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INELASTIC ENERGY-LOSS STRUCTURE IN NONVIOLENT HEAVY-ATOM COLLISIONS*

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Inelastic energy-loss measurements for small-angle scattering in $Ne^+ \to Ne$ and $Ar^+ \to Ar$ collisions are reported. The resulting energy-loss spectra display a structure which may be explained in terms of curve crossing and preionization.

Ions of energy 30-100 keV are scattered through very small angles ($\theta < 2°$) by one collision and then energy analyzed. By precise determination of the scattering angle θ (which is known within 15′) and the secondary energy (the energy resolution of the analyzer is better than 4×10^{-4}), the inelastic energy loss Q can be calculated as well as the distance of closest approach r_0 (using the Born-Mayer potential as given by Abrahamson[1]). The experiments on 30-keV $Ar^+ \to Ar$ and 30-keV $Ne^+ \to Ne$ revealed a structure in Q for distance of closest approach of $r_0 \sim 1$ Å. An example of the secondary energy spectrum in the $Ne^+ \to Ne$ case, which clearly shows the Q structure, is given in Fig. 1. The inelastic energy losses for 30 keV $Ar^+ \to Ar$ and $Ne^+ \to Ne$ are given in Fig. 2 for a range of distances of closest approach. The relative peak intensities in the latter case are given in Fig. 3.

At first glance these results resemble earlier studies of similar collision phenomena wherein the measured Q structure for violent heavy-particle collisions is reported.[2-5] These earlier results were explained by inner-shell electron promotion through curve crossing according to the model of Fano and Lichten.[6] However Lichten[7] remarks that an electron promotion by such a mechanism in the outer shell is questionable. Nevertheless it is possible to explain the inelastic energy-loss structure in the $Ar^+ \to Ar$ case by curve-crossing-induced promotion of a $3p$ electron to a $4p$ state. The peaks in the Ar^+ energy spectrum can be assigned to the following transitions:

Peak I: $Ar^+(3s^2, 3p^5) + Ar(3s^2, 3p^6) \to Ar^+(3s^2, 3p^5) + Ar(3s^2, 3p^6)$ with $Q = 0$ eV (elastic scattering).

Peak II: $Ar^+(3s^2, 3p^5) + Ar(3s^2, 3p^6) \to Ar^+(3s^2, 3p^5) + Ar(3s^2, 3p^5, 4p)$ with $Q = 13.1$ eV (excitation of the target particle).

Peak III: $Ar^+(3s^2, 3p^5) + Ar(3s^2, 3p^6) \to Ar^+(3s^2, 3p^4, 4p) + Ar(3s^2, 3p^5, 4p)$ with $Q = 35.9$ eV (excitation of projectile and target particle).

However, the results of $Ne^+ \to Ne$ cannot be fitted by the Fano-Lichten model. The energy dif-

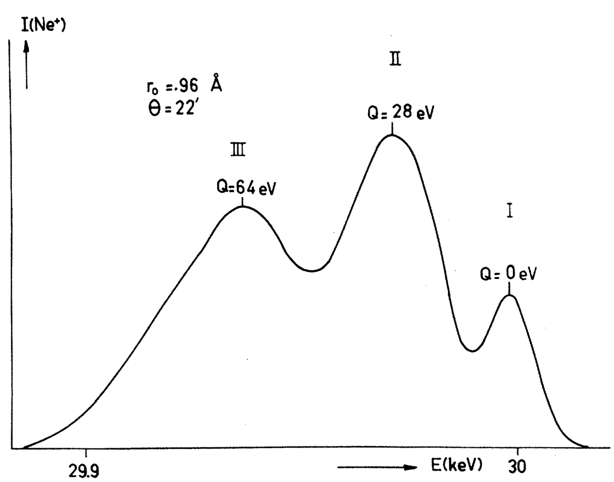

FIG. 1. Energy spectrum of scattered Ne⁺ ions, which shows the Q structure.

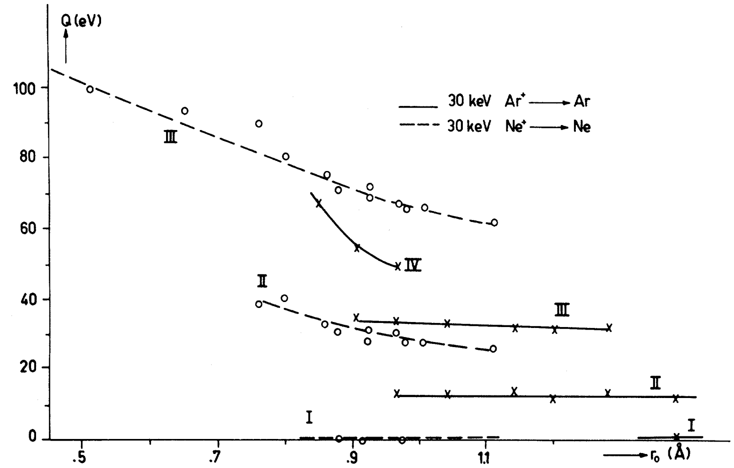

FIG. 2. Inelastic energy losses as a function of distance of closest approach.

ferences between the peaks I and II and between peaks II and III are larger than the first and second ionization potentials, respectively. This cannot be caused by a single $2p$ electron promotion per particle. Furthermore it is observed that, unlike the Ar case, the peaks II and III in the $Ne^+ \rightarrow Ne$ case shift towards higher inelastic energy losses with decreasing r_0. This is also in contradiction with a model where the inelastic loss is explained by an excitation to a more or less fixed discrete final state. Peak I is the elastic peak. To explain peaks II and III in the $Ne^+ \rightarrow Ne$ case we think that instead of considering the single-electron levels during the collision, one has to consider the total potential energy of the system of colliding particles. One of the $Ne_2{}^+$ molecule potential curves is thought to cross $(Ne_2{}^+)^{**}$ molecule curves at around 1 Å.

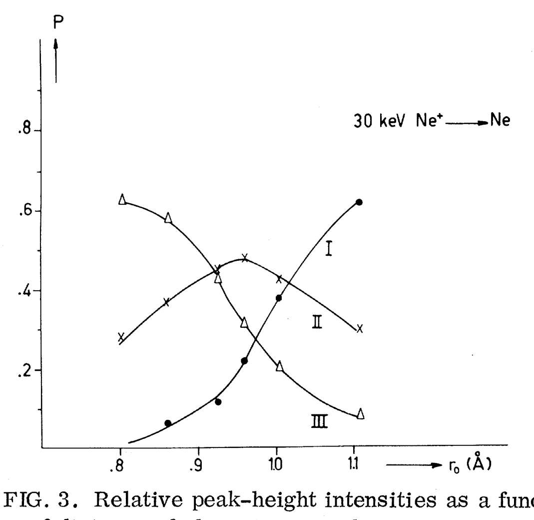

FIG. 3. Relative peak-height intensities as a function of distance of closest approach.

The $(Ne_2{}^+)^{**}$ states are pre- or auto-ionizing states. Peak II is attributed to an excitation by means of such a curve-crossing mechanism to a preionizing state followed by a de-excitation at ±1.5 Å, which results in two Ne^+ ions. The inelastic energy loss is thus larger than 21.6 eV. Peak III is thought to arise from processes where excitation to an autoionization state takes place that de-excites to one Ne^{2+} and one Ne^+ ion. The inelastic energy loss will there be larger than 63.6 eV as is observed.

It is not quite clear why single-electron promotion takes place in the $Ar^+ \rightarrow Ar$ case while a collective description in the $Ne^+ \rightarrow Ne$ seems to be necessary. The velocity is perhaps the clue to this problem. The single-electron energy levels are, due to the uncertainty principle, broadened by the velocity of the collision. For 30-keV $Ne^+ \rightarrow Ne$ this effect is larger than for 30-keV $Ar^+ \rightarrow Ar$. It is noteworthy that in a very recent paper of Barat et al.[8] a difference is also noted between the Ne^+-Ne pair and the Ar^+-Ar pair in regard to the lowest state that is excited. In that paper, the inelastic energy losses are always attributed to excitation of one of the collision partners, which is in disagreement with our interpretation.

Finally, it must be noted that at internuclear distances of ~1 Å the inelastic energy loss can be of the order of the potential energy. Therefore it is doubtful whether one should calculate r_0 without taking into account this inelastic loss.

This work is part of a series of inelastic energy-loss measurements involving several primary ion species, the purpose of which is to test the modified Firsov theory in range calculations of ion penetration in solids.[9]

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DETECTION OF X-RAY TRANSITION RADIATION BY MEANS OF A SPARK CHAMBER*†

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A new method for x-ray transition radiation detection by a streamer spark chamber is suggested. The use of the chamber secures a separate observation of both the radiation and the particle. It is shown that the mean number of the transition quanta linearly increases in the electron energy range 1.2 to 2.46 GeV. When plastic foam was used instead of a layered medium the efficiency of electron detection by transition radiation was 86 %.

The advancement of superhigh-energy physics has called for new methods of measuring particle energies. The Cherenkov radiation commonly used makes it possible to measure only $\beta = v/c$ (v is the particle velocity, c is the velocity of light) which gives rise to considerable difficulties when using it in an ultrarelativistic region. Transition radiation[1] has recently attracted more and more attention due to the fact that the total intensity in the direction of the ultrarelativistic particle motion depends linearly on $\gamma = E/\mu c^2$.[2] In addition, it was shown by Garibian[2] and Barsukov[3] that the main fraction of this radiation is in the x-ray frequency region. In Ispirian and Oganessian and Alikhanian et al.[4] the conditions were found and experimentally supported where, in the optical region as well, the transition-radiation intensity increases strongly with γ.

Nevertheless, a small number of photons and small emission angles with respect to the direction of the particle motion cause considerable difficulties both in investigation and in the use of x-ray radiation.

The first attempts to this effect were made by Arutunian, Ispirian, and Oganessian, Arutunian et al., and Alikhanian,[5] where the idea of detecting transition quanta, suggested by Alikhanian et al.,[6] was put into effect by the use of characteristic radiation.

The x-ray transition radiation in a layered medium has recently been studied on an electron beam of energy from 1 to 4 GeV from the Yerevan electron accelerator. The x-ray transition radiation was detected by means of a CsI scintillation counter with a hole in its central portion for free passage of primary electrons. The efficiency of electron detection, i.e., the fraction of cases where at least one of the transition-radiation quanta is detected by the counter, proved to be 10 % for electron energies of 3-4 GeV. In Yuan, Wang, and Prunster[7] charged particles were deflected from the propagation direction of transition quanta by a magnetic field and later the quanta were detected by a germanium solid-state detector. The efficiency of detection of positrons of 2-GeV energy in this work was 27 %.

However, a preliminary spatial separation of a particle from the accompanying radiation usually gives rise to a decrease in the instrument's transmission, and the detection of radiation quanta by means of scintillation or semiconductor counters makes it difficult to calculate their quantity. But the successful application of transition radiation to measuring energies of individual particles depends not only on the presence of a great quantity of transition quanta emitted from a layered medium, but on the efficiency of detecting them with a simultaneous possibility