SOVIET PHYSICS JETP VOLUME 27, NUMBER 6 DECEMBER, 1968

RESONANT CHARGE TRANSFER OF LOW-ENERGY CARBON AND NITROGEN IONS

V. A. BELYAEV, B. G. BREZHNEV, and E. M. ERASTOV

Submitted February 2, 1968

Zh. Eksp. Teor. Fiz. 54, 1720–1725 (June, 1968)

The resonant charge-transfer cross sections of nitrogen and carbon ions are measured between 7 and 100 eV by the merging beam technique. In a control experiment the resonant charge transfer cross section of helium ions is measured in the same energy range.

1. INTRODUCTION

IT has been shown in[1-3] that the merging beam technique is a suitable means of measuring cross sections for ion-atom collisions at energies of at most a few electron volts. By this technique we investigate the interaction between two superposed monochromatic beams of particles moving in an identical direction. This experimental arrangement makes it possible to measure interaction energies that are many times smaller than the energies of the particles in each beam. We are thus enabled to work with high-energy beams for the purpose of studying processes that involve very low interaction energies. In this way we avoid, to a considerable extent, the difficulties that arise in work with low-energy beams (repulsion of a charged-particle beam by its own space charge, strong scattering on residual gases etc.). This technique also permits the study of collisions between practically any atomic objects.

In the present work the merging beam technique is used to measure the resonant charge transfer cross section of carbon:

$$C^+ + C \rightarrow C + C^+$$

and of nitrogen:

$$N^+ + N \rightarrow N + N^+$$

in the energy range 7–100 eV.

2. EXPERIMENTAL APPARATUS

Our apparatus did not differ significantly from that described in[3,4]. Using an ion source, a magnetic monochromator with an aperture D_1 at its focus (Fig. 1), and a set C_1 of collimating apertures, we obtained a beam of ions having a fixed mass and energy ~1 keV with ±40′ angular spread and 0.2% monochromaticity. Directly in front of the apertures C_1 we placed a gas-filled neutralization chamber NC, which neutralized ~ 10% of an ion beam that traversed the chamber. The resulting monoenergetic mixed atom-ion beam was collimated by apertures C_1 and D_1 before entering the collision chamber CC. The latter (a cylinder with a hole at each end) was insulated from the system and bore an electric potential that slowed the ions, thereby (1) creating an energy difference between the ions and atoms, which was necessary for obtaining the required interaction energy, and also (2) fixing the length of the interaction region, since nonreacting ions reacquired their original energy upon traversing the collision chamber. The ions of the desired effect, which were those formed from atoms through the process of resonant charge transfer in the collision chamber, acquired additional energy upon emerging from the chamber. They could then be registered after being separated from the total particle beam by means of an energy analyzer.

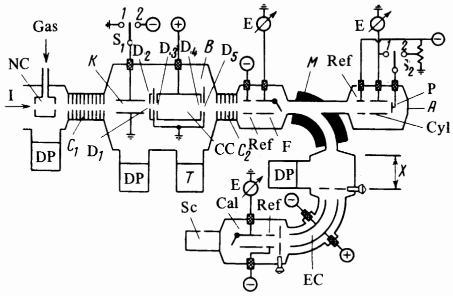

FIG. 1. Experimental arrangement. I–initial ion beam, NC – neutralization chamber, D_1 – D_5 – apertures, C_1 and C_2 – collimating apertures, K – condenser, CC – collision chamber, B – high-vacuum chamber, F –Faraday cup, A – atom detector, Cyl-collecting cylinder, P–molybdenum plate, Ref–reflector, M-analyzing magnet, EC–electrostatic condenser, Cal–calibrating cylinder, Sc–scintillation counter of ions, E–electrometer, S_1 and S_2 – switches, DP–diffusion pump, T–titanium pump, X–straight segment of ion trajectory.

The energy analyzer consisted of a sector magnet M for spatial focusing (first stage) and a cylindrical electrostatic condenser EC (second stage). Ions separated out by the analyzer were registered with a detector Sc similar to that described in[5]; this was a scintillation counter that registered secondary electrons ejected by the ions from a metal plate and accelerated to 15 keV.

To reduce the spurious current of ions resulting from atom stripping by the residual gas, the collision chamber was maintained at $(1-2) \times 10^{-9}$ Torr while in operation. The primary ion beam entering the chamber was measured with a Faraday cup F having a removable bottom. The atom beam intensity was measured by the detector A (after switching on the condenser K) from the current of secondary electrons to the cylinder Cyl these ions had been ejected by atoms from a molybdenum plate P (P_2 in position 2). The detector was calibrated using the current of secondary electrons ejected from the plate P (after switching off the condenser K) by an ion beam of known intensity measured by the same detector A (P_2 in position 1). To perform this calibration we needed the ratio between the secondary electron emission coefficients of the molybdenum plate when struck by atoms and ions of the same substance having identical energies. We determined this ratio by the method described in the Appendix of[3].

From the current of desired ions (when the characteristics of the interacting beams were known) we calculated the cross section for resonant charge transfer [see Eq. (2) of[3]]. We neglected the contribution to this current coming from the ionization of beam atoms by ions because the cross section for this process was negligibly small compared with the cross section for resonant charge transfer in the investigated energy region.

3. PRELIMINARY EXPERIMENTS

We measured the cross section for the resonant charge transfer of helium ions in advance of the main experimental work, thus testing the functioning of the apparatus. Figure 2 shows our results, along with previously published results obtained by several investigators and a curve calculated by Smirnov and Chibisov.[6]

To determine the possible systematic errors in the measurement of the primary ion energy, we varied the latter from 700 to 1200 eV but detected no effect on the magnitude of the measured cross section.

A fraction of the neutralized helium ions could capture an electron into either one of the two metastable levels $2s^3S_1$ and $2s^1S_0$. The neutralization chamber was filled with helium in order to reduce the fraction of metastable atoms in the atomic beam. When a helium ion captured an electron into the ground state we had the resonant charge transfer process

$$\mathrm{He}^+(1s) + \mathrm{He}(1s)^2 \rightarrow \mathrm{He}(1s)^2 + \mathrm{He}^+(1s), \tag{3}$$

whereas for the formation of a metastable atom nonresonant charge transfer would take place with the expenditure of ~ 20 eV:

$$\begin{aligned} \mathrm{He}^+(1s) + \mathrm{He}(1s)^2 &\rightarrow \mathrm{He}(1s2s\,{}^3S_1) + \mathrm{He}^+(1s) - 19.8\,\mathrm{eV} \\ \mathrm{He}^+(1s) + \mathrm{He}(1s)^2 &\rightarrow \mathrm{He}(1s2s\,{}^1S_0) + \mathrm{He}^+(1s) - 20.6\,\mathrm{eV} \end{aligned} \tag{4}$$

Although the cross sections for these processes are unknown, we may expect them to be considerably smaller than the resonant charge transfer cross section. A rough estimate is obtained from the process of helium atom ionization by helium ions, which is associated with a very similar expenditure of energy. According to[16] the cross section for this process at 1 keV is 3×10^{-17} cm^2, whereas the cross section for resonant charge transfer at the same energy is ~ 1×10^{-15} cm^2 (Fig. 2).

The ratio between the numbers of secondary electrons ejected from the molybdenum plate by atoms and ions in the range 700–2000 eV was $\chi(\mathrm{He}) = 1$ with 7% accuracy.

The uncertainties of the cross sections that are shown in the figure resulted from statistical errors in measuring the current of present interest, and because of the energy spread and the angular divergence in the interacting beams. The figure shows that the results agree well with those of several other experimenters. We note the practically complete agreement of our results with those calculated by Smirnov and Chibisov.

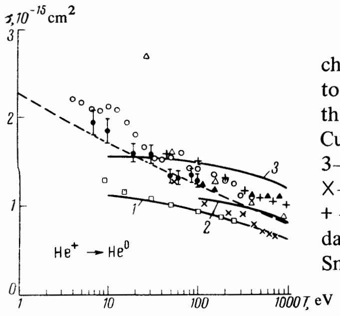

FIG. 2. Cross section for resonant charge transfer from helium ions to helium atoms as a function of the collision interaction energy. Curve 1–from [7], 2–from [8], 3–from [9]; data of □–[10], ×–[11], ▲–[12], ○–[13], Δ–[14], +–[15], ●–present work. The dashed curve is that calculated by Smirnov and Chibisov.[6]

4. MEASUREMENTS ON CARBON AND NITROGEN

For the purpose of obtaining primary beams of nitrogen and carbon ions the ion source was filled with nitrogen and carbon dioxide gas, respectively. In both instances the ion beams were partially neutralized in carbon dioxide gas.

It has been shown in[17] that a considerable fraction of N_2^{++} ions may accompany the N_1^+ beam obtained from an electron-impact source. The conditions for N_2^{++} formation were changed in our gas discharge source, but there still remained the possibility that the N_1^+ beam would be contaminated with N_2^{++}. This could seriously affect the value obtained for the cross section, mainly because the N_1^+ current measurement would be inaccurate. Since in the case of an ion source containing natural nitrogen the N_1^+ and N_2^{++} beams cannot be separated electromagnetically, the source was operated under conditions that yielded a N_1^+ source with a sufficiently small N_2^{++} admixture. The percentage of this impurity in the ion beam was monitored as follows.

An ion beam of known intensity, containing N_1^+ plus N_2^{++}, was directed by an analyzing magnet M (Fig. 1) to the input of the electrostatic condenser EC. Some N_2^{++} ions were converted into N_2^+ by capturing electrons from the N_2 gas while traversing the distance X. Since the energy of these ions was double that of N_1^+, the N_2^+ ions were easily separated out by the condenser EC. From the current of these ions, the gas pressure at X and the length of this path segment, and the known cross section for electron capture by N_2^{++} in nitrogen,[17] we calculated the N_2^{++} current (to within a factor ≈ 2). The measurements showed that the N_2^{++} content of the N_1^+ beam depended essentially on the pressure in the discharge chamber of the source (Fig. 3), but was practically independent of the discharge voltage and current.

For the measurements of the cross section for resonant charge transfer of nitrogen ions the pressure in the source was maintained in the range (2.5–4) × 10^{-2} Torr; the N_2^{++} contamination of the N_1^+ beam was then below one percent.

5. RESULTS

Figures 4 and 5 show the cross sections for resonant charge transfer of carbon and nitrogen ions. As in the case of helium, the uncertainties of the cross section values shown in the figures resulted from statistical errors of the current measurements and also from the energy and angle spreads of the interacting beams.

The absolute calibration of the atomic beam detector led to $\chi(\mathrm{N}) = 1$ with 4% accuracy for 1-keV particles. In the case of carbon, because of poor reproducibility of the results (perhaps due to rapid contamination of the surface by the carbon beam) $\chi(\mathrm{C})$ was measured less accurately, and its value for 1-keV particles exceeded

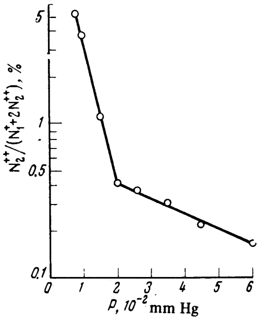

FIG. 3. Percentage of N_2^{++} in the primary ion beam as a function of nitrogen pressure in the gas discharge chamber of the ion source (having 60-V discharge voltage).

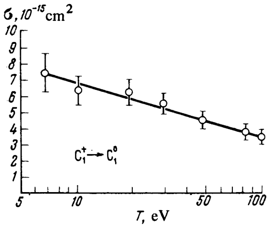

FIG. 4. Cross section for resonant charge transfer from carbon ions to carbon atoms as a function of the interaction energy.

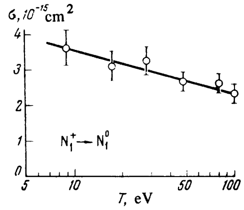

FIG. 5. Cross section for resonant charge transfer from nitrogen ions to nitrogen atoms as a function of the interaction energy.

unity. This result could have been caused by an admixture of metastable atoms in the atomic beam; the percentage of such metastable atoms in the beam was not determined. However, a wide variation in the operating conditions of the source and in the gas pressure inside the neutralization chamber led to no significant variation of the measured cross section. This may indicate that there is both little difference between the resonant charge transfer cross sections for the ground state:

$$C^+(^2P) + C(^3P) \to C(^3P) + C^+(^2P) \tag{5}$$

and the metastable states:

$$\begin{gathered} C^+(^2P) + C(^1D) \to C(^1D) + C^+(^2P), \\ C^+(^2P) + C(^1S) \to C(^1S) + C^+(^2P), \end{gathered} \tag{6}$$

and only a small contamination of the beam with metastable atoms. However, the small difference between the ionization potentials of the ground state (^{3}P – 11.3 eV) and metastable states (^{1}D – 10.0 eV, ^{1}S – 8.6 eV) of carbon suggests that the measured cross sections are insensitive to the presence of metastable atoms in the carbon beam.

There is also a very small difference between the ionization potentials of the ground and metastable states of nitrogen atoms (ground state ^{4}S – 14.5 eV; metastable states: ^{2}D – 12.2 eV and ^{2}P – 11.0 eV). Therefore an admixture of metastable atoms would here also hardly cause a significant change in our measured cross sections.

6. CONCLUSION

Our use of the merging beam technique enabled us to measure the cross sections for processes involved in the collisions of atomic objects each of which is unstable under normal conditions. We obtained interaction energies of a few electron volts, although these were not the lower limiting values attainable with the technique. It was shown in[18] that experimental modifications (specifically, the use of modulated beams) permits this same technique to reach collision energies ~0.1 eV. Since the broadening of the energy range in the direction of higher energies would not be hindered by any fundamental new difficulties, we can now regard the merging beam technique as the most universal method for its energy range.

The merging beam technique also makes it theoretically possible to investigate processes involved in the collisions of practically any ionic, atomic, or molecular objects that can be produced with the aid of ion sources and then neutralized whenever necessary. The technique is therefore a highly suitable one for physical investigations of atomic collisions.

The authors are grateful to L. A. Artsimovich for discussions of the technique and the results, and to L. N. Nikitin for technical assistance with the experimental preparations.

---

[1] V. A. Belyaev, B. G. Brezhnev, and E. M. Erastov, ZhETF Pis. Red. **3**, 321 (1966) [JETP Lett. **3**, 207 (1966)].

[2] S. M. Trujillo, R. N. Neynaber, and E. W. Rothe, Rev. Sci. Instr. **37**, 1655 (1966).

[3] V. A. Belyaev, B. G. Brezhnev, and E. M. Erastov, Zh. Eksp. Teor. Fiz. **52**, 1170 (1967) [Sov. Phys.-JETP **25**, 777 (1967)].

[4] V. A. Belyaev, B. G. Brezhnev, and E. M. Erastov, in Fizika plazmy (Plasma Physics), Atomizdat (Moscow Engineering Physics Inst.), 1967, p. 86.

[5] V. V. Afrosimov, I. P. Gladkovskiĭ, Yu. S. Gordeev, I. F. Kalinkevich, and N. V. Fedorenko, Zh. Tekh. Fiz. **30**, 1456 (1960) [Sov. Phys.-Tech. Phys. **5**, 1378 (1960)].

[6] B. M. Smirnov and M. I. Chibisov, Zh. Tekh. Fiz. **35**, 117 (1965) [Sov. Phys.-Tech. Phys. **10**, 88 (1965)].

[7] J. B. Hasted, Proc. Roy. Soc. (London) **A205**, 421 (1951).

[8] J. B. Hasted and J. B. H. Stedeford, Proc. Roy. Soc. (London) **227**, 466 (1955).

[9] H. B. Gildbody and J. B. Hasted, Proc. Roy. Soc. (London) **238**, 334 (1957).

[10] R. F. Potter, J. Chem. Phys. **22**, 974 (1954).

[11] J. A. Dillon, W. F. Sheridan, H. D. Edwards, and S. N. Ghosh, J. Chem. Phys. **23**, 776 (1955).

[12] S. N. Ghosh and W. F. Sheridan, Ind. J. Phys. **31**, 337 (1957).

[13] W. H. Cramer and J. H. Simons, J. Chem. Phys. **26**, 1272 (1957).

[14] E. Gustafsson and E. Lindholm, Arkiv Fysik **18**, 219 (1960).

[15] H. C. Hayden and N. G. Utterback, Phys. Rev. **135A**, 1575 (1964).

[16] H. B. Gilbody and J. B. Hasted, Proc. Roy. Soc. (London) **A240**, 382 (1957).

[17] W. McGowan and L. Kerwin, Proc. Phys. Soc. (London) **82**, 357 (1963).

[18] R. N. Neynaber, S. M. Trujillo, and E. W. Rothe, Phys. Rev. **157**, 101 (1967).

Translated by I. Emin
200