophys. **22**, 87 (1942).
[3] H. J. Brudner and S. Borowitz, Phys. Rev. **120**, 2053 (1960).
[4] D. S. Villars, J. Opt. Soc. Am. **42**, 552 (1952).