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Experimental Evidence for the Mechanism of Charge Transfer into Continuum States*

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Experimental data of Rudd and Jorgensen[1] and of Rudd, Sautter, and Bailey[2] show definite humps in energy spectra of electrons ejected at 10° in collisions of protons on gases. These occur approximately where the ejected-electron velocity is equal to the velocity of the incident ion. This led to the development of theoretical treatments[3,4] which predict a very strong peak in the energy spectrum of electrons ejected in the forward (0°) direction. We have now recorded such peaks in spectra from 100- to 300-keV proton impacts on helium gas. The measured cross sections are in agreement with the theory of Macek.[3]

The Born approximation fails to predict this peak and also does not reproduce the cross section even approximately over a large energy region on either side of the peak. This is a case in which the Born theory predicts fewer electrons than observed for ionization by positive particles, but, conversely, it can be expected to predict too many electrons for ionization by negative particles.[5] This effect has been observed by Heckman and Lindstrom[6] who find that positive pions lose energy in emulsions faster than negative pions. The difference has been interpreted in terms of the second-order Born approximation. However, the second term of the Born expansion contains no mechanism by which the peak observed in our data can be produced. The Macek theory, which is based on the first term of a Neumann expansion of Faddeev's equations,[7] does contain such a mechanism, namely, charge exchange to a continuum state of the incident proton. This mechanism is described theoretically by selectively summing an infinite number of terms in the Born expansion.[7] This experiment, which measures electrons ejected at 0°, provides a stringent test of this theory and other theories of ionization.

A simplified schematic of the experimental apparatus is shown in Fig. 1. The proton beam from a Cockcroft-Walton accelerator was collimated by two 0.34-mm apertures spaced 5 mm apart. A biased aperture at the end of the beam tube prevented secondary electrons generated in the beam tube from reaching the scattering re-

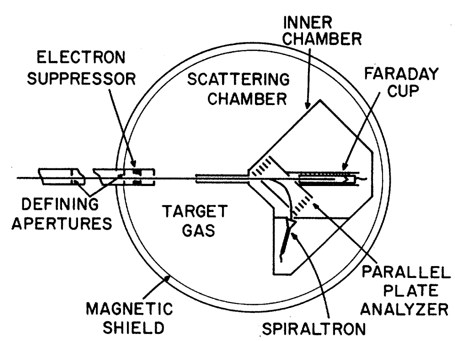

FIG. 1. The experimental arrangement for measuring the ejected-electron spectrum in the forward direction.

gion. The protons interact with the target gas in the outer chamber and enter the inner chamber with the forward ejected electrons through a 1-mm slit at the end of an electron pipe. Here both the protons and electrons enter a parallel-plate analyzer having an energy resolution of 1.6%. The proton beam exits through a slit in the back plate of the analyzer and is collected by a Faraday cup, while the electrons are energy analyzed and individually counted by a Bendix Spiraltron electron multiplier.

An energy spectrum of the ejected electrons is obtained by sweeping a multichannel analyzer at 4 msec per channel, producing a ramp voltage proportional to the channel number. This voltage is amplified and used as the analyzing voltage on the back plate of the analyzer while the electron counts are stored in their respective channels.

The target gas pressure was maintained at 1×10^{-3} Torr in the outer chamber, while the pressure in the inner chamber was about 6×10^{-6} Torr, yielding a differential pumping ratio of about 165. The base pressure of the system was 1×10^{-6} Torr. The entire chamber was shielded from the Earth's magnetic field by a high-permeability canister.

The shift in energy of the peak with incident proton energy can be seen in Fig. 2. The measured energies at the peaks are within 2% of that predicted by theory, without being corrected for the effects of contact potentials. The background counts have been subtracted and the three spectra have been normalized to 10.6×10^{-6} C of integrated proton-beam current. The relative heights tend to follow measured charge-exchange cross sections,[8] as one would expect from the mechanism mentioned above. To obtain relative cross sections from these curves, each ordinate must be divided by the electron energy at that point to correct for the variation of analyzer resolution with energy. To put the cross sections on an absolute basis we have normalized at 40 eV to data of Rudd, Sautter, and Bailey[2] extrapolated to 0°. The results are shown in Fig. 3 along with the Born-approximation predictions for 0° and the Macek theory for 0° and 1.4°. The latter angle was chosen because the angular resolution of the apparatus was ±1.4°. The actual results lie be-

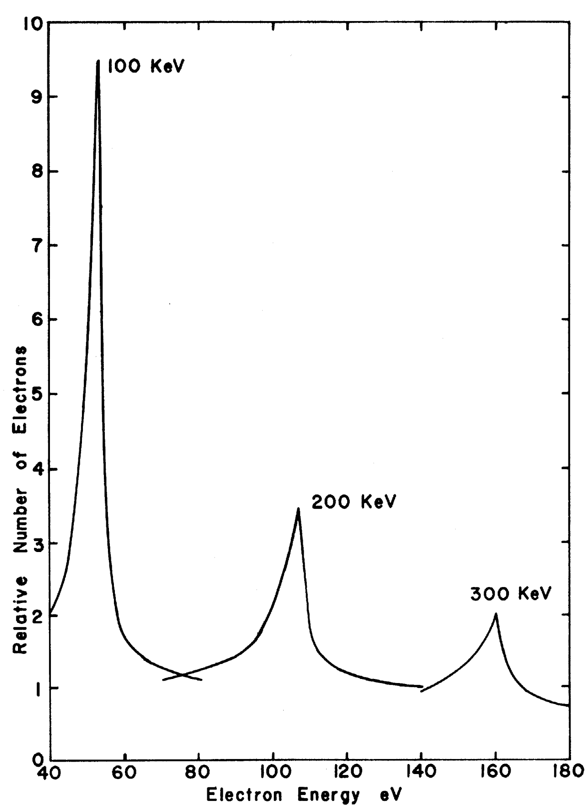

FIG. 2. Electron spectra from three runs at different proton energies. The peaks are at 53, 107, and 160 eV.

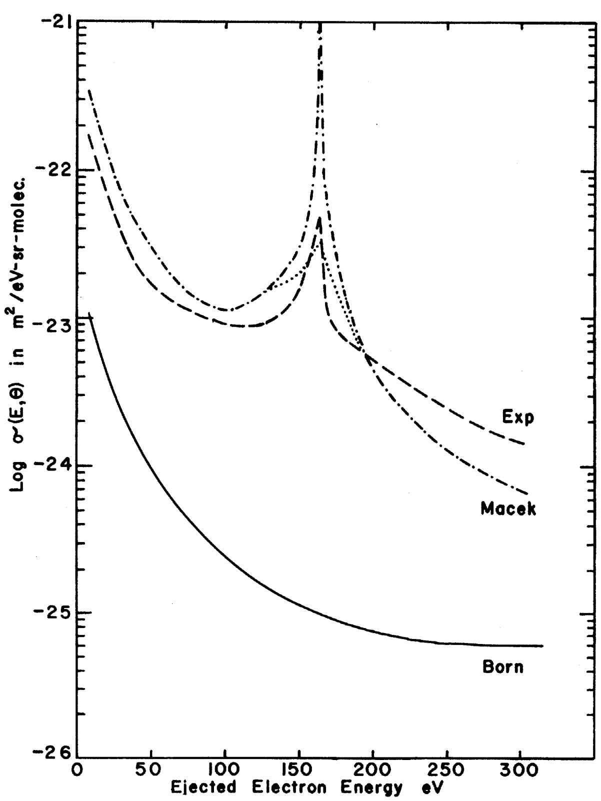

FIG. 3. Cross sections for electrons ejected from He at 0° by 300-keV H^+ calculated from experimental data and from two theoretical treatments. Dash-dot curve is Macek theory at 0°; dotted curve at 1.4°.

tween these two extremes as expected. However, the experimental peak appears to be narrower than expected and also the Macek theory predicts a cross section that is too large for lower energies and too small for the higher energies even when the experimental uncertainty of 30% is taken into account. The Born results are too low by a factor of 20.

The peak was also observed using other projectiles and other target gases. It is reasonable to expect that the effect would be appreciable in emulsions and might be useful in explaining the difference in the energy-loss rates of the positive and negative pions.[6]

This experiment provides the first conclusive evidence that charge exchange into continuum states is an important mechanism of ionization by ion impact. Furthermore, in contrast to earlier speculations,[9] these results show that the Faddeev equations, which provide a natural means of formulating this mechanism in a theory, may apply to the electrostatic interaction.

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Hyperfine Interactions of Fe^{57} in a Frozen Argon Matrix*

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We describe technique for the isolation and observation of iron atoms frozen into a rare-gas matrix. A large quadrupole interaction points to the existence of a stable iron molecule (Fe_2) in an argon matrix at $T = 4.2$°K.

For a decade now, the Mössbauer effect has been used to investigate the hyperfine interactions of Fe^{57} in a great variety of materials. During this time, however, little effort has been concentrated on isolating and observing iron particles which consist of a few atoms only. In view of the paucity of data on such systems we have constructed an apparatus which uses the principle of matrix isolation[1] as developed by optical spectroscopists. Here an absorber is created which consists of many small aggregates of atoms that can be studied with the Mössbauer effect. The object of this communication is to describe briefly the technique (which will be reported fully elsewhere) and report the first results that we have obtained with its use.

The purpose of the instrumentation is to generate an atomic beam of iron. It is subsequently trapped, atom by atom, in a simultaneously produced frozen rare-gas matrix, which allows isolation of the iron with negligible crystal-field interactions. A schematic plan diagram of the experimental layout is shown in Fig. 1. Iron metal powder enriched to 70% Fe^{57} is loaded into an alumina crucible which in turn is placed in a tantalum furnace F which can be electrically heated to a maximum temperature ≈1400°C. The furnace housing H is attached to the side of a liquid helium cryostat so that Fe which evaporates from the crucible can be condensed onto a Be disk B suspended from the bottom of the liquid-He^4 bath. The geometry of the furnace and cryostat produces a collimated beam of evaporated iron atoms with a diameter ≈2 cm at the Be disk which is situated 10 cm from the mouth of the alumina crucible. Data on the absorber which is formed from the atomic beam are collected with a conventional constant-acceleration Möss-