FROM THE HISTORY OF PHYSICS

PACS numbers: **34.70.+e**, **52.20.–j**, 52.25.Fi

The Sena effect

B M Smirnov

DOI: 10.1070/PU2008v051n03ABEH006542

Abstract. The Sena effect relates to the transport of atomic ions in a parent gas, when this transport results from the resonant charge exchange process involving ions and atoms. The physics of this process and its role in a gas discharge plasma are analyzed briefly.

In connection with the 100-year jubilee of the birth of Lev Aronovich Sena on 28 December 2007, I would like to return to an elegant effect known as the Sena effect. This effect relates to plasma transport as a whole. Let us consider a low-temperature plasma, i.e., a gas consisting of atoms or molecules with a small concentration of electrons and ions, and this plasma is quasineutral, i.e., the number densities of electrons and ions are equal. Violation of plasma quasineutrality leads to induction of a strong electric field that returns the plasma to quasineutrality. If electrons and ions are located in a restricted volume, they tend to occupy all the space. Plasma transport proceeds in a specific way, so that the electrons, as a more mobile plasma component, will pass ahead of the ions, and the electric field that arises will retard electrons, so that the plasma will propagate as a whole in a surrounding space with an ion velocity. This process of ambipolar diffusion determines propagation of a plasma at its boundary. In particular, in a gaseous discharge this plasma transport is realized in the cathode layer and on the walls of the positive column of gas discharge, where ambipolar diffusion is responsible for the ionization balance in this gas discharge plasma.

Thus, the velocity of propagation of a low-temperature plasma as a whole is determined by the rate of ion transport in a gas, and we now examine the character of ion transport in a gas as a result of collisions between ions and atoms (molecules) of the gas. There are two types of collisions between ions and atoms or molecules: elastic ion – atom scattering through a large angle, and the resonant charge exchange process, as takes place, for example, in an inert gas with atomic ions. In the latter case, electron transfer from one atomic core to another is possible while moving along straight trajectories of the colliding ion and atom, as shown in Fig. 1. The Sena effect refers to charge transfer as a result of electron transition between two colliding atoms and ions moving without changing the trajectories of colliding particles, which turns out to be equivalent to ion scattering.

B M Smirnov Joint Institute for High Temperatures,
Russian Academy of Sciences,
Izhorskaya ul. 13/19, 127412 Moscow, Russian Federation
Tel./Fax (7-499) 190 42 44
E-mail: bsmirnov@orc.ru

Received 26 December 2007
Uspekhi Fizicheskikh Nauk **178** (3) 309 – 311 (2008)
DOI: 10.3367/UFNr.0178.200803e.0309
Translated by B M Smirnov; edited by A Radzig

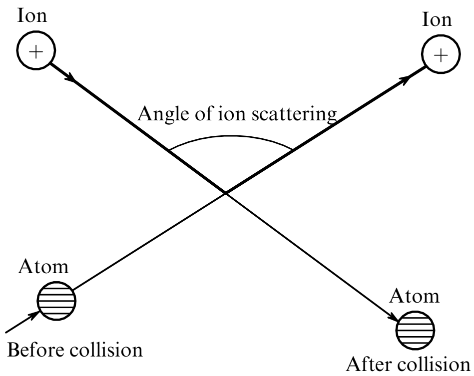

Figure 1. The Sena effect: the character of ion – atom scattering as a result of electron transfer from one core to another in the absence of elastic ion – atom scattering.

This understanding of ion scattering in a gas may be expressed in formulas which link the measurable ion parameters. The measure of ion scattering is the ion mean free path λ in a gas, i.e., a distance passed by an ion without charge exchange. This quantity is connected with the cross section of resonant charge exchange σ_{res} by the relationship $\lambda = 1/(N\sigma_{\mathrm{res}})$, where N is the atom (molecule) number density. If atomic or molecular ions are moving in a parent gas in an electric field of strength E, they acquire from the electric field an energy of the order of $eE\lambda$ between sequential acts of charge exchange, where e is the ion charge. We consider the field to be strong if the acquired energy exceeds the atomic thermal energy, and will follow L A Sena to determine the ion energy distribution function in this limiting case. Taking as an initial time $t = 0$, the moment of a given charge exchange event, we have for the ion velocity $v = eEt/m$ at time t, where m is the ion mass. We assume the atoms to be motionless, i.e., the ion is stopped at $t = 0$, and the next charge exchange act does not proceed up to time t. Let us define the probability $P(t)$ that charge exchange is absent at the time t. Evidently, this quantity satisfies the equation of the radioactive decay type:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = -\frac{v}{\lambda} P$$

and its solution is given by

$$P = \exp\left(-\int_0^t \frac{v}{\lambda}\,\mathrm{d}t'\right).$$

Since the ion velocity v in the field direction is linked unambiguously with time t after the previous charge exchange event, the ion velocity distribution function $f(v)$

satisfies the relation $f(v)\,dv = P\,dt$ and is given by

$$f(v) = C\exp\left(-\frac{mv^2}{2eE\lambda}\right), \qquad v > 0,$$

where C is the normalization factor, and we assumed that the ion mean free path (or the cross section of resonant charge exchange) is independent of the collision velocity. This leads to the following expressions for the ion drift velocity w_i and the ion average energy $\bar{\varepsilon}$:

$$w_i = \langle v \rangle = \sqrt{\frac{2eE\lambda}{\pi m}}, \qquad \bar{\varepsilon} = \left\langle \frac{mv^2}{2} \right\rangle = \frac{eE\lambda}{2}.$$

In particular, from this it follows that the ion mobility K, which is defined as the ratio of the ion drift velocity to the electric field strength: $K = w_i/E$, depends on the electric field strength as $E^{-1/2}$, i.e., the ion mobility is not constant. As is seen, a simple idea leads us to simple formulas for measurable quantities. Returning to real cases, note that the contribution of elastic scattering of atomic ions in inert gases to the ion mobility at room temperature in a weak electric field is about 10%. An increase in the gas temperature or the electric field strength results in a decrease in this contribution.

The significance of the Sena effect is also such that the cross section of resonant charge exchange replaces the cross section of elastic scattering in transport phenomena, when the particle transport is determined by elastic collisions. In the latter case, the diffusion coefficient or the mobility of ions in a gas is expressed through the diffusion cross section σ^* of elastic scattering that is defined as $\sigma^* = \int (1 - \cos\vartheta)\,d\sigma(\vartheta)$, where ϑ is the scattering angle. If charge exchange proceeds without elastic scattering, the ion–atom scattering angle equals $\vartheta = \pi$ in the center-of-mass system, which leads to the following relation between the diffusion cross section of ion–atom scattering and the cross section of resonant charge exchange [1]: $\sigma^* = 2\sigma_{res}$. One can use this replacement in formulas for the ion transport coefficients in a gas if these formulas account for elastic ion–atom scattering.

At first, L A Sena called the above mechanism of ion transport as the relay charge transfer [2–4]. Along with this mechanism, he gave an obvious method to evaluate the cross section of resonant charge exchange [2] that is suitable, as it turned out subsequently, in the case of participation of excited atoms in this process. Indeed, let us consider a slow ion–atom collision, when the relative collision velocity is small compared to the electron velocity in an atomic orbit. We introduce an ion–atom distance R_0 at which the potential barrier for the electron residing between two atomic cores disappears. Since for the impact collision parameters below R_0 the average probability of a valence electron remaining with its core or transferring to the other core is 1/2, the cross section of resonant charge exchange is equal to

$$\sigma_{res} = \frac{\pi}{2} R_0^2.$$

Assuming the electron interaction with each atomic core to be the Coulomb one, we find the ion–atom distance $R = R_0$ at which the potential barrier separating electric fields of the cores disappears (see Fig. 2):

$$U(R_0) = -\frac{e^2}{r_1} - \frac{e^2}{r_2} + \frac{e^2}{R_0} = -\frac{3e^2}{R_0} = -J.$$

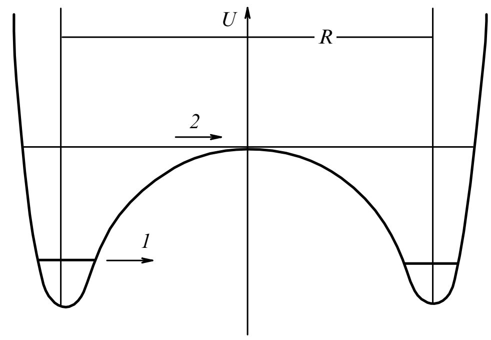

Figure 2. Character of electron transfer from the field of one atomic core to the other one: *1* — tunnel or subbarrier transition, *2* — over-barrier transition.

Here r_1, r_2 are the electron distances from the first and second cores, R is the distance between cores, and J is the atomic ionization potential. From this follows that the cross section of resonant charge exchange in the limit of small collision velocities and low atomic ionization potential corresponding to the transition of a classical electron is expressed as [2]

$$\sigma_{res} = \frac{9\pi e^4}{2J^2}.$$

It is appropriate to give here the expression for the probability of resonant charge exchange in the quantum case. As seen from Fig. 2, the ion–atom system is characterized by the symmetry plane that is perpendicular to the axis joining the nuclei and bisects it. Correspondingly, the eigenstates of the system of interacting ions and atoms are divided into even and odd in accordance with the property of the wave functions ψ_g, ψ_u of these states to conserve or change the sign as a result of reflection with respect to the symmetry plane. At large ion–atom distances, when the valence electron is located in the field of the first core, the wave function ψ_1 of this system has the form

$$\psi_1 = \frac{1}{\sqrt{2}}\psi_g + \frac{1}{\sqrt{2}}\psi_u.$$

From this we can determine the wave function $\Psi(t)$ of the ion–atom system if the ion–atom distance $R(t)$ varies according to a certain law:

$$\Psi(t) = \frac{1}{\sqrt{2}}\psi_g \exp\left(-i\int_{-\infty}^{t} \frac{\varepsilon_g(R)\,dt'}{\hbar}\right) + \frac{1}{\sqrt{2}}\psi_u \exp\left(-i\int_{-\infty}^{t} \frac{\varepsilon_u(R)\,dt'}{\hbar}\right),$$

where $\varepsilon_g(R)$, $\varepsilon_u(R)$ are the energies of the given states. From this we have for the probability of resonant charge exchange [5]:

$$P = \left|\left\langle \Psi(\infty) \middle| \psi(\infty) \right\rangle\right|^2 = \sin^2 \int_{-\infty}^{\infty} \frac{\left[\varepsilon_g(R) - \varepsilon_u(R)\right] dt'}{2\hbar},$$

and, correspondingly, the cross section of resonant charge exchange is given by

$$\sigma_{res} = \int_0^{\infty} 2\pi\rho\,d\rho\, \sin^2 \int_{-\infty}^{\infty} \frac{\left[\varepsilon_g(R) - \varepsilon_u(R)\right] dt'}{2\hbar}.$$

As is seen, the resonant charge exchange process is interference in character, i.e., electron transitions between eigenstates of the system are absent, but the phase shift for eigenstates leads to changing the resultant state of the system.

The above concepts and results are fundamental for the physics of atomic collisions and gas discharge plasma, but at that time these findings were not accepted by Western scientists who had understood the role of resonant charge exchange in atomic processes earlier. The basis of the contemporary physics of atomic collisions was created by the English physical school that was guided by processes in the upper atmosphere of the Earth and astrophysics. In particular, we can emphasize the first fundamental book on the theory of atomic collisions [6]. Probably, the paper [7] reported on the first theoretical study of the resonant charge exchange process where both the electrons and nuclei were considered within the framework of quantum mechanics. This consideration leads to cumbersome formulas for the parameters of the resonant charge exchange process, which are not reproducible here, and the realization of these formulas requires an additional assumption about ion–atom interaction.

In order to understand the possibility of a classical description of nuclear motion in the resonant charge exchange process, it is necessary to check the classical criterion under real conditions. For this goal we evaluate a number of collision momenta which determine the cross section of resonant charge exchange in the hydrogen and helium cases at the ion–atom collision energy of 0.03 eV in the center-of-mass system, corresponding to room temperature. Assume that at the collision momenta $l \leqslant l_0$ the probability of charge exchange is equal to $1/2$, and at collision momenta $l > l_0$ this probability is zero. Using values of the cross section of resonant charge exchange at an indicated collision energy, we find within the framework of this model that $l_0 = 24$ for charge exchange involving a proton and hydrogen atom, and $l_0 = 36$ in the case of charge exchange with the participation of the helium ion and atom. As is seen, the classical consideration for nuclear motion is valid at an indicated collision energy. Correspondingly, the Sena effect is suitable for the analysis of ion transport processes in a parent gas at such collision energies. Since l_0 grows with an increase in an ion mass and collision energies, the classical description of nuclear motion holds true for heavier nuclei and higher collision energies.

Thus, both the Sena effect and concomitant methods of evaluation of the cross sections of resonant charge exchange, taking into account the classical character of nuclear motion, on the one hand, are clear and exhibit the physical peculiarities of the process, and, on the other hand, allow one to determine the numerical parameters of the processes under certain conditions. Therefore, all this possessed an important place both in the physics of atomic collisions and in the physics of gas discharge plasma.

References

1. Holstein T *J. Phys. Chem.* **56** 832 (1952)
2. Sena L A *Zh. Eksp. Teor. Fiz.* **9** 1320 (1939)
3. Sena L A *Zh. Eksp. Teor. Fiz.* **16** 734 (1946)
4. Sena L A *Stolknoveniya Elektronov i Ionov s Atomami Gaza* (Collisions of Electrons and Ions with Gas Atoms) (Leningrad–Moscow: Gostekhizdat, 1948)
5. Firsov O B *Zh. Eksp. Teor. Fiz.* **21** 1001 (1951)
6. Mott N F, Massey H S W *The Theory of Atomic Collisions* (Oxford: Clarendon Press, 1933)
7. Massey H S W, Mohr C B O *Proc. R. Soc. London Ser. A* **144** 188 (1934)