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REGULAR PAPERS

High Resolution Time-of-Flight Analyzer for Charge Exchange Process

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New time-of-flight energy analyzer for the fast neutral particles are described. The effect of the sweeping field on the ion packet length, the energy spread, and the direction divergency are discussed on the ground of experimental findings. Triple focusing conditions are given by combining the sweeping field with a sector type toroidal electric field. The toroidal field is realized by the application of the Matsuda plates which terminate a cylindrical condenser. A high resolution T-O-F analyzer is installed in the triple focusing geometry, and the time resolution of the analyzer is estimated to be 36,000.

1. Introduction

A typical fundamental energy analyzer for the neutral particles produced by charge exchange process consists of a field free straight flight tube; see Fig. 1. The flight time of the particle from the starting point to the detector gives the velocity of the particles. The time-of-flight method is almost exclusive for the determination of the kinetic energy change of the neutral products for the charge exchange collision, $A^+ + B \longrightarrow A + B^+ + \Delta E$, where ΔE is the exothermicity or endothermicity which is the energy converted from internal to translational freedom.

When the kinetic energy change spectra are measured at different scattering angles, the doubly differential cross sections are determined for the understanding of the dynamics of the charge exchange process.

The energy resolution, $T/\Delta T$, is usually about 500 for the straight type T-O-F analyzer. The detection efficiency of secondary electron emission type multiplier is very small for the neutral particles when the kinetic energy is less than 500 eV. When the kinetic energy is around 500 eV, the ambiguity for the energy spectra is in the order of 1 eV at FWHM, which is not sufficient resolution for the fine structures in the simple atomic collision process as

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well as for the polyatomic molecular system.

We have analyzed our experimental results and found that the limit of resolution for the straight type T-O-F analyzer is mainly depend on the ion packet length, the energy spread, and the direction divergency of the projectile ions, and that these are mainly owing to the incidental effects of the pulsing system with finite slit width. For the high energy resolution, the incidental effects are more influential than the initial energy spread of ions from the ion source.

W. P. Poschenrieder has proposed several types for multi-focusing T-O-F analyzer by combining straight flight space with sector fields.¹⁾ However, the proposed types assume a pulsed projectile beam and have no focusing property for the ion packet length.

We have analyzed the first order focusing properties of the T-O-F analyzer ion optics including the incidental effects of the sweeping field, and developed a new geometry for high resolution T-O-F analyzer. The energy resolution of the triple focusing T-O-F analyzer can be expected as better than 10,000 for the neutral product particles.

2. Experimental Problems for the High Resolution T-O-F Analyzer for the Neutral Particles

1) Straight flight path T-O-F analyzer

Figure 1 is the basic arrangement for the straight flight path T-O-F analyzer. The projectile ions from ion source are

Fig. 1. Schematic diagram of the straight path T-O-F analyzer.

accelerated and collimated through both slit 1 and 2. The steady ion beam is swept around slit 3 by means of the applied rectangular potential on the chopper electrodes, and pulsed ion packet enters through slit 3 into the collision chamber. Only small fraction of the projectile ions are converted into the high speed neutral particles owing to the charge exchange reaction with the target particles, and remaining projectile ions are swept away by the additional electric or magnetic field. When the fast neutral particle arrives at the detector mounted at the end of the straight flight path, it gives a pulse signal, STOP signal. The applied rectangular sweep voltage gives another pulse signal, START signal, and the time-of-flight difference for neutral particles is determined by the START-STOP method. The time-of-flight spectra of the product neutrals correspond to the ΔE . The precision of the flight time measurement is limited to about $1 \sim 2$ nano-sec depending on the scaling system. The best resolution of the straight type T-O-F analyzer is $0.3 \sim 0.5$ eV for the charge exchange scattering in "zero" angle

at the "low" energy region,²⁾ and this limit corresponds to the initial energy spread from the ion source.

2) Effect of beam sweeping field on the resolution

The effect of the sweeping field is originally to convert the steady ion beam into the ion packets through slit 3. We have analyzed our experimental results³⁾ and found that the sweeping field has the incidental effects on the velocity, the direction, and packet length of projectile ions in the collision chamber as far as the width

of steady ion beam is finite. When the sweeping field changes its polarity, ions travelling near the median trajectory between the sweeping electrodes receive additional small forward accelerations both near slit 2 and slit 3. This gives additional energy spread to the ion packet which enter the collision chamber. This additional energy spread is directly proportional to the beam width, the width of slit 2, and to the sweeping amplitude. The ion packet length is also directly proportional to the slit 3 width, however, the packet length reduces when the sweeping amplitude is

Fig. 2. Schematic arrangement for the triple focusing T-O-F analyzer.

increased. Both slit 2 width and slit 3 width must be as small as possible.

The installation of a monochromator for the initial ion energy spread does not make any essential improvement on the time resolution owing to the incidental effects of the sweeping field. The monochromatization reduces the intensity of projectile ions very much, so that it is necessary to increase the slit length in order to improve the transmissivity. The long slits reduce the angular resolution for the scattered particles which is another important property for the determination of doubly differential cross sections.

3. The Multiple Focusing

Directional focusing and vanishing energy-dependent dispersion in time-of-flight and imaging for the projectile ions are obtained by combining straight flight spaces with electric sector fields.¹⁾ However, when the sweeping field is combined to produce pulsed projectile, those geometry are not practical for the high resolution system because of the incidental effects of the sweeping field.

Figure 2 is a schematic arrangement for the triple focusing T-O-F analyzer with following components; 1) ion source, 2) main slit S_2 , 3) sweeping field, 4) electric sector field, 5) sweeping slit S_3 , 6) collision chamber, and 7) detector. The sweeping field is installed in front of the sector field, and the electrode

planes are parallel to the median line in the field free space and vertical to the median plane in the sector field. The direction of ion beam in the sweeping field must be limited narrowly by means of collimator slit. The median line of the projectile ion is perpendicular both to the entrance plane and the exit plane of the sector field. We have selected the toroidal electric field because of its large velocity dispersion. The main slit S_2 and the sweeping slit S_3 are at the focal points of the sector field.

The ion packet length is caused by the difference for the "starting" points of ions

Fig. 3. The relation between the relative distance of main slit from the entrance of sector field, l'/a , and deflection angle, ϕ , for the different field index c -values according to the directional focusing condition, eq. (1).

travelling near the median line between the sweeping electrodes at the moment of the polarity change of the rectangular potential applied on the electrodes. The starting position of an ion decides the exist angle of the ion at slit 3 in the arrangement of Fig. 1. When a sector field is installed between the sweeping field and slit 3, Fig. 2, it is possible to cancel the incidental effects of the sweeping field on the time-of-arrival of the particle at the detector. We have found following conditions for the first order triple focusing T-O-F analyzer.

The directional focusing condition is,

Fig. 4. The relation between the relative distance of detector from the exit of sector field, L/a , and deflection angle, ϕ , for the different field index c -values according to the velocity focusing condition, eq. (2).

$$\frac{l'}{a} = -\frac{1}{k} \tan \frac{k\phi}{2} + \frac{l_c}{2a} \left(\frac{k}{2 \sin k\phi} \right)^2, \quad (1)$$

where a is radius of the median trajectory in the toroidal sector field, l' is distance from the main slit S_2 to the entrance of the sector field, and l_c is one half length of the sweeping electrodes. And, $k = \sqrt{2-c}$, $c = a/r$, and r is radius of the curvature for the equipotential surface in the vertical direction at the median plane, and ϕ is the deflection angle.

The velocity focusing condition is,

$$\frac{L}{a} = -\frac{4}{k^3} (k\phi - \sin k\phi) - \phi - \left(\frac{l_c + l'}{a} \right), \quad (2)$$

where L is straight path length from exit of the deflector to the detector through the collision region and $(l_c + l')$ is distance from the center of the sweeping field to the entrance of the deflector.

The ion packet length focusing condition is,

$$\frac{eFa}{V_0} = \frac{k}{2} \tan \frac{k\phi}{2} + \left(\frac{l_c + l'}{a} \right) \sin k\phi, \quad (3)$$

where V_0 is kinetic energy of the initial ion, F is maximum field strength in the sweeping field and corresponds to the rectangular amplitude, and e is elementary electric charge. When the focusing conditions are satisfied, there remains only the aberration owing to the main slit width. Then the time resolution R_T is defined as the ratio of the time-of-flight from the center of the sweeping field to detector

to the spread of the time-of-arrival at the detector, then,

$$R_T = k \cdot \frac{a}{s},$$

$$K = -\frac{D}{a} \left(\frac{2}{k} \sin k\phi + \frac{eFa}{2V_0} \frac{l_c}{a} \right) \quad (4)$$

where s is width of main slit, and D is total flight path length from the center of the sweeping field to the detector.

The index c -value for the sector field is 0.0 for the cylindrical field and 1.0 for the spherical field. The components for cylindrical field electrodes are convenient at machine work. When the Matsuda plates terminates the top and bottom of a cylindrical electrode setup, the curvature of equipotential surface near the median line can be controlled by changing the electrostatic potential applied at the Matsuda plates, and the toroidal-like field is achieved with cylindrical electrodes.⁴⁾

Directional focusing condition, eq. (1), gives Fig. 3 for the relation of l'/a and ϕ for the different field index c -values.

Velocity focusing condition, eq. (2), gives Fig. 4 for the relation of L/a and ϕ . As for the value of $\frac{l_c + d'}{a}$ is constant, it is eliminated in Fig. 4. In order to realize high resolution for the time-of-flight of the fast neutral particles, the distance L must be as large as possible, because the precision of the time-of-flight measurement is limited to about 1 nano-sec. at the present scaling system.

Ion packet focusing condition, eq. (3), gives Fig. 5 for the relation of $\frac{Fa}{V_0}$ and ϕ . When the initial energy V_0 and radius a are given, it is to be desired that F value is small.

4. Conclusion

We have inspected Figs. 3, 4 and 5 collectively, and selected 270° for ϕ and 1.29 for the toroidal field index c -value. We selected 100 mm for the radius a of main path in the sector field. For the sweeping electrodes, the length $2l_c$ is 12 mm and the gap is 4 mm, and the $\frac{l_c + d'}{a}$ is 0.3, then $F = 0.0238 V_0/e$ (volt/cm). Then, for the main slit S_2 , 0.05×1.5 mm,

Fig. 5. The relation between the relative sweeping field strength, Fa/V_0 , and deflection angle, ϕ , for the different field index c -values according to the ion packet length focusing condition, eq. (3).

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Fig. 6. Schematic diagram of the triple focusing T-O-F analyzer.

l' is 271 mm, and for the sweeping slit S_3 , 0.3×1.4 mm, l'' is 270 mm. The focal point is 2392 mm from the slit 3.

With these geometry, and $a=100$, $s=0.05$, and $K=18.0$ for eq. (4), the estimated time resolution R_T is 36000.

Figure 6 is schematic diagram of the triple focusing T-O-F analyzer including the additional electrode system for steering the direction of steady ion beam and compensating the fringing effects at the deflector.

We have designed every parts for the analyzer in detail, and have assembled the whole instrument. Starting at the atmospheric pressure, the typical ultimate pressure of the analyzer is achieved below 3×10^{-7} mmHg in two hours by means of three differential exhaust systems for the

ion source, the toroidal electric field, and the collision chamber including the straight path tube. We have also assembled the scaling system for the START-STOP method including the home-made high voltage pulser and delay circuit and found that the time resolution is 1 nano-sec.

We have confirmed experimentally the usefulness of the Matsuda plates for the toroidal field since the beam width at slit 3 was found to be about 0.1 mm at FWHM for Li^+ in the toroidal condition. The angular resolution is about 0.1° with a window of 8 mm diameter in front of the detector which is rotatable for the different scattering angles.

It may be concluded that the new triple focusing T-O-F analyzer is promising for the high resolution studies on the charge

exchange process.

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Keywords

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