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Self Crossed-Beam Method for Investigation of Ion-Ion Collisions

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A new method of self crossed-beam technique is proposed for investigation of ion-ion collisions at moderate energies. Background scatterings from residual gas molecules are shown to be discriminated by use of kinematics relations. Collision yields are expected to be practically sufficient under ordinary experimental conditions.

I. INTRODUCTION

The crossed-beam method is the most promising technique to obtain the important informations on the single encounter of two particles. The ionization collision between electron and atom has been successfully investigated by this method. The most important and difficult problem to be solved in the crossed-beam method is the discrimination of the background contributions from the encounters with residual gas molecules. Beam-chopping is one of the commonly used technique for this discrimination.[1~4]

Up to now, there is only limited ion-atom crossed-beam experiments.[5,6] In this paper is proposed the new technique of self crossed-beam method for investigation of collisions between identical ions having different charge states. Two crossing beams are produced from single beam by using the charge converter and charge state selector. The scatterings of two beams take place at rather low relative colliding energies. The scattered ions, however, have large kinetic energies in the frame of laboratory system, and this fact make possible a SSD (semiconductor solid state detector) to be used as an ion-detector. Kinematics relations of the self crossed-beam are shown to be useful for discrimination of residual gas background. Under accessible experimental conditions the collision yield of the self crossed-beam has practically sufficient order of magnitude.

II. OUTLINE OF METHOD

The ion beam with given charge state from an accelerator is passed through a gas chamber to convert into several charge states. Two of these states are selected out with the charge state selector which consists of electrostatic fields or magnetic fields and selecting slits, and are allowed to emit into two different directions. After some flight path, one of these beam is bended with an electric field or a magnetic field so as to cross the other beam. The scattered ions from the crossing region are analyzed with the analyzing magnet to determine their charge fraction. A position sensitive SSD is

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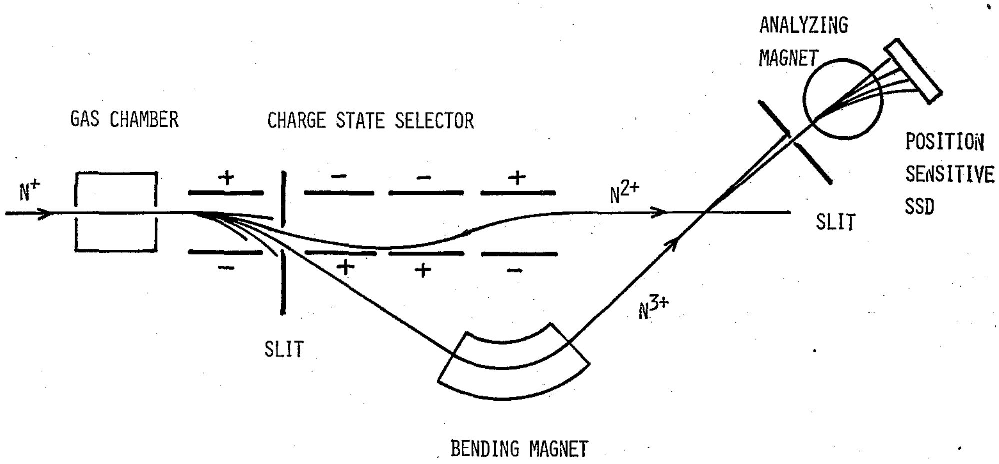

Fig. 1. Schematic illustration of typical self crossed-beam apparatus.

used for detection of the analyzed ions and its energy outputs are used for background–discrimination. A schematic illustration of this method is shown in Fig. 1.

III. YIELD RELATIONS

We designate one of the two beams as the incident beam and the other the target beam, and distinguish each quantities with suffix i and t, respectively. For simplicity, both beams are assumed to have rectangular cross sections whose dimentions are $a_i \times b_i$ and $a_t \times b_t$, respectively. When two beams cross with common height x and with crossing angle θ, as shown in Fig. 2, the collision yield per unit time, y, is given by

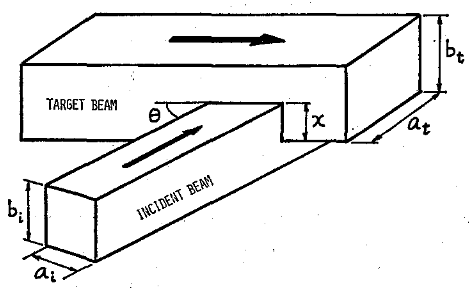

Fig. 2. Crossing of two beams having rectangular cross sections with crossing height x and crossing angle θ.

$$y = \sigma(v_0) \frac{I_i I_t}{z_i z_t e^2} \frac{1}{v_t} \frac{x}{b_i b_t} \frac{1}{\sin\theta} . \tag{1}$$

Here I_i and I_t are the beam currents, z_i and z_t are the charge numbers, e is electronic charge, and v_t is the velocity of ions in the target beam. The collision cross section under consideration, $\sigma(v_0)$, is the function of the velocity of relative motion, v_0, of the incident ion and the target ion. This velocity is calculated from

$$v_0^2 = v_i^2 + v_t^2 - 2v_i v_t \cos\theta \tag{2}$$

For the self crossed-beam one may put $v_i = v_t \equiv v$,* and Eq. (2) simplifies to

$$v_0 = \sqrt{2(1-\cos\theta)}\,v = 2v\sin(\theta/2). \tag{3}$$

The crossing height x is restricted by

$$x \leq \min(b_i, b_t), \tag{4}$$

and the maximum yield is obtained when the one beam is confined completely in the other beam. If $b_i \leq b_t$, this maximum yield is obtained when $x = b_i$:

$$y_{\max} = \sigma(v_0)\frac{I_i I_t}{z_i z_t e^2}\frac{1}{v}\frac{1}{b_t}\frac{1}{\sin\theta}. \tag{5}$$

This expression shows the larger yield for smaller b_t. In the present case, the smallest possible value of b_t is b_i. It is concluded, therefore, that the largest yield in the self crossed-beam is obtained when the heights of the cross sections of two beams are equal. Denoting this height as b, one obtains the expression for the largest yield:

$$Y = \sigma(v_0)\frac{I_i I_t}{z_i z_t e^2}\frac{1}{v}\frac{1}{b}\frac{1}{\sin\theta}. \tag{6}$$

As a typical example, we estimate the yield of charge-changing-collisions between 2 MeV N^{2+} and N^{3+} ion beams at the crossing angle of 20°. The velocity of ion is calculated from

$$v(\text{cm/sec}) = 1.4\times10^9\sqrt{T(\text{MeV})/A}, \tag{7}$$

where T is the kinetic energy of the ion in unit of MeV and A is the mass number of the ion. For 2 MeV ion, v is 5.3×10^8 cm/sec. Let both the beams to have square cross sections of 1 mm × 1 mm and total currents of 1 μA. The collision cross section σ is assumed to be 1×10^{-16} cm^2.[7] The collision yield calculated from Eq. (6) is

$$Y \simeq 50 \text{ events/sec} \tag{8}$$

The counting rate for detection of ions with the limited scattering angle may be reduced to about one-tenth of this value.

Background scattering counts from residual gas molecules must be compared with this beam-beam collision yield. If the gas pressure in the beam-crossing region is p Torr, the density of residual gas molecules, n_g, is calculated from

$$n_g(\text{cm}^{-3}) = 3.5\times10^{16}p\,(\text{Torr}). \tag{9}$$

If $p = 1\times10^{-8}$ Torr, one obtains $n_g = 3.5\times10^8$ cm^{-3}. On the other hand, ion density n_t in the target beam is given by

$$n_t = I_t/(v_t a_t b_t z_t e). \tag{10}$$

For 2 MeV N^{2+} beam of total current of 1 μA and with square cross section of $a_t = b_t =$

* When electric fields are used for beam deflection, the deflected ion gains some energy. For not so large crossing angle, however, this energy gain may be neglected.

1 mm, one obtains $n_t = 5.9 \times 10^5$ cm^{-3}. Since the scattering cross sections of target ion and of residual gas molecule are the same order of magnitude, relative contributions to the detection counts from target beam and from gas are roughly represented by the ratio of n_t to n_g. In the present example, this ratio is 1.7×10^{-3}. This value means the following stability requirement: in order to obtain the data of beam-beam collisions by the method of subtraction of background counts, the fluctuation of beam current must be smaller than 1.7×10^{-3}. This requirement for beam stability is very difficult to be fulfilled for long time of data acquisition, and any discrimination technique must be devised. In the self crossed-beam method, there is possibility of background-discrimination by the use of energy differences of scattered ions as shown in the following.

IV. KINEMATICS RELATIONS

Consider the elastic scattering* of two particles having equal mass m and equal kinetic energy T incident each other with angle θ as shown in Fig. 3. The energies

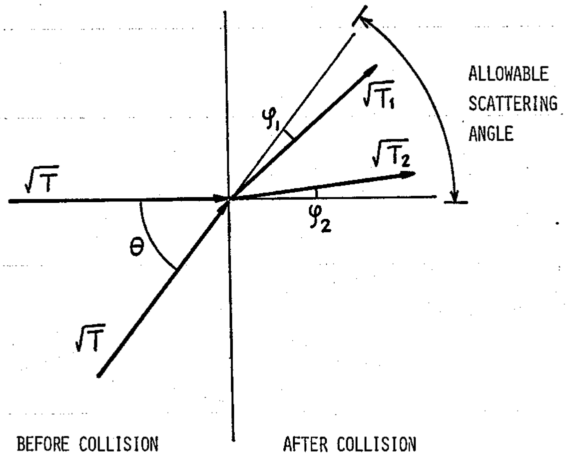

Fig. 3. Dynamics of two-body scattering in the frame of laboratory system.

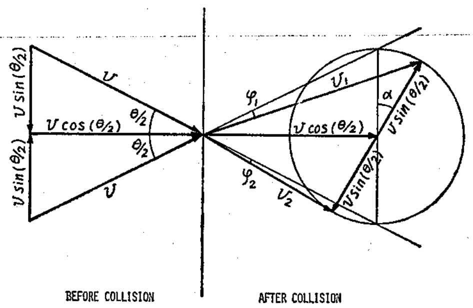

Fig. 4. Separation of the scattering process of the self crossed-beam into the center-of-mass motion and the relative motion.

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* Since the energy transfer in the charge changing collision is very small, this collision may be approximated as the elastic scattering in the consideration of kinematics.

T_1 and T_2 of scattered particles at the scattering angle φ_1 and φ_2 are given by

$$\sqrt{T_1}=\frac{1}{2}\sqrt{T}\{\cos\varphi_1+\cos(\theta-\varphi_1)\pm\sqrt{[\cos\varphi_1+\cos(\theta-\varphi_1)]^2-4\cos\theta}\} \quad (11)$$

Expression for T_2 is obtained from this equation by substituting φ_2 instead of φ_1. The relation of φ_1 and φ_2 may be clearly seen in Fig. 4. From the requirement of $\sqrt{T_1}$ and $\sqrt{T_2}$ to be real positive, it follows that the allowable scattering angle is limited as

$$0\lesssim\varphi_1\lesssim\theta \quad \text{and} \quad 0\lesssim\varphi_2\lesssim\theta. \quad (12)$$

This limitation of scattering angle is interesting in comparing with the scatterings from gas molecules. In the latter cases, all over angles are allowable for scatterings from the target molecules whose masses are not smaller than that of incident ion. When the crossing angle θ is larger than 90°, all over angles are allowable for scatterig of the self crossed-beam. One can easily see these behavior by dividing the collision process into the motion of center-of-mass and the relative motion as shown in Fig. 4. In Fig. 5

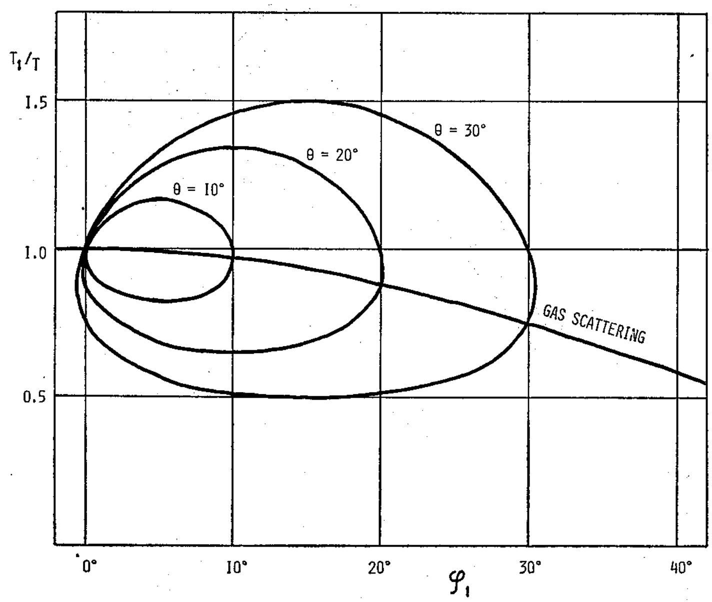

Fig. 5. Energetics of the self crossed-beam and of the gas scattering.

are illustrated the variations of the energies of scattered ions with the scattering angles for crossing angles of 10°, 20°, and 30°. For comparison, energetics of the scatterings from gas molecules is also, drawn.* In contrast to the decrease with $\cos^2\varphi_1$ for gas scattering, beam scattering give two energies, the one is larger and the other is smaller ones than the incident energy, at given angles within allowable range of scattering angle. The increment of energy of the larger energy ion is fairly large. For example, for cross-

* In the following, for simplicity, gas molecule is assumed to have the same mass as that of incident ion and to be at rest before collision in the frame of laboratory system.

ing angle of $\theta=20°$ the energy of the ion scattered in $\varphi_1=1°$ is 1.1 times as large as the incident energy. When the incident energy is 2 MeV, the energy of the ion from gas scattering is nearly equal to 2 MeV, while that from beam scattering is 2.2 MeV. The difference of these energies is sufficiently large to be discriminated with a SSD. With this energy discrimination it is possible to extract the collision events of the crossed–beam even if there are gas contributions of about 1000 times as large as that of true events.

The energy of relative motion for gas scattering, T_{0g}, is given by

$$T_{0g}=T/2, \qquad (13)$$

where T is the incident energy. On the other hand, that of self crossed-beam, T_{0b}, is given by

$$T_{0b}=2T\sin^2(\theta/2), \qquad (14)$$

For the illustrative example of $T=2$ MeV, these equations give $T_{0g}=1$ MeV and $T_{0b}=$ 60 keV, 240 keV and 540 keV for $\theta=10°$, 20°, and 30°, respectively. With small θ we can investigate the collisions of rather low colliding energies using the ions of large energies. This is the one of the merit of the self crossed-beam method.

The relations of the scattering angles in the center-of-mass frame (α) and in the laboratory frame (φ) are given by

$$\varphi=\alpha/2 \qquad \text{for gas scattering,} \qquad (15)$$

$$\tan\varphi=\frac{\cos\alpha}{\cot(\theta/2)+\sin\alpha} \qquad \text{for self crossed–beam.} \qquad (16)$$

The precission of the measurement of angle α in the self crossed-beam is rather poor.

V. SUMMARY

The self crossed-beam technique for investigation of ion-ion collisions is proposed. The method consists of the beam splitting following to the charge state conversion in the gas chamber and crossing of two beams at small angle. With energy discrimination of scattered ions, beam-beam collision events can be separated from beam-gas collision background. With beam currents of 1 μA of both the beams and residual gas pressure of the order of 10^{-8} Torr in the colliding region, one may obtain the data of beam-beam collision. The technical difficulty of the beam transportation in this method is not so hard to be overcome.

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