Recoil Momentum of Molecular Ions in Collisions of \( \text{Ar}^{6+} + \text{N}_2 \) at Energies below 300 eV/u

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Abstract. To elucidate the collision energy dependence of the recoil momentum of non-dissociated molecular ions for single electron capture collisions of \( \text{Ar}^{6+} \) with \( \text{N}_2 \) at collision energies from 7.5 to 240 eV/u. The measured collision energy dependence of the recoil momentum is compared with those obtained by a theoretical calculation using a deflection function with polarization potential. We obtain fairly good agreement between the measured and calculated results.

1. Introduction
Charge transfer processes involving ionization, electron capture, and molecular fragmentation in collisions of multiply charged ions (MCIs) with atoms and molecules play important roles not only in atomic physics but also in astrophysics and plasma physics [1, 2]. In particular, in the last few decades, the field of fragment processes of diatomic molecules in electron capture collisions of MCIs at energies above 1 keV/u has grown rapidly. In molecular fragmentation, it is understood that a diatomic molecular target undergoes Coulomb explosion after electron capture, and then, the two fragments fly in opposite directions, their kinetic energies given by the dissociation energy [3]. Kaneyasu et al.[4] and Ohyama-yamaguchi et al.[5] conducted studies on molecular fragmentation processes induced by MCI collisions at low energies below 1 keV/u. Kaneyasu et al. measured two fragment ions in a direction perpendicular to a projectile beam axis in coincidence with a projectile after double and triple electron capture. As a result, an interesting observation was reported that recoil momenta of non-dissociated molecular ions depend on collision energy.

In this study, in order to investigate the collision energy dependence of recoil momentum, we measure recoil momenta of the target of a \( \text{Ar}^{6+} + \text{N}_2 \) collision system at energies from 7.5 to 240 eV/u. The energy dependence of the measured recoil momentum is compared with those obtained by theoretical calculations performed using the Coulomb potential and the polarization potential.

2. Experiment
The experiment was performed using a mini-EBIS (electron beam ion source) atomic collision facility of Nara Women’s University [6, 7]. MCI beams extracted from the mini-EBIS were made to collide with effusive \( \text{N}_2 \) gas in the collision region. Outgoing projectile ions from the collision region were analyzed using a parallel-plate electrostatic analyzer with a two-dimensional...
Figure 1. TOF spectra of molecular ions and fragment ions in collisions of Ar\(^{6+}\) + N\(_2\) at energies from 7.5 to 240 eV/u.

position sensitive detector. Two fragment ions or non-dissociated molecular ions were detected separately by two time-of-flight (TOF) analyzers installed at 90° and -90°, respectively, with respect to the projectile beam axis. It should be noted that no-extraction fields in the collision region made it possible to identify the recoil momentum of target ions after collisions at low energy. In this experiment, we measured the time difference between the projectile ions and the target ions. All signals were directly recorded as a single event by a PC, using digitizers.

3. Results and Discussion

Single electron capture (SC) processes of Ar\(^{6+}\) + N\(_2\) are given as follows:

\[
\text{Ar}^{6+} + \text{N}_2 \rightarrow \text{Ar}^{5+}(nl) + \text{N}_2^+ + Q_1, \\
\rightarrow \text{Ar}^{5+}(n'l') + \text{N}^+ + \text{N} + Q_2, \\
\rightarrow \text{Ar}^{5+}(n''l'') + \text{N}_2^{2+} + e^- + Q_3, \\
\rightarrow \text{Ar}^{5+}(n''l'''m') + \text{N}^+ + \text{N}^+ + e^- + Q_4.
\]

Reaction(1) indicates that Ar\(^{6+}\) ions capture an electron into the energy state of Ar\(^{5+}(nl)\) from a N\(_2\) molecule with reaction energy \(Q_1\). Reaction(2) represents a molecular dissociative process occurring via reaction(1). Reactions(3) and (4) represent transfer ionization processes occurring via double electron capture with non-dissociative and dissociative processes of N\(_2^{2+}\) ions, respectively.

Measured TOF spectra of SC processes in collisions of Ar\(^{6+}\) with N\(_2\) at energies from 7.5 to 240 eV/u are shown in Figure 1. At first glance, the peak positions of N\(^+\) fragment ions appear to be independent of the collision energy but those of non-dissociated N\(^2+\) and N\(_2^{2+}\) molecular ions appear to depend on the collision energy. The correlation diagram (Newton Diagram) of the velocity vectors of projectile ions and targets in the laboratory frame and the center of mass (C-M) frame is shown in Figures 2(a) and 2(b). In the Newton Diagram, vectors \(\vec{v}_i\) and \(\vec{v}_t\) are the velocities of projectile and target molecules, respectively, after inelastic collisions in the laboratory frame. Vectors \(\vec{v}_C\) and \(\vec{v}_r\) are the velocity for the center of mass and the relative velocity between projectile and target ions in the C-M frame, respectively. Experimentally, the
Figure 2. Correlation diagram (Newton Diagram) of velocity vectors in the laboratory frame and the C-M frame for non-dissociative process (a) and dissociative process (b). The θ_{lab} and Θ_{CM} are scattering angles in the laboratory frame and the C-M frame, respectively.

vectors for N_{2}^{+} and N_{2}^{2+} molecular ions correspond to \vec{v}_t and the vector for the N^{+} fragment ion corresponds to \vec{v}_f or \vec{v}_0. Here, \vec{v}_f and \vec{v}_0 are given by \vec{v}_f = \vec{v}_t + \vec{v}_1 and \vec{v}_0 = \vec{v}_t + \vec{v}_2, respectively, where \vec{v}_1 and \vec{v}_2 are the dissociation velocity vectors due to Coulomb explosion. In the case of a homonuclear diatomic molecule, \vec{v}_1 is equal to -\vec{v}_2. In general, the velocity vectors of molecular ions, \vec{v}_t, depend on the collision energy, but those of fragment ions, \vec{v}_1 and \vec{v}_2, are independent of the collision energy. Furthermore, the dissociation velocity vectors \vec{v}_1 and \vec{v}_2 are considerably larger than the velocity vector \vec{v}_t of the non-dissociated molecular ion, i.e., \vec{v}_f \cong \vec{v}_1 and \vec{v}_0 \cong \vec{v}_2. Therefore, the energy dependence of the experimental TOF spectra can be qualitatively explained by using the velocity vectors in the Newton Diagram.

In order to elucidate the collision energy dependence of recoil momenta, we compare experimental recoil momenta with theoretical ones. The experimental recoil momentum\( (P_{\perp}) \) is estimated as \( P_{\perp} = \mu v'_{t} \sin \Theta_{CM} \) (see Figures 2(a) and 2(b)), where \( \mu, v'_{t}, \) and \( \Theta_{CM} \) are the reduced mass, relative velocity, and scattering angle, respectively, in the C-M frame. Assuming \( \sin \Theta_{CM} \approx \Theta_{CM} \) and noting the energy conservation before and after the collision, \( E'_{CM} = E_{CM} + Q, \) and the recoil momentum is expressed as \( P_{\perp} \propto \sqrt{E'_{CM}} \Theta_{CM}. \) We calculate the energy dependence of recoil momentum by using the deflection function \( d\varphi/dr \) in the classical trajectory equation with interaction potential \( V(r), \) which is given as

\[
\frac{d\varphi}{dr} = \pm \frac{b}{r^2} \sqrt{1 - \frac{b^2}{r^2} - \frac{V(r)}{E'_{CM}}},
\]

where \( \varphi, r, \) and \( b \) are the deflection angle, internuclear distance, and impact parameter, respectively [8]. In the case of \( V(r) \) in powers of \( r, V(r) = C/r^s, \) we obtain \( \Theta_{CM} \propto (b^s E'_{CM})^{-1}. \)

It is well known that electron transfer occurs at some particular internuclear distance \( R, \) and in this study, we have used \( R \) of the closest approach. Practically, \( R \) is calculated by the classical over-barrier model [9, 10] using the Atomic Spectra Database of the NIST [11]. According to this model, \( R \) is given by \( R = (2\sqrt{q} + q)/I_t, \) where \( q \) is the charge state of the incident ion and \( I_t \) is the \( t \)-th ionization potential of the target. The relation between \( b \) and \( R \) is given by \( b^2 = R^2(1 - V(R)/E'_{CM}). \)

In the present calculation, we have theoretically estimated the energy dependence of recoil momentum using two types of potentials—the Coulomb potential and the polarization potential. In the case of the Coulomb potential \( (s = 1), \) assuming \( b \approx R, \) \( P_{\perp} \) is expressed as follows:

\[
P_{\perp} \propto (\sqrt{E'_{CM}} R)^{-1}.
\]

On the other hand, for the polarization potential \( (s = 4), \) \( V(r) = -(\alpha q^2)/(2r^4), \) and \( P_{\perp} \) is

\[
P_{\perp} \propto (\sqrt{E'_{CM}} R)^{-1}.
\]
expressed as follows:

\[ P_\perp \propto \left( \sqrt{E_{CM}'} R^4 \left[ 1 + \frac{\alpha q^2}{2 R^4 E_{CM}'} \right]^2 \right)^{-1}, \]  

where \( \alpha \) is the polarizability of \( \text{N}_2 \). Figures 3(a) and 3(b) show the experimental and theoretical energy dependences of recoil momenta of molecular ions. The experimental dependence for \( \text{N}_2^{2+} \) is good agreement with the theoretical dependence obtained using the polarization potential rather than that using the Coulomb potential. The relative dependence in the case of \( \text{N}_2^+ \) agrees with the theoretical dependence obtained using the polarization potential only at low energies below 100 eV/u. This suggests that the polarization potential plays a crucial role in the low-energy region. The disagreement between experimental and theoretical results of \( \text{N}_2^{2+} \) at high energies above 100 eV/u may be due to the fact that internuclear distances vary with an increase in the collision energy, although we have used energy-independent \( R \) in this model.

4. Conclusion

We have experimentally measured the recoil momentum of molecular ions for SC collisions and compared it with the theoretical one in order to elucidate the collision energy dependence of the recoil momentum. The experimental energy dependence of recoil momenta of \( \text{N}_2^{2+} \) and \( \text{N}_2^+ \) are in agreement with the theoretical dependence obtained using polarization potential at energies below 100 eV/u. It is concluded that polarization potential plays a crucial role in the low-energy region. To gain a better understanding of the energy dependence of recoil momentum, coincidence measurements of TOF spectra with energy gain spectra of the projectile after the collision are necessary.

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