Repeating 3-body collisions in a trap and the evaluation of interactions of neutral particles

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A model of a device is proposed and related theoretical calculation is performed to study the weak interactions among neutral atoms and molecules. In this model 3-body collisions among the neutral particles occur repeatedly in a trap. Results of calculation demonstrate that information on interaction can be obtained by observing the time-dependent densities of the system.

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I. INTRODUCTION

An important way to understand the interactions among particles is via the study of scattering. In related experiments, the initial status of a scattering state is required to be precisely controlled. This is relatively easy for charged incident particles because their initial momentum can be tuned by adjusting the electromagnetic forces imposing on them. For neutral incident particles, the initial momentum is in general difficult to control precisely. However, the recent progress in the technology of trapping neutral atoms via optical trap might open a new way for studying the scattering of neutral particles with precisely controllable initial status [1–3]. In this paper a model of a device is proposed and related theoretical calculation is performed to show how the mentioned scattering is realized. It turns out that in this device, as we shall see, the collisions among particles occur regularly and repeatedly. Thereby the effect of each individual collision can be accumulated. This would be helpful for the understanding of the very weak interactions among neutral atoms (molecules).

Traditionally, the scatterings would at most have two incident channels (say, in the experiments with head-on colliders). However, in the following device, three or more incident channels can be realized. As an example, a three-body scattering with three incident channels is chosen to be studied. This is a generalization of a previous work on a two-body scattering in a trap with two incident channels [4].

It is assumed that, in the beginning, there are three narrow optical traps located at the three vertexes of a regular triangle, and each optical trap provides a harmonic confinement. The total potential is $U_p(\mathbf{r}) = \frac{1}{2}M\omega_p^2\sum_{j=1}^{3}|(\mathbf{r}-\mathbf{a}_j)|^2$, where $\mathbf{a}_j$ points from the origin to the $j-th$ vertexes, and M is the mass of a particle. When the center of the triangle is placed at the origin, $|\mathbf{a}_j| = a$. It is further assumed that each trap contains an atom in the ground state of a harmonic oscillator, the three atoms are identical bosons with spin zero, and ω_p is large enough so that the atoms are well localized initially. Suddenly the three narrow traps are cancelled. Instead, a broader new trap located at the origin $U_{evol}(r) = \frac{1}{2}M\omega^2 r^2$ is created, $\omega < \omega_p$. Then, the system begins to evolve. The evolution is affected not only by $U_{evol}(r)$ but also by the atom-atom interaction $V(|\mathbf{r}_i - \mathbf{r}_j|)$. In what follows the details of the evolution is studied, three-body head-on collisions occurring repeatedly are found, and the effect of interaction is demonstrated.

II. INITIAL STATE

We shall use $\hbar\omega$ and $\sqrt{\hbar/M\omega}$ as units of energy and length. The symmetrized and normalized initial state

$$\Psi_I = \frac{1}{\sqrt{6}}(\frac{\eta}{\pi})^{9/4} \times \sum_P e^{-\frac{\eta}{2}(|\mathbf{r}_{p_1}-\mathbf{a}_1|^2+|\mathbf{r}_{p_2}-\mathbf{a}_2|^2+|\mathbf{r}_{p_3}-\mathbf{a}_3|^2)} \quad (1)$$

where $\sum_P$ implies a summation over the permutations $p_1p_2p_3$, and $\eta = \omega_p/\omega$. Without loss of generality, $\mathbf{a}_3$ is given lying along the Z-axis, while the triangle is given lying on the X-Z plane. For convenience, three sets of Jacobi coordinates denoted by α, β, and γ, respectively, are introduced. The coordinates of the α set are defined as, $\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$, $\mathbf{R} = \mathbf{r}_3 - (\mathbf{r}_1 + \mathbf{r}_2)/2$, and $\mathbf{R}_c = (\mathbf{r}_1+\mathbf{r}_2+\mathbf{r}_3)/3$. The other two sets can be obtained from the α set by cyclic permutations. In terms of the α set, we introduce the harmonic oscillator (h.o.) states $\phi^{(\mu)}_{nlm}(\mathbf{s}) \equiv f^{(\mu)}_{nl}(s)Y_{lm}(\hat{s})$ as basis functions, where $\mathbf{s} = \mathbf{r}$, $\mathbf{R}$, or $\mathbf{R}_c$. They are normalized eigenstates of the Hamiltonian $-\frac{1}{2\mu}\nabla^2_{\mathbf{s}} + \frac{1}{2}\mu S^2$ with the eigenenergy $2n + l + 3/2$ and with the angular momentum l and its Z-component m, where $\mu = 1/2$, $2/3$, and 3 when $\mathbf{s} = \mathbf{r}$, $\mathbf{R}$, and $\mathbf{R}_c$, respectively. Then the initial state can be expanded as

$$\Psi_I = \frac{1}{\sqrt{6}}\sum_{N_c} c_{N_c}\phi^{(3)}_{N_c00}(\mathbf{R}_c) \cdot \sum_{J,m,\Pi,q} G_{Jm\Pi q}\Phi_{Jm\Pi q}(\mathbf{r},\mathbf{R}) \quad (2)$$

where the first factor is for the c.m. motion which is completely separated from the internal motion,

$$c_{N_c} = \sqrt{4\pi}(\frac{\eta}{\pi})^{9/4}\int R_c^2 dR_c f^{(3)}_{N_c0}(R_c)e^{-\frac{3\eta}{2}R_c^2} \quad (3)$$