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ABSOLUTE CROSS SECTIONS,
DIFFERENTIAL IN ENERGY AND ANGLE,
FOR EJECTION OF ELECTRONS FROM XENON BY FAST PROTONS*

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Previous measurements of the energy and angular distributions of electrons ejected from target atoms by fast protons have been confined primarily to target atoms of low atomic numbers (i.e., H_2 , He, N_2). The present measurements extend this work to include xenon, atomic number 54. The energy range of our proton beam, 0.3 to 2.0 MeV, is sufficient to produce primary vacancies in the M, N, and O shells (principal quantum numbers 3, 4, and 5, respectively) of xenon by proton impact. The fact that these shells are ionized is deduced from M- and N-Auger electrons observed in the ejected electron spectra. No evidence of L-shell ionization was observed in our results and K-shell ionization is not expected since sufficient energy cannot be transferred to an electron from an incident proton in a single collision to overcome the K-shell binding energy.

A schematic drawing of the apparatus used for our cross section measurements is shown in Figure 1. The proton beam was provided by a Van de Graaff generator, momentum analyzed, and the beam collimated to 0.34 mm before entering the interaction region. After passing through the target cell, the protons were collected in a shielded Faraday cup. Electrons

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ejected from the target gas were energy analyzed by an electrostatic analyzer of the cylindrical mirror design and were then detected by a continuous channel electron multiplier. The number of electrons ejected with energies between E and $E + \Delta E$ for a given number of incident protons passing through the target gas was recorded by a multichannel analyzer operated as a multiscaler; ΔE then being the width of each channel of the multiscaler. Voltage was applied to the electrostatic analyzer through a potential divider driven by a stepping motor. The potential was increased in small increments by the stepping motor; each step was triggered after a preset number of protons had passed through the target gas. Magnetic fields in the interaction region were reduced to a few milligauss by means of three mutually perpendicular pairs of seven-foot square Helmholtz coils.

The electron energy distributions as a function of emission angle are shown in Figures 2, 3, and 4 for electron ejection from xenon by protons with incident energies of 0.3, 1.0, and 2.0 MeV, respectively. The distributions are basically similar: a maximum in the cross section is observed for electron energies of a few electron volts; a peak corresponding to N-00 Auger emission is found at approximately 32 eV; a rather well defined group of M-Auger lines are observed at approximately 520 eV and the cross sections show a sharp decrease for electron energies greater than the kinematic maximum energy transfer in a proton-electron collision.

A more detailed comparison of the structure in the cross section as a function of the proton energy can be obtained from those results obtained at 130 degrees which are shown in Figure 5. The structure due to

Auger electrons is most evident at large angles due to the relatively smaller number of electrons ejected at these angles in direct interactions between the incident proton and bound electron. A comparison of the intensities of the lines (groups of lines) found at 32 and 518 eV shows that the intensity of the 32 eV line increases as the proton energy is increased for 0.3 MeV to 1.0 MeV then decreases with increasing proton energy, whereas, the 518 eV line intensity increases with increasing proton energy throughout the energy range studied. These changes in line intensities along with calculations of the Auger transition energies help to confirm that the 32 eV line group is associated with initial vacancies in the N-shell and the 518 eV line group results from an initial vacancy in the M-shell. Absolute cross sections for inner shell ionization were not obtained from these results, however, qualitatively, one can observe that the cross section for N-shell ionization reaches a peak value for incident proton energies near 1.0 MeV, whereas, the M-shell ionization cross sections continues to increase as the proton energy is increased from 0.3 to 2.0 MeV. Further experimental work is necessary to obtain quantitative results with regard to inner shell ionization.

Some rather interesting features can be seen in the angular dependence of the emission cross sections. In Figure 6 are plotted emission cross sections for several electron energies as a function of ejection angle for 0.3 MeV proton impact. Similar cross sections for electron ejections from a hydrogen gas target are also plotted in Figure 6 for comparison to the xenon results. One striking features of the xenon results is the large cross section for electron ejection into large emission

angles. The corresponding cross sections for hydrogen fall off much faster at large angles. Also, the kinematic peak is sharper with hydrogen than with xenon as the target gas. A strong indication of forward peaking is also evident for emission of electrons with velocities near that of the incident proton. This forward peaking has been observed previously for low atomic number⁽¹⁾ target atoms and recently has been described theoretically^(2,3) as an electron being captured into a continuum state of the proton. The remarkable point here is that this forward enhancement can be seen at angles as large as 30 degrees, whereas, for low atomic numbers forward peaking was confined to angles of 10 degrees or smaller. Figure 7 is a similar plot of angular distributions except that the incident proton energy is 2.0 MeV. For 2.0 MeV, there is possibly a greater enhancement of the cross section at large angles for electrons with velocities near that of the proton than was evident from the results of 0.3 MeV proton impact. The forward peaking is still evident but is observed at smaller emission angles. The peak in these distributions at the kinematically predicted angle for a 2.0 MeV proton impact is somewhat sharper than the 0.3 MeV results of Figure 6; this, however, is to be expected since the binding energy of the electrons is less significant when compared to the ejected electron energy. No attempt has been made to analyze the small peak in the angular distribution at emission angles of approximately 40 degrees which appears in the results shown in Figure 7. Further experimental work is necessary to verify that this is indeed a real peak.

If the doubly differential cross sections are integrated with respect to emission angle, the resulting cross sections can be compared to those calculated by binary encounter theory. This comparison is made in Figure 8. The binary encounter calculation is from the program of Rudd and Gregoire.⁽⁴⁾ Two calculations were made: one in which the kinetic energy of each bound electron was taken as equal to its binding energy ($\gamma = 1$) and one in which the kinetic energy was estimated from Slater's rules.⁽⁵⁾ For electron energies greater than 100 eV, there is very good agreement between experimental cross sections and those calculated from binary encounter theory with $\gamma = 1$. The low-energy end of the electron emission spectra is best fit by calculations which use the kinetic energy of the bound electrons as estimated by Slater's rules. From these comparisons, it is evident that the results of binary encounter theory can be used to obtain results which are accurate to within a factor of 2 throughout most of the energy range of the ejected electrons.

If one integrates the doubly differential cross sections with respect to emission angle and electron energy, the result is a total ionization cross section. Total ionization cross section obtained in this way includes contributions from multiple ionization as well as single ionization, however, the effects of multiple ionization are considered to be small. The ionization cross sections obtained from our measured double-differential cross section are compared to other measurements in Figure 9. The present results agree quite well with the previous measurements,^(6,7) which are for electron impact ionization of xenon; the results are compared at equal velocities of the incident protons and electrons. Also shown are

the single ionization cross sections calculated by means of binary encounter theory. The best agreement between calculated and measured values is obtained when the calculations are made using the kinetic energy of the bound electrons as estimated from Slater's rules. For $\gamma = 1$, the binary encounter cross sections are approximately a factor of 2 too small. The energy dependence of the calculated cross sections does not agree with the measured dependence in that the calculated cross sections appear to decrease more rapidly with increasing velocity of the incident particle than do the measured values. The results of binary encounter theory utilizing Slater's rules begin to diverge from the measured cross sections for proton energies below approximately 0.8 MeV.

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FIGURE CAPTIONS

1. A schematic drawing of the apparatus used in the cross section measurements.
2. Electron energy distributions as a function of emission angle for electrons ejected from xenon by 0.3 MeV proton impact.
3. Electron energy distributions as a function of emission angle for electrons ejected from xenon by 1.0 MeV proton impact.
4. Electron energy distributions as a function of emission angle for electrons ejected from xenon by 2.0 MeV proton impact.
5. Comparison of the electron energy distributions observed at 130 degrees for 0.3, 1.0, and 2.0 MeV protons on xenon.
6. Angular dependence of electron emission cross sections for several energies of electrons ejected from xenon by 0.3 MeV proton impact. Representative cross sections for electron ejection from hydrogen are shown for comparison.
7. Angular dependence of electron emission cross sections for several energies of electrons ejected from xenon by 2.0 MeV proton impact.
8. Electron energy distributions after integration over emission angles. The binary encounter calculations are from the program of Rudd and Gregoire. ⁽¹⁾
9. Total ionization cross sections for protons and electrons on xenon. The electron impact cross sections are compared to the proton results for electron velocities equal to the proton velocities. Previous measurements: (a) see reference 7; (b) see reference 6.

Fig. 1

0.3 MeV H^+ ON Xe

1.0 MeV H^+ ON Xe

H^+ ON XENON
ELECTRONS EJECTED AT 130°

IONIZATION OF XENON BY FAST PROTONS AND ELECTRONS