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Atomic Collision Research in the eV-KeV Energy Region

N.N. Semashko, V.A. Belyaev, M.M. Dubrovin
and A.N. Khlopkin
I.V. Kurchatov Institute of Atomic Energy

Work performed under IAEA Contract 2936/RB
as part of the Coordinated Research Programme on
Atomic Collision Data for Diagnostics of Magnetic Fusion Plasmas

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PROGRESS REPORT ON IAEA RESEARCH CONTRACT 2936/RB

Contract No. 2936/RB

Title of project: Atomic collision research in the eV-keV region (part of a co-ordinated programme on atomic collision data for diagnostics of magnetic fusion plasmas)

Institute where research is carried out:

I.V. Kurchatov Institute of Atomic Energy

Chief Scientific Investigator:

Professor N.N. Semashko, Doctor of Physico-Mathematical Sciences

Scientific collaborators:

V.A. Belyaev, M.M. Dubrovin and A.N. Khlopkin

Period covered: Nine months from 1 November 1981

In accordance with the first year's plan of work, which has been conducted since 1 November 1981 in the ATOS device [1] under the IAEA research contract aimed at determining the charge-exchange cross-sections in collisions of hydrogen atoms with multiply-charged ions of impurity elements in tokamaks in the region of eV-keV per nucleon, a number of steps have been taken to improve the accuracy of the measurements.

As was shown in Ref. [2], in order to determine the cross-section we need to know the values of the parameters entering into the expression

$$\sigma = \frac{i_e}{i_1 i_2} \cdot \frac{S}{L} \cdot \frac{v_1 v_2}{v} = K \frac{i_e}{i_1 i_2} \cdot \frac{S}{L} \cdot \frac{\sqrt{E_1 E_2}}{\sqrt{T}} . \quad (1)$$

Here i_1, i_2 and i_e are the beam intensities of the atoms, ions and newly formed particles (effective current) in particles per second, S is the cross-section of the atom beam (fully covering the ion beam) in cm^2, L is the length of the beam interaction region in cm, $v_1(E_1)$ and $v_2(E_2)$ are the atom and ion velocities (energies) in cm/s (eV/nucleon), and v(T) is the relative velocity (collision energy) of the atoms and ions in cm/s (eV/nucleon).

The error of the cross-section value being measured is associated with the uncertainty of all the quantities entering into the given expression:

$$\frac{\Delta\sigma}{\sigma}=\frac{\Delta i_e}{i_e}+\frac{\Delta i_1}{i_1}+\frac{\Delta i_2}{i_2}+\frac{\Delta S}{S}+\frac{\Delta L}{L}+\frac{1}{2}\cdot\frac{\Delta E_1}{E_1}+\frac{1}{2}\cdot\frac{\Delta E_2}{E_2}+\frac{1}{2}\frac{\Delta T}{T} \qquad (2)$$

As analysis shows, the most substantial contribution to $\Delta\sigma/\sigma$ is made by the first and last terms of this expression.

In order to evaluate the magnitude of the last term, we take it that the collision energy will lie in the region [2]

$$(\sqrt{E_1}-\sqrt{E_2})^2\leqslant T\leqslant(\sqrt{E_1}-\sqrt{E_2})^2+\varphi^2\sqrt{E_1E_2}\ ,$$

where ϕ is the maximum possible angle of intersection of the trajectories in the combined beams ($\phi \ll 1$). Taking the following as the average value

$$T=(\sqrt{E_1}-\sqrt{E_2})^2+\frac{1}{2}\varphi^2\sqrt{E_1E_2}\ ,$$

we re-write the last term of expression (2) in the form

$$\frac{1}{2}\frac{\Delta T}{T}=\frac{1}{2}\sqrt{\frac{E_1}{T}}\frac{\Delta E_1}{E_1}+\frac{1}{2}\sqrt{\frac{E_2}{T}}\cdot\frac{\Delta E_2}{E_2}+\frac{1}{4}\varphi^2\frac{\sqrt{E_1E_2}}{T}\ .$$

Thus the minimum collision energy attained during the specific experiment, in the case of strictly monokinetic beams, equals $T_{min} = \phi^2E/2$ (here $E = E_1 \approx E_2$) and has a 100% uncertainty, thereby contributing 50% to the error in σ.

In the ATOS device T is varied in each measurement cycle by retarding the ions at the entrance to the collision chamber so that E_2 decreases while E_1 remains unchanged. If the minimum values of T are to be obtained, the retardation will have to be minimum but not zero, since some retarding potential is always applied to the collision chamber in order to cut off the background current of protons generated through stripping of the hydrogen atoms by the residual gas outside the collision chamber. Because of the resultant debunching of the ion beam, the value of angle ϕ cannot be made smaller than $\approx 1^{\circ}(0.02)$.

Hence, energy E of the beam particles should not exceed 5×10^3 eV/nucleon in order to obtain $T_{min} = 1$ eV/nucleon. Energy E should, of course, be made still smaller in order to reduce ΔT and $\Delta\sigma$.

These considerations apply to the case of strictly monokinetic beams. The presence of energy spreads ΔE_1 and ΔE_2 increases the values of ΔT and $\Delta\sigma$. Then the greatest contribution to error $\Delta\sigma/\sigma$ will, in our case, be made by the term $\frac{1}{2}\sqrt{\frac{E_2}{T}} \cdot \frac{\Delta E_2}{E_2}$, owing to the difference in the degree to which the ATOS beams are monokinetic: $\Delta E_1 = \pm 0.5\%$, $\Delta E_2 = \pm 2\%$ [3]. Here it is likewise more advantageous to perform measurements for smaller E.

The reductions necessary (in accordance with the above considerations) in the beam particle energy can be achieved either by retarding the multiply-charged ions at the entrance to the collision chamber and the protons at the entrance to the neutralization chamber, or else by reducing the energy of beam particles during beam shaping by the ion-source lens systems. In both cases the reduction in particle energies may lead to a drop in the intensity of the interacting beams and, consequently, to a decrease in the effective current. This means an increase in the measurement time affecting the value of the first term in expression (2). Let us consider the matter in greater detail.

As follows from expression (1), the drop in E_1 and E_2 for specified values of the remaining terms in the expression also allows i_e to be increased, thereby reducing the measurement time required to obtain the target measurement error $\Delta i_e/i_e$. In order to evaluate the expected value of this error, we take into account the fact that, when we record i_e, we simultaneously record the background proton current i_b formed as a result of hydrogen atom stripping by the residual gas in the collision chamber. The value of i_e is determined as the difference between the results of two measurements: $i_e = I - i_b$, where $I = i_e + i_b$ - the total current recorded by the detector. (For measurement of i_b the ion beam is switched off.) In the case of measurements with the ATOS, expression (1) can be written as

$$i_e \approx 4 \cdot 10^{32} i_1 i_2 \sigma \frac{\sqrt{T}}{E} \tag{3}$$

and the background current will equal (see Ref. [1])

$$i_b \approx 4 \cdot 10^{19} i_1 \sigma_0 n \tag{4}$$

where n is the density of the residual gas in the region of the collision chamber, and σ_0 is the cross-section for hydrogen atom stripping by the residual gas. (In these expressions i_1 and i_2 are given in amperes and i_e and i_b in particles per second). Since $i_b >> i_e$, therefore $\Delta i_e = \Delta I + \Delta i_b \approx 2\Delta i_b$. Hence

$$\frac{\Delta i_e}{i_e} \approx \frac{2\Delta i_b}{i_e} \approx \frac{2\sqrt{i_b t}}{i_e t} \approx 6 \cdot 10^{-15} \frac{E}{i_2 \sigma} \sqrt{\frac{\sigma_0 P}{i_1 T t}}$$

which has the strongest dependence on the multiply-charged ion current i_2 and energy E. (P is the residual gas pressure in mm of mercury column and t the measurement time in seconds.)

After improvements had been made in the ion-optic channel of the multiply-charged ion beam and in the ion-source lens system in the ATOS, and the ion-optic system of proton retardation at the entrance to the neutralization chamber had been redesigned, it proved possible to obtain stable multiply-charged ion currents sufficient for systematic measurements of σ in the collision chamber (see Table 1). The equivalent current for hydrogen atoms for E_1 = 400 eV passing through the collision chamber is 5 x 10^{-7} A. The value of 400 eV/nucleon was chosen as optimum for $E_1 \approx E_2$ (wherever such is allowed by the ratio of the masses of the colliding particles) on the basis of analysis of the preliminary measurements for T ≈ 1 eV/nucleon.

Hydrogen atoms with 400 eV were obtained by neutralizing 5 keV protons retarded at the entrance to the neutralization chamber and multiply-charged ions by retardation at the entrance to the collision chamber. Considering that $\Delta E_1/E_1 = \pm 0.005$ and $\Delta E_2/E_2 = \pm 0.02$, the contribution of the particle-energy-dependent terms (the last three in expression (2)) to $\Delta\sigma/\sigma$, for T = 1 eV/nucleon, will be about ±30%. (If T is increased to 10 eV/nucleon, the error drops to as low as ±10%).

Substituting into the expression $\Delta i_e/i_e$ the values of $\sigma_0 \approx 2 \times 10^{-17}$ cm^2 and $\sigma \approx 1 \times 10^{-14}$ cm^2 [4], $P \approx 2 \times 10^{-9}$ mmHg, $i_1 \approx 5 \times 10^{-7}$, $i_2 \approx 2 \times 10^{-8}$, we obtain the value of ±10% for T = 1 eV/nucleon and for measurement time $2t = 2000$ s. (For T = 10 eV/nucleon we shall accordingly have about 3%.)

Thus, the maximum error $\Delta\sigma/\sigma$ in the forthcoming measurements for T = 1 eV/nucleon is expected to be about ±40%, decreasing according to a law close to inverse square dependence on collision energy T.

During the remaining three months of the first year of the contract, we shall improve the system for determining the absolute beam intensity of particles passing through the collision chamber with a view to minimizing the possibility of systematic errors which occur in connection with the need to compare the coefficients of secondary electron emission from protons and hydrogen atoms during variation of their energy and of the degree of purity of the detector plate surface.

CONCLUSIONS

As a result of the improvements to the ion-optic and the recording systems of the ATOS device made during the first nine months of IAEA Research Contract 2936/RB, and analysing the results of the preliminary experiments and the possible sources of measurement errors, we expect that in the forthcoming measurements of the charge-exchange cross-sections in collisions of hydrogen atoms with multiply-charged ions of impurity elements in tokamaks the maximum measurement error at a collision energy of 1 eV/nucleon will be about ±40%, decreasing according to a law close to inverse square dependence on collision energy.

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REFERENCES

[1] V.A.Belyaev, A.P.Dorovskij, M.M.Dubrovin, A.N.Khlopkin, Report INDC(CCP)-152/GA, IAEA, Vienna, Austria, August, 1980.

[2] BELYAEV, V.A., BREZHNEV, B.G., ERASTOV, E.M., Zh. Ehksp. Teor. Fiz. 52 (1967) 1170.

[3] BELYAEV, V.A., DOROVSKIJ, A.P., DUBROVIN, M.M., LAZAREVA, G.A., SOKOLOV, N.I., TERESHKINA, A.G., KHLOPKIN, A.N., SHCHUROV, O.A., Report IAEh-3363/7, Moscow (1980) [in Russian].

[4] Y.Kaneko, T.Arikawa, Y. Itikawa, T. Iwai, T.Kato, M.Matsuzawa, Y. Nakai, K. Okuno, H. Ryufuku, H. Tawara, T. Watanabe, Preprint, IPPJ-AM-15, Nagoya, Japan, 1980.

Table 1. Multiply-charged ion current in microamperes in the collision chamber of the ATOS device for different elements and charges

	Charge								
	2	3	4	5	6	7	8	9	I0
Ar	0,30	0,40	0,02	0,03	0,I2	0,0I	0,008	0,0I	
Xe	0,04	0,I0	0,04	0,02	0,008	0,008	0,02	0,0I	0,0I
Fe	0,I2	0,08	0,0I	0,02	0,02	0,0I	0,02		
Mo	0,0I	0,02	0,0I		0,02				
Ta	0,0I				0,03				
C	0,04	0,03							