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If instead the moving atom decays by autoionization, the ejected electron should also show a shift in energy analogous to the Doppler shift. We have now observed this effect in the autoionization electron spectrum from $Ar^+$-Ar collisions at 50 to 150 keV. Viewing the electrons ejected in a nearly backward direction (160°) relative to the beam of ions, we have found a number of characteristic peaks which shift with beam energy and a number of others which do not. Furthermore, there is a detailed correspondence between the shifted and unshifted sets. The latter sets come from the (nearly) stationary target atoms, while the shifted electrons are from the fast beam particles.

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## OBSERVATION OF DOPPLER-SHIFTED PEAKS IN THE ENERGY SPECTRUM OF AUTOIONIZATION ELECTRONS FROM $Ar^+$-Ar COLLISIONS*


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If instead the moving atom decays by autoionization, the ejected electron should also show a shift in energy analogous to the Doppler shift. We have now observed this effect in the autoionization electron spectrum from $Ar^+$-Ar collisions at 50 to 150 keV. Viewing the electrons ejected in a nearly backward direction (160°) relative to the beam of ions, we have found a number of characteristic peaks which shift with beam energy and a number of others which do not. Furthermore, there is a detailed correspondence between the shifted and unshifted sets. The latter sets come from the (nearly) stationary target atoms, while the shifted electrons are from the fast beam particles.

During the collision a temporary $Ar_2^+$ molecular ion is formed[2] and electrons are transferred back and forth between the nuclei.[3] By the time the two nuclei separate they have lost all "memory" of which was the projectile and which the target. Thus we have a completely symmetric situation and would expect to find the same spectrum from both participants in the collision.

Making the assumption that the beam particles are not appreciably deflected or slowed down in the collision, it is a very simple matter to calculate the expected shift in energy from a velocity vector triangle. If $E'$ is the shifted energy, $E$ the unshifted energy, and $E_2$ the beam energy, the relation is

$$E = E' - 2(E'E_2 m/M)^{1/2}\cos\theta + E_2 m/M,$$

where $m$ and $M$ are the masses of the electron and the emitting atom and ion, respectively, and $\theta$ is the angle of observation. In this work $M = 40\times 1836m$ and $\cos\theta = -0.940$. Using this equation we have calculated the expected shift in energy to compare with the measurements.

The actual deflection of the beam particles depends on the beam energy and on $r_0$, the distance of closest approach of the interacting particles. The deflection can, for this energy range, be calculated with good accuracy by classical methods using an exponentially screened Coulomb potential. This has been worked out by Everhart, Stone, and Carbone.[4] For 100 keV the deflection is less than 4° for a collision with $r_0 = 0.25$ Å. Therefore the correction due to the deflection is small and has been ignored here.

The apparatus is the same as that used previously[5] except for some modifications in the plotting system.[6] The energy scale was initially calibrated with an electron gun but because of space charge present when gas is admitted the scale is uniformly shifted by a few tenths of an electron volt. Therefore we have calibrated our scale by comparison with the 27.55-eV line measured by Simpson, Chamberlain, and Mielczarek.[7] Subtracting the ionization potential from this value yields 11.79 eV for the energy of the peak we have designated "*E*" in this work. If this identification is correct our energy scale should have an uncertainty of less than about 0.1 eV.

Figure 1 shows the energies of the unshifted peaks, most of which are averages taken from 20 to 25 runs. Also shown are the energies of the shifted peaks for three different beam energies as calculated from the equation above. These may be compared with the measured values plotted on the same diagram. All but one of the measured lines are within 0.1 eV of the calculated energies. At the lower electron energies, the large cross section for the background continuum tended to obscure the peaks. Sometimes overlapping of shifted and unshifted sets made identification and measurement difficult. For example, at 150 keV the shifted *H* line falls on the unshifted *A* line and at 50 keV the shifted *I* line is at the same energy as *C*. At 50 and 100 keV there is an additional shifted line between *D* and *E* which shows up only weakly in the unshifted spectrum.

Most of the transitions represented by the peaks have not yet been identified. It is reasonably clear that the line *E* is due to the transition $(3s3p^6 3d)\,^1D \rightarrow (3s^2 3p^5)\,^2P + 1e$. The line *C* is of the proper energy to originate at the $(3s3p^6 4s)\,^1S$ level identified by Simpson, Chamberlain, and Mielczarek.[7] The *F* line also agrees in energy with a level reported by them.

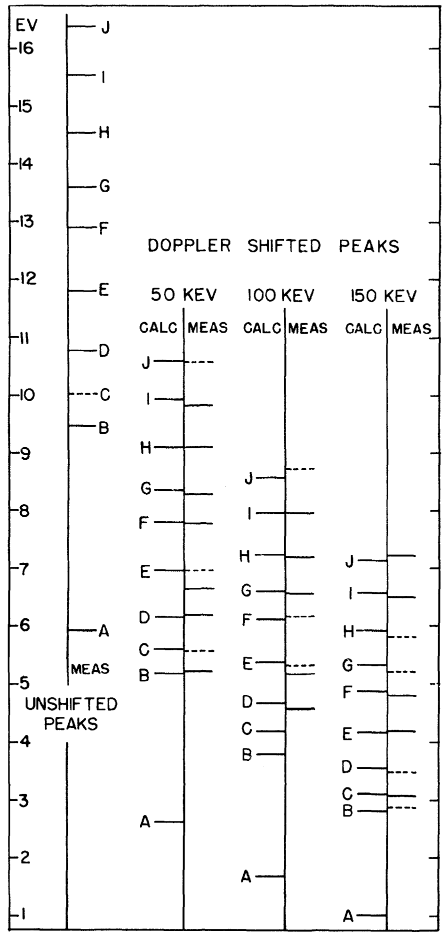


FIG. 1. Energy spectrum of electrons from argon gas bombarded by argon ions. Unshifted lines are ones which appear at the same energy regardless of beam energy. Doppler-shifted lines appear at different places for different beam energies. The calculated positions of the shifted lines are from the equation in the text. Dashed lines represent weak or uncertain lines.

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