Ion-atom cold collision: Formation of cold molecular ion by radiative processes

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We discuss theoretically ion-atom collisions at low energy and predict the possibility of formation of cold molecular ion by photoassociation. We present results on radiative homo- and hetero-nuclear atom-ion cold collisions that reveal threshold behaviour of atom-ion systems.

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1. INTRODUCTION

Molecular ions are important for a variety of fundamental studies in physics. For instance, it is proposed that cold molecular ions would be useful for measuring electron dipole moment (EDM) \(^1\), \(^2\). Study of cold molecular ions has relevance in diverse areas such as metrology \(^3\), \(^4\) and astrochemistry \(^5\). Recently, molecular ions are cooled into ro-vibrational ground states by all optical \(^6\), laser and sympathetic cooling methods \(^7\), \(^8\). A large variety of diatomic and triatomic molecular ions are also cooled by sympathetic method \(^9\), \(^10\), \(^11\). Other methods such as photoassociative ionisation \(^12\), \(^13\), buffer gas \(^14\), and rotational cooling \(^15\) have been widely used for producing low energy molecular ions. Since cooling of neutral atoms and atomic ions down to sub-milliKelvin temperature regime is possible with currently available technology of laser cooling, it is now natural to ask ourselves: Is it possible to form cold molecular ion by atom-ion cold collision? Recent progress in developing hybrid traps \(^16\), \(^17\) where both atomic ions and neutral atoms can be simultaneously confined provides new opportunity for exploring ion-atom quantum dynamics and charge transfer reactions at ultralow temperatures. As neutral cold atoms can be photoassociated \(^18\) into cold dimers, the same association method should also apply to atoms colliding with atomic ions forming cold molecular ions. Understanding ion-atom cold collision \(^19\), \(^20\), \(^21\), \(^22\), \(^23\), \(^24\), \(^25\) is important for realizing a charged quantum gas, studying charge transport \(^26\) at low temperature, exploring polaron physics \(^27\), \(^28\) and producing ion-atom bound-states \(^29\), \(^30\) and cold molecular ions \(^31\).

Although in recent times there have been several studies on ion-atom cold collisions, formation of molecular ion by photoassociation (PA) is yet to be demonstrated. There are qualitative differences between atom-atom and ion-atom PA. In contrast to atom-atom PA, hetero-nuclear atom-ion PA is accompanied by charge transfer. Neutral atom-atom PA involves excited diatomic molecular states which in the separated-atom limit correspond of one ground (S) atom and the other excited (P) atom. Hetero-nuclear atom-ion PA may involve excited molecular...
l lar states which asymptotically correspond to separated atom and ion both belonging to $S$ electronic states. The long-range potentials of ion-atom system behave quite differently from those of neutral atom-atom system.

Here we show that it is possible to form translationally and rotationally cold molecular ion by PA. We specifically focus on hetero-nuclear radiative processes. However, we study in general both homo- and hetero-nuclear ion-atom cold collisions to reveal the contrast between the two processes. At ultralow collision energies, radiative charge transfer processes dominate over non-radiative ones. Starting from a cold alkaline metal earth ion and an ultracold alkali atom (such as an atom of alkali Bose-Einstein condensates) as the initial reactants, formation of ground state molecular ion requires a three-step radiative reaction process. In the first step, the ion-atom pair in the continuum of the excited electronic state undergoes radiative charge transfer to the continuum of the ground electronic state. In the second step, the ground continuum ion-atom pair is exposed to laser radiation of appropriate frequency to photoassociate them into excited molecular ion. In the third and final step, another laser is used to stimulate the excited molecular ion to deexcite into a particular rovibrational level of ground electronic state. Since molecular ion is formed from initially cold atom and ion, the molecular ion remains translationally and rotationally cold. One noteworthy feature of this method is the selectivity of low lying rotational level. We present selective results on elastic and radiative charge transfer scattering cross sections for both homo- and hetero-nuclear ion-atom collisions. For model potentials of (LiBe)$^+$ system, we calculate the PA rate of formation of LiBe$^+$ molecular ion.

This paper is organised in the following way. In Sec.2, we describe our model focussing on possible elastic and inelastic processes. Results are presented and discussed in Sec.3. In the last section we draw our conclusions.
are smoothly joined by spline.

The short range and long range parts of the potentials + 1
+ 2 2 lision between Be + Li systems, the excited state potential 2 + + is given by

given by

ection. The qualitative feature of this long range interac-
tion is dominated by the long range polarization interac-
ction. The polarisation interaction falls off much more slowly than van der Waals interaction abilities of atom concerned. The polarisation interaction is governed by effective length which is

given by

\[ V(r) = -\frac{1}{2} \left( \frac{C_4}{r^4} + \frac{C_6}{r^6} + \cdots \right) \] (1)

where \( C_4 \), \( C_6 \) correspond to dipole, quadrupole polaris-
abilities of atom concerned. The polarisation interaction falls off much more slowly than van der Waals interaction which represents the long range part of interaction between neutral atoms. Hence collision between atom and ion is dominated by the long range polarization interaction. The qualitative feature of this long range interaction of atom-ion is governed by effective length which is given by

\[ \beta_4 = \sqrt{2\mu C_4/\hbar^2} \] where \( \mu \) is the reduced mass. The short range and long range parts of the potentials are smoothly joined by spline.

Since Li + may be formed due to charge transfer collision between Be + and Li, we need to consider the interaction between this Li + and other Li atoms present in the condensate. The data for \( 2\Sigma^+_g \), \( 2\Sigma^+_u \) and \( 2\Pi_u \) potentials of Li2 + are taken from Ref. 39. Dissociation energy \( D \), equilibrium position \( r_e \) and effective range \( \beta_4 \) of the ground and excited state potentials of (LiBe)+ and LiLi+ systems are given in Table I. A comparison of potentials of these two systems reveals that ground state potential \( 1\Sigma^+_g \) of (LiBe)+ is much shallower than \( 2\Sigma^+_g \) potential of Li2 +. The equilibrium positions of both ground and excited state potentials of (LiBe)+ system lie almost at the same separation. Unlike the asymptotic behavior of the excited \( 2\Sigma^+_u \) potential of (LiBe)+ system, the excited state potential \( 2\Pi_u \) of homonuclear Li2 + molecular ion asymptotically corresponds to one Li + ion in the electronic ground S state and one neutral Li atom in the excited P state. The equilibrium positions \( r_e \) of ground and excited state potentials of Li2 + system are shifted by 1.5 Bohr radius. For of (LiBe)+ system, we notice that \( \beta_4 \) of excited \( (2\Sigma^+_g) \) potential is almost twice that of the ground \( (1\Sigma^+_g) \) potential.

Let us first consider cold collision between Li and Be + with both of them being in \( 2\Sigma \) electronic state. So, our initial system corresponds to the continuum of \( 2\Sigma^+_g \) potential. Due to charge transfer collision neutral Be atom and Li + ion are generated. In the separated two-particle limit of this system, dipole transition to ground state at the single particle level is forbidden. Furthermore, since at low energy non-radiative charge transfer is suppressed, the dominant inelastic channel is the radiative charge transfer transition that occurs at intermediate or short separations. Electronic transition dipole moment between two ionic molecular electronic states vanishes at large separation. Therefore, transitions occur at short range where hyperfine interaction is negligible in comparison to central(Coulombic) interaction. The total molecular angular momentum is given by

\[ \vec{J} = \vec{S} + \vec{L} + \vec{\ell} \] where \( S \) and \( L \) are the total electronic spin and orbital quantum number, respectively; and \( \ell \) stands for the angular quantum number of the relative motion of the two atoms. For the particular model for (LiBe)+ system chosen here, we have \( L = 0 \) and \( S = 0 \) for both the ground and the excited electronic states. Thus here the total angular momenta for both the ground and excited states are given by \( J = \ell \). However, it is more appropriate to denote total angular quantum number of a molecular bound state by \( J \) and that of the continuum or collisional state of this atom-ion system by simply \( \ell \). The parity selection rule for the electric dipole transition between the ground and excited states dictates \( \Delta J = \pm 1 \).

To investigate ion-atom elastic scattering and free-bound transitions, we need to calculate continuum wave functions which are obtained by solving the partial wave

\[ \begin{align*}
\text{FIG. 5: (Color online)Same as in Fig.4 but for Li}^+ + \text{ Be } (1\Sigma^+). \\
\begin{align*}
\text{FIG. 6: (Color online)Partial wave cross sections for Li}^+ + \text{ Be } (1\Sigma^+) \text{ collision are plotted as a function of } E \text{ (in K) for } \ell = 0 \text{ (solid) and } \ell = 2 \text{ (dashed).}
\end{align*}
\end{align*} \]
Schrödinger equation given by
\[ \left[ \frac{d^2}{dr^2} + k^2 - \frac{2\mu}{\hbar^2} V(r) - \frac{\ell(\ell + 1)}{r^2} \right] \psi_\ell(kr) = 0 \quad (2) \]
where \( r \) is the ion-atom separation. The wave function \( \psi_\ell(kr) \) has the asymptotic form \( \psi_\ell(kr) \sim \sin[kr - \ell\pi/2 + \eta] \) with \( \eta \) being the phase shift for \( \ell \)-th partial wave. The total elastic scattering cross section is expressed as
\[ \sigma_{el} = \pi \left( \frac{\mu c^2}{\hbar^2} \right)^\frac{\ell}{2} \left( 1 + \frac{\pi^2}{16} \right) E^{-\frac{\ell}{2}} \quad (3) \]
where \( k = \sqrt{2mE/\hbar^2} \). As the energy gradually increases more and more partial waves start to contribute to total elastic scattering cross sections and the scattering cross section at large energy is

\[ \sigma_{el} \sim \pi \left( \frac{\mu c^2}{\hbar^2} \right)^\frac{\ell}{2} \left( 1 + \frac{\pi^2}{16} \right) E^{-\frac{\ell}{2}} \quad (4) \]

As \( k \to 0 \), according to Wigner threshold laws \( \eta_\ell(k) \sim k^{2\ell+1} \) if \( \ell \leq (n-3)/2 \) with \( n \) being the exponent of long-range potential behaving as \( \sim 1/r^n \) as \( r \to \infty \). If \( \ell > (n-3)/2 \) then the threshold law is \( \eta_\ell(k) \sim k^{n-2} \). Since the long-range part of ground as well as excited ion-atom potentials goes as \( \sim 1/r^4 \) as \( r \to \infty \), Wigner threshold laws tell us that s-wave \( (\ell = 0) \) ion-atom scattering cross section should be independent of \( k \) while all the higher partial wave scattering cross sections should go as \( \sim k^2 \) in the limit \( k \to 0 \).

Ion-atom inelastic collisions are mainly of two kinds - charge transfer reactions and radiative- or photoassociative transfer [40–44]. The radiative charge transfer cross section [40–42] is given by
\[ \sigma_{ct} = \int_{E_{min}}^{E_{max}} \frac{d\sigma_{ct}}{d\omega} d\omega \quad (5) \]

where \( \omega \) is the angular frequency of emitted photon and
\[ \frac{d\sigma_{ct}}{d\omega} = \frac{8\omega^3\pi^2}{3e^2k_n^2} \sum_{\ell} [\ell M^2_{\ell,\ell-1}(k_m, k_n) + (\ell + 1)M^2_{\ell,\ell+1}(k_m, k_n)] \quad (6) \]

\[ D(r) \] is the magnitude of the molecular transition dipole moment. Here \( k_m = \sqrt{2\mu[E-V_m(\infty)]} \) and \( k_n = \sqrt{2\mu[E-V_n(\infty)-\hbar\omega]} \) are the momentum of entrance and exit channels, respectively, and \( E \) is collision energy of entrance \((m)\) channel. \( V_m \) and \( V_n \) are the potential energies of the entrance \((m)\) and exit \((n)\) channels, respectively. \( \psi_i^\ell(k_i r) \) is the wave function of \( \ell \)-th partial wave for \( i \)-th channel of momentum \( k_i \). The total radiative transfer [41] from the upper state \((m)\) to the lower state \((n)\) is given by
\[ \sigma_{ct} = \frac{\pi}{k_m^2} \sum_{\ell} (2\ell + 1) \left[ 1 - \exp(-4\zeta_\ell) \right] \quad (8) \]

where
\[ \zeta_\ell = \frac{\pi}{2} \int_0^\infty \left| \psi_i^\ell(k_m r) \right|^2 A_{nm}(r) dr \quad (9) \]

is a phase shift and
\[ A_{nm}(r) = \frac{4}{3} D^2(r) \frac{|V_n(r) - V_m(r)|^3}{e^3} \quad (10) \]
is the transition probability.

The ground continuum atom-ion pair, formed by radiative charge transfer process, can be photoassociated.
orbital angular momentum of the excited and ground where Λ′ of (LiBe) system is plotted against collisional energy E (in mK).

FIG. 9: Charge transfer scattering crosssection \( \sigma_{el} \) (in a.u.) of (LiBe) system is plotted against collisional energy E (in mK).

to form excited molecular ion. This process is basically one photon PA process. The photoassociation rate coefficient is given by

\[
K_{PA} = \left\langle \frac{\pi v_r}{k^2} \sum_{\ell=0}^{\infty} (2\ell + 1) |S_{PA}(E, \ell, \omega_L)|^2 \right\rangle
\]

(11)

where \( v_r = \hbar k/\mu \) is the relative velocity of the two particles and \( \langle \cdots \rangle \) implies averaging over thermal velocity distribution. Here \( S_{PA} \) is S matrix element given by

\[
|S_{PA}|^2 = \frac{\gamma \Gamma_\ell}{\delta_E^2 + (\Gamma_\ell + \gamma)^2/4}
\]

(12)

where \( \delta_E = E/\hbar + \delta_{el}, \delta_{el} = \omega_L - \omega_{el} \) with \( E_{el} = \hbar \omega_{el} \) being binding energy of the excited ro-vibrational state, \( \omega_L \) being the laser frequency and \( \gamma \) the spontaneous line width. Thus PA rate is primarily determined by partial wave stimulated line width \( \Gamma_\ell \) given by

\[
\hbar \Gamma_\ell = \frac{8\pi^2 J}{3\epsilon_0 c} h(J, \ell) |D_{\ell, l}|^2
\]

(13)

where

\[
D_{\ell, l} = \langle \phi_{\ell, l} | D(r) | \psi_\ell(kr) \rangle
\]

(14)

is the radial transition dipole matrix element between the continuum and bound state wave functions \( \psi_\ell(kr) \) and \( \phi_{\ell, l}(r) \), respectively. \( J \) is the intensity of laser, \( c \) is the speed of light and \( \epsilon_0 \) is the vacuum permittivity. Here \( h(J, \ell) \) is Hönig London factor \([42]\) which in the present context is given by

\[
h(J, \ell) = (1 + \delta_{\Lambda^0 \Lambda'} + \delta_{\Lambda'' \Lambda'} - 2\delta_{\Lambda^0 \Lambda''})
\]

\[
(2J + 1)(2\ell + 1) \left( \begin{array}{c} J \\ \Lambda'\Lambda'\Lambda'' \end{array} \right)
\]

(15)

where \( \Lambda' \) and \( \Lambda'' \) are the projections of the total electronic orbital angular momentum of the excited and ground states, respectively, on molecular axis and \( (\cdots) \) is the Wigner 3j symbol. The spontaneous line width \( \gamma \) of the excited state \((\nu, J)\) is given by

\[
\hbar \gamma = \frac{1}{3\pi \epsilon_0 c^3} \int \frac{(\Delta E)^3}{(\Delta_{\nu', J'} \langle \phi_{\nu, J} | D(r) | \phi_{\nu', J'} \rangle)^2} dE
\]

(16)

where \( \Delta E = (E_{\nu, J} - E)/\hbar, \Delta_{\nu', J'} = (E_{\nu, J} - E_{\nu', J'})/\hbar, |\psi_E\rangle \) is the scattering wave function and \( |\phi_{\nu', J'}\rangle \) stands for all the final bound states to which the excited state can decay spontaneously.

3. RESULTS AND DISCUSSION

Standard renormalized Numerov-Cooley method \([46]\) is used to calculate the bound and scattering state wave functions. The molecular transition dipole matrix element of (LiBe) system is calculated using GAMESS. This matrix element strongly depends upon separation and goes to zero at a large \( r \) as shown in Fig.3. In Figs. 4 and 5, we have plotted the excited and ground state elastic scattering cross section \( \sigma_{el} \) as a function of energy \( E \) for Li + Be\(^+\) and Li\(^+\) + Be collisions, respectively. We find that at least 35 partial waves are required to get converging results on elastic scattering for energies higher than 1 \( \mu \)K. In our calculations we have used 51 partial waves. At high energies, for both the cases, \( \sigma_{el} \) decreases as \( E^{-\frac{3}{4}} \). The proportionality constant \( c \) in the expression \( \sigma_{el}(E \to \infty) = c E^{-\frac{3}{4}} \) calculated using Eq. 13 for excited 2\(^1\)\( \Sigma^+ \) and ground 1\(^1\)\( \Sigma^+ \) potentials are 2936 and 1091 a.u., respectively, whereas linear fit to \( \sigma_{el} \) vs. \( E \) curves provides \( c = 3548 \) and 1335 a.u., respectively. Figures 6 and 7 exhibit s- and d-wave partial scattering cross section as a function of energy for Li\(^+\)+Be and Li+Li\(^+\) collisions, respectively. These figures show that
the Wigner threshold behavior begins to set in as the collision energy decreases below 0.1 μK. In Fig. 8, we have plotted total elastic scattering cross section for Li+Li+ collisions in $2\Sigma_g^+$ and $2\Sigma_u^+$ potentials.

Starting from the low energy continuum state of Li + Be+ collision in the $2\Sigma^+$ potential, there arise two possible radiative transitions by which the system can go to the ground electronic state $1\Sigma^+$. One is continuum-continuum and the other is continuum-bound dipole transition. The transition dipole moment as a function of separation as shown in Fig. 3 shows that the dipole transition probability will vanish as the separation increases above 20$\alpha_0$. So, a dipole transition has to take place at short separations. Let us consider radiative transfer processes from the upper ($2\Sigma^+$) to the lower ($1\Sigma^+$) state of (LiBe)$^+$. We then need to apply the formulae (4) and (5) where $m \equiv 2\Sigma^+$ and $n \equiv 1\Sigma^+$ in our case. Continuum-continuum charge transfer cross section $\sigma_{ct}$ between $2\Sigma^+$ and $1\Sigma^+$ states of (LiBe)$^+$ system is plotted against $E$ in Fig.9. We evaluate the photoassociative (continuum-bound) transfer cross section $\sigma_{ct}$ from the total radiative transfer cross section $\sigma_{rt}$ calculated using the formula (5). At energy $E = 0.1$ mK, $\sigma_{ct}$ and the photoassociative transfer cross section are found to be 10.39 a.u. and 0.03 a.u., respectively. Thus we infer that the continuum-continuum radiative charge transfer process dominates over the radiative association process. Also, we notice that $\sigma_{ct}$ is smaller than both the excited and ground state elastic scattering cross sections $\sigma_{el}$ (as given in Fig.4 and 5, respectively) by several orders of magnitude.

Molecular dipole transitions between two ro-vibrational states or between continuum and bound states are governed by Franck-Condon principle. According to this principle, for excited vibrational (bound) states, bound-bound or continuum-bound transitions primarily occur near the turning points of bound states. In general, highly excited vibrational state wave functions of diatomic molecules or molecular ions have their maximum amplitude near the outer turning points. Spectral intensity is proportional to the overlap integral. This means that the spectral intensity for a continuum-bound transition would be significant when the continuum state has a prominent node near the outer turning point of the bound state. For transitions between two highly excited bound states, Franck-Condon principle implies that the probability of such transitions would be significant when the outer turning points of these two bound states lie nearly at the same separation. The upper panel of Fig.10 shows the variation of the square of fransk Condon overlap integral for both the ground s-wave ($\ell = 0$) scattering and the excited ro-vibrational ($v = 26, J = 1/2$) states of Li-Li$^+$ system as a function the collision energy $E$. The lower panel of Fig.10 displays the same as in the upper panel but for (LiBe)$^+$ system with $v = 68$ and $J = 1$. The excited ro-vibrational state $v = 26, J = 1/2$ of Li-Li$^+$ is very close to dissociation threshold while the excited ro-vibrational state $v = 68, J = 1$ of (LiBe)$^+$ system is a deeper bound state. Thses two excited states are so chosen such that free-bound Franck-Condon overlap integral for both the systems become significant. Comparing these two plots, we find that $|\eta(J)|^2$ of Li-Li$^+$ system is smaller than that of (LiBe)$^+$ system by seven orders of magnitude. To understand why the values $|\eta(J)|^2$ for the two systems are so different, we plot the the energy-normalized s-wave ground scattering and the bound state wave functions of (LiBe)$^+$ system in Fig.11 and those of Li-Li$^+$ system in Fig.12. A comparison of Figs.11 and 12 reveals that, while in the case of (LiBe)$^+$ the maximum of the excited bound state wave function near the outer turning point coincides nearly with a prominent antinode of the scattering wave function, in the case of Li-Li$^+$ the maximum of the bound state wave function near the outer turning point almost coincides with a minimum.
TABLE II: Ro-vibrational energy \((E_{vJ})\), inner \((r_i)\) and outer turning points \((r_o)\) of two selected bound states of \((\text{LiBe})^+\) molecular ion - one bound state in excited \((2^1\Sigma^+)\) and the other in ground \((1^1\Sigma^+)\) potential. The energy \(E_{vJ}\) is measured from the threshold of the respective potential.

| Potential | \(v\) | \(J\) | \(E_{vJ}\) (a.u.) | \(r_i\) (a.u.) | \(r_o\) (a.u.) |
|-----------|-----|-----|----------------|-------|-------|
| \(2^1\Sigma^+\) | 68 | 1 | \(-3.30 \times 10^{-3}\) | 3.4 | 16.3 |
| \(1^1\Sigma^+\) | 29 | 0 | \(-2.55 \times 10^{-3}\) | 3.8 | 16.6 |

(node) of the scattering wave function. These results indicate that the possibility of the formation of excited LiLi\(^+\) molecular ion via PA is much smaller than that of \((\text{LiBe})^+\) ion. We henceforth concentrate on PA of \((\text{LiBe})^+\) system only.

We next explore the possibility of PA in Li\(^+\)-Be cold collision in the presence of laser light. As discussed before, continuum-bound molecular dipole transition matrix element depends on the degree of overlap between continuum and bound states. PA rate \((11)\) is proportional to the square of free-bound radial transition dipole moment element \(|D_{vJ}|^2\). In Fig. 13 we plot \(|D_{vJ}|^2\) against \(E\) for s- \((\ell = 0)\) and d-wave \((\ell = 2)\) ground scattering states and \(v = 68\), \(J = 1\) excited molecular state. It is clear from this figure that the contributions of both \(\ell = 0\) and \(\ell = 2\) partial waves are comparable above energy corresponding to 0.1 mK. At lower energy \((E < 0.1\) mK), only s-wave makes finite contribution to the dipole transition. Figure 14 exhibits \(|D_{vJ}|^2\) as a function of \(E\) for the transition from s-wave \((\ell = 0)\) scattering state of the excited \((2^1\Sigma^+)\) continuum to the ground \((1^1\Sigma^+)\) ro-vibrational state with \(v = 36\), \(J = 1\). A comparison between the Figs.13 and 14 reveals that the probability for the transition from the upper continuum to the ground bound state is smaller by several orders of magnitude than that from ground continuum to an excited bound state. In Fig 15, we have plotted the rate of photoassociation \(K_{PA}\) (in \(\text{cm}^3\ \text{s}^{-1}\)) of \((\text{LiBe})^+\) is plotted against temperature (in K) at \(I = 1\) \(\text{W/cm}^2\) and \(\delta_{vJ} = \omega_L - \omega_{vJ} = 0\).
states is possible or not, we calculate Rabi frequency $\Omega$ given by

$$\hbar \Omega = \left( \frac{I}{4 \pi \epsilon_0} \right)^{\frac{1}{2}} |\langle v, J | \tilde{D}(r) \hat{\epsilon}_L | v', J' \rangle|$$  \hspace{1cm} (17)$$

where $\hat{\epsilon}_L$ is the unit vector of laser polarization and $|v, J\rangle$ and $|v', J'\rangle$ are the two bound states with $\langle r | v, J \rangle = \phi_{v,J}(r)$. Rabi frequency corresponding to this bound-bound transition is found to be 285 MHz for laser in-bound state calculated using the formula (16), we infer the spontaneous line width $\gamma$ and where $\hat{I}$ of laser intensity $I$ (in kW/cm$^2$) at temperature $T = 0.1$ mK with laser tuned at PA resonance.

![Image of graph showing $K_P$ (in cm$^3$s$^{-1}$) of (LiBe)$^+$ as a function of laser intensity $I$ (in kW/cm$^2$) at temperature $T = 0.1$ mK with laser tuned at PA resonance.](image)

FIG. 16: $K_P$ (in cm$^3$s$^{-1}$) of (LiBe)$^+$ is plotted as a function of laser intensity $I$ (in kW/cm$^2$) at temperature $T = 0.1$ mK with laser tuned at PA resonance.

4. CONCLUSION

In conclusion, we have shown that alkaline earth metal ions immersed in Bose-Einstein condensates of alkali atoms can give rise to a variety of cold chemical reactions. We have analyzed in detail the elastic and inelastic processes that can occur in a system of a Beryllium ion interacting with cold Lithium atoms. We have predicted the formation of translationally and rotationally cold (LiBe)$^+$ molecular ion by photoassociation. Theoretical understanding of low energy atom-ion scattering and reactions may be important for probing dynamics of quantum gases. Since both Bose-Einstein condensation and fermionic superfluidity have been realized in atomic gases of Lithium, understanding cold collisions between Lithium and Beryllium ion may be helpful in probing both bosonic and fermionic superfluidity. In particular, this may serve as an important precursor for generating and probing vortex ring in Lithium quantum gases.

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