

CROSS SECTIONS FOR IONIZATION OF GASES BY 1–3-MeV PROTONS

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The total cross sections for ionization of H₂, N₂, He, Ne, Ar, and Kr gases by 1–3-MeV protons are measured. These results are compared with the experimental data on the ionization of gases by fast protons and electrons, and with theoretical predictions based on the Born approximation and the classical theory of inelastic collisions.

1. INTRODUCTION

IN the present work we have measured the total cross sections for the ionization of atoms and molecules of the gases He, Ne, Ar, Kr, H₂, and N₂ by fast protons. There have been many investigations of ionization induced by fast heavy particles, especially protons, bombarding atoms and molecules of different gases.^[1–9] Hooper et al.^[8,9] recently measured cross sections for gas ionization by protons in the 0.15–1.1-MeV range. All other measurements of total ionization cross sections by ions were performed at lower energies. However, the study of the ionization processes involved in ion-atom collisions within the million-electron-volt region is extremely important both for practical reasons and for the more profound interpretation of inelastic interactions between fast heavy atomic particles. It is of considerable interest to compare our results with the available theoretical calculations, as well as with experimental data on the ionization of atoms and molecules by fast electrons. Our measurements were obtained with 1–3-MeV protons.

2. EXPERIMENTAL APPARATUS AND TECHNIQUE

The protons having energies up to 3 MeV were obtained by using a tandem electrostatic accelerator developed and constructed at the Physico-technical Institute of the Ukrainian Academy of Sciences. The accelerated-proton energy was determined from their deflection in a magnetic field that was measured by means of magnetic resonance. The proton energy was measured with $\pm 0.1\%$ accuracy.

Figure 1 shows the experimental arrangement for measuring the ionization cross sections. The proton beam emerged from the accelerator with an initial divergence of 10^{-3} radians. It was then

deflected in the magnetic field of a 120° mass monochromator with a mean effective radius $\rho = 130$ cm before passing through the slit 1, consisting of two equal parts that were insulated from each other. This slit, 4 mm wide, served as a sensing element for the accelerator-voltage stabilizer and for maintaining constancy of the beam direction. The circular 1-mm diameter collimating slit 2 was positioned in front of the collision chamber. The cylindrical tubes 3, each of 13-mm inside diameter and 50-mm length, were used to produce pressure differences at the entrance and exit of the collision chamber. In order to obviate possible errors of measurement due to secondary electron emission from the edges of the collimating slit the diaphragm 4 having a hole of 3-mm diameter was positioned ahead of the entrance capillary. This diaphragm was insulated from the apparatus housing, to which a positive potential was applied. The electric field associated with the latter did not penetrate into the measuring region because of shielding by the entrance capillary 3. Similarly, the exit capillary 3 of the collision chamber shielded the electric field that was applied to suppress electron emission from the Faraday collector 5 that measured the primary proton beam intensity.

Our proton beam geometry, in conjunction with the dimensions of the collimating slits and capillaries, practically eliminated the possibility that beam protons might strike the capillary walls; in this way secondary electrons were kept out of the measuring region. This effect was confirmed by special measurements of the distribution of currents from the measuring and guard electrodes. The primary proton beam current was measured with a Faraday collector 5 in which secondary electron emission was suppressed. The transmission and scattering of the proton beam were moni-

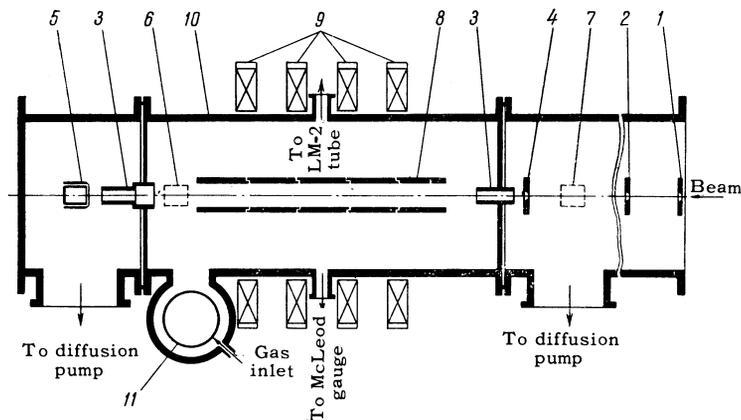


FIG. 1. Diagram of apparatus.

tored by means of the Faraday cups 6 and 7 which were moved into the beam path by remote magnetic control. With 10^{-5} Torr residual gas pressure in the collision chamber the proton beam transmission was practically 100%.

To check the influence of the entrance aperture on the measurements we performed control experiments with slits of different diameters at the collision chamber entrance. As the collimating slit diameter was increased from 1 to 4 mm the cross sections remained unchanged within experimental error limits. A transverse electric field in the collision chamber drew away the slow ions and electrons. This field was generated by five flat condensers 8 placed parallel to the beam axis; the condenser plates were 80 mm long and their separations were 40 mm. Spurious electron currents caused by secondary emission from the surface of the measuring plates were eliminated from the chamber by a longitudinal magnetic field of about 200 Oe parallel to the plates. This field was generated by four coils 9 placed close to and around the copper housing of the collision chamber 10.

For each investigated gas we recorded the dependence of the secondary particle to primary particle current ratio on the magnetic field strength H and on the potential difference V between the measuring electrodes. From these characteristic curves we determined the values of H and V required to achieve current saturation. We investigated an energy region in which the probability of electron capture by fast protons was negligibly small^[10] and could be neglected. We therefore considered only those inelastic interactions between the protons and the gas atoms and molecules that produced slow ions. The total ionization cross sections were determined assuming single collisions; the validity of this condition was verified

for all the gases from the linear relation between the secondary-to-primary current ratio and the gas pressure in the collision chamber. The primary current and the currents in the measuring electrodes were determined with vacuum-tube electrometers of 10^{-14} A/division sensitivity. The primary proton current was $\sim 5 \times 10^{-7}$ A.

To reduce the background and contamination of the collision chamber we introduced the liquid nitrogen trap 11. The residual gas pressure in the collision chamber did not exceed 10^{-5} Torr. The apparatus was evacuated with an oil vapor pump (M-1000) that was equipped with a liquid nitrogen trap. The working pressure did not exceed $(3-5) \times 10^{-6}$ Torr. The gas pressure in the collision chamber was measured with an LM-2 ionization gauge tube that had been calibrated by means of a McLeod gauge. Because of possible errors caused by the directed stream of mercury vapor in the operation of the McLeod gauge equipped with a cold trap,^[11] the LM-2 ionization gauge was recalibrated while eliminating such errors as far as possible. For this purpose the McLeod gauge walls were maintained at 0°C by means of melting ice. This recalibration was performed for neon; the resulting correction was compared with the calculation based on a formula in^[12]. The experimental correction for neon was 5.5%, while the corresponding theoretical value was 5.3%. This good agreement permitted us to limit ourselves to the calculated corrections for the other gases. A maximum of 0.1% impurities was contained in the target gases.

The total ionization cross sections were calculated from the formula

$$\sigma_+ = \left[\frac{d(I^+/I_0)}{d(nl)} \right]_{nl \rightarrow 0}$$

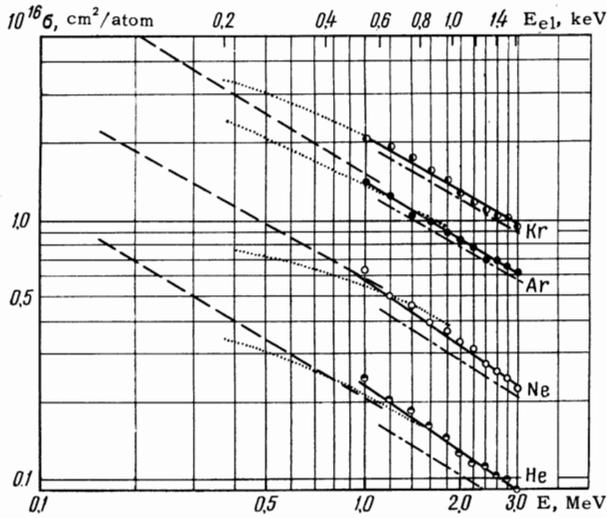


FIG. 2. The total cross sections for inert-gas ionization by protons and electrons. Dashed lines from [9]; dot-dash lines— from [13]; dotted lines—from [14].

where I^+ is the positive ion current flowing to the measuring electrode, I_0 is the primary proton current, n is the gas molecule concentration in the collision chamber, and l is the length of the measuring electrode.

The systematic errors involved in determining the molecular concentration in the collision chamber and in measuring the currents comprised about 10%.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The total cross sections σ_+ for the production of slow positive ions were measured. Since, as already mentioned, in our energy region the probability of electron capture by fast protons was

negligibly small, the cross section σ_+ can be equated to the cross section σ_- for the production of free electrons. Figures 2 and 3 show the measured total cross sections for the ionization of He, Ne, Ar, Kr, H₂, and N₂ atoms and molecules by 1-3-MeV protons.

A. Comparison with experimental data on the ionization of atoms and molecules by protons and electrons. Figures 2 and 3 show the measured values of total cross sections for ionization by 0.15-1.1-MeV protons in [8,9]. Our results are seen to join the other results smoothly within error limits. It must be remembered that we did everything possible to reduce the errors arising, while determining the gas pressure in the collision chamber, as a result of the directed mercury vapor flow in the McLeod gauge.

For the proton-induced ionization of gases Hooper et al. used the empirical formula $\sigma = AE^{-\alpha}$ to represent the energy dependence of the ionization cross section, where the constants A and α have determinate values for each gas. The same formula applies to our energy interval, since constant values of A and α are maintained, within error limits, for hydrogen, nitrogen, and argon. Our curves for helium and neon fall off somewhat more steeply.

It has frequently been noted in the literature that equal total cross sections are obtained in bombardments with electrons and protons of equal high velocities. This result has been verified in [8] for protons up to 1.1 MeV. Approximate equality of the respective total cross sections has been observed for proton energies above 0.6 MeV.

Schram et al. [13] recently measured the ionization cross sections of several atoms and molecules undergoing bombardment by 0.6-20-keV electrons. Results obtained with electrons from 200 to 1000 eV were soon afterward published in [14]. Since in the present work we investigated the ionization of gas atoms and molecules by protons whose velocities corresponded to electrons in the range ~540-1630 eV a comparison with the aforementioned investigations was of interest. In Figs. 2 and 3 the data of [13] are represented by dot-dash lines and those of [14] by dotted lines.

For hydrogen, argon, and krypton agreement is observed, within experimental error limits, between our results and those in [13] over our entire energy range. For helium, neon, and nitrogen we find discrepancies exceeding the error limits. A comparison with [14] yields better agreement in the given cases for protons above 800-1100 keV. Small discrepancies occur for hydrogen and neon.

It is noteworthy that the different authors pre-

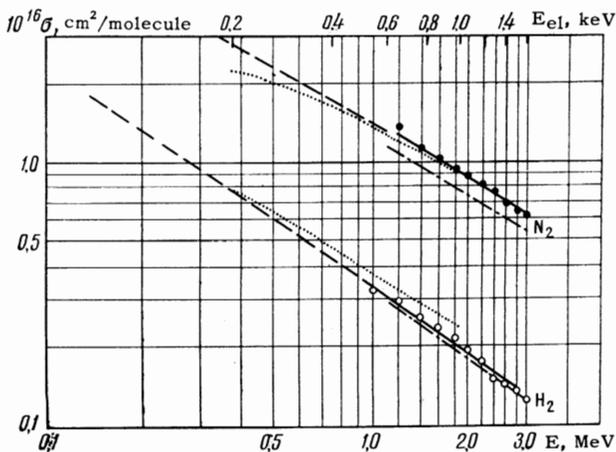


FIG. 3. Total cross sections for hydrogen and nitrogen ionization by protons and electrons. Dashed lines—[9]; dot-dash lines—[13]; dotted lines—[14].

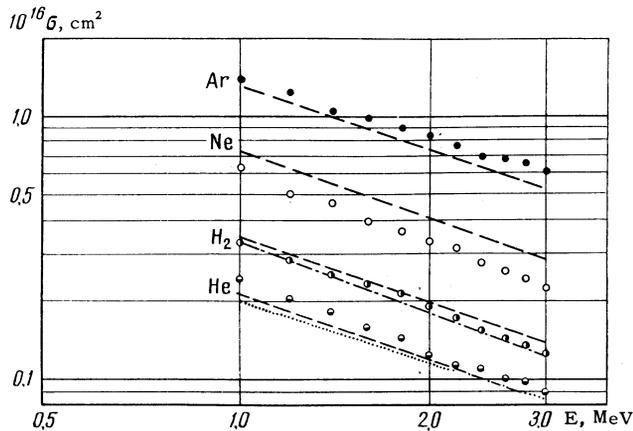


FIG. 4. Experimental and theoretical cross sections for proton-induced ionization. Dashed lines—^[17]; dot-dash lines—^[15]; dotted lines—^[16].

sent data disagreeing by more than the possible errors. It is evident that the experimenters are unaware of some additional sources of systematic errors.

B. Comparison with theory. Our present measurements of total ionization cross sections obtained for high relative velocities of the colliding particles can be compared with the available theoretical calculations of ionization cross sections. For the ionization of hydrogen atoms by fast protons Bates and Griffing^[15] calculated the cross section as a function of proton energy in the first Born approximation. Since these experimental results were obtained for molecular (not atomic) hydrogen, the comparison was made using the procedure of ^[5,8], where a hydrogen molecule was considered equivalent to two atoms, but the difference between the ionization potentials of diatomic molecules and atoms of hydrogen was taken into account. In the corresponding (dot-dash) theoretical curve of Fig. 4 good agreement is observed. Mapleton^[16] calculated the total cross section in the Born approximation for helium atoms ionized by fast protons. In the corresponding (dotted) curve of Fig. 4 we also observe satisfactory agreement with experiment.

Since the possible comparisons of our data with quantum-mechanical theories are exhausted by the considered cases, an additional comparison was made with the classical theory of Gryziński^[17] for most of the investigated gases. For light molecules and atoms of H₂ and He his calculations

practically coincide with the theoretical Born-approximation curves; somewhat inferior agreement is observed for neon and argon, although the discrepancy is at most 20%. In view of the very approximate character of Gryziński's theory we can consider this to be sufficiently good agreement.

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