APPENDICES

APPENDIX A

RUBIDIUM-85 D LINE DATA

A.1 Data Tables [55]

Table A.1. Fundamental physical constants

Speed of light	c	2.997 924 58 × 10^{8} m/s
Permittivity of vacuum	ε_0	8.854 187 817 . . . × 10^{-12} F/m
Planck's constant	h	6.626 068 96(33) × 10^{-34} J·s
	$\hbar$	1.054 571 628(53) × 10^{-34} J·s
Elementary charge	e	1.602 176 487(40) × 10^{-19} C
Bohr magneton	μ_B	9.274 009 15(23) × 10^{-24} J/T
Atomic mass unit	u	1.660 538 782(83) × 10^{-27} kg
Bohr radius	a_0	0.529 177 208 59(36) × 10^{-10} m
Boltzmann's constant	k_B	1.380 6504(24) × 10^{-23} J/K

Table A.2. ^{85}Rb physical properties

Atomic Number	Z	37
Total Nucleons	$Z + N$	85
Atomic Mass	m	1.409 993 199(70) × 10^{-25} kg
Nuclear Spin	I	5/2

Table A.3. ^{85}Rb D_2 ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$) transition optical properties

Frequency	ω_0	$2\pi \cdot 384.230\ 406\ 373(14)$ THz
Transition Energy	$\hbar\omega_0$	1.589 049 139(38) eV
Wavelength (Vacuum)	λ	780.241 368 271(27) nm
Decay Rate/ Natural Line Width (FWHM)	Γ	$38.117(11) \times 10^6$ s^{-1} $2\pi \cdot 6.0666(18)$ MHz
Absorption oscillator strength	f	0.695 77(29)
Recoil Velocity	v_r	6.0230 mm/s
Recoil Energy	ω_r	$2\pi \cdot 3.8597$ kHz
Recoil Temperature	T_r	370.47 nK
Doppler Temperature	T_D	145.57 μK

Table A.4. ^{85}Rb D_1 ($5^2S_{1/2} \rightarrow 5^2P_{1/2}$) transition optical properties

Frequency	ω_0	$2\pi \cdot 377.107\ 385\ 690(46)$ THz
Transition Energy	$\hbar\omega_0$	1.559 590 695(38) eV
Wavelength (Vacuum)	λ	794.979 014 933(96) nm
Decay Rate/ Natural Line Width (FWHM)	Γ	$36.129(35) \times 10^6$ s^{-1} $2\pi \cdot 5.7500\ (57)$ MHz
Absorption oscillator strength	f	0.342 31(97)
Recoil Velocity	v_r	5.9113 mm/s
Recoil Energy	ω_r	$2\pi \cdot 3.7179$ kHz
Recoil Temperature	T_r	356.86 nK

Table A.5. ^{85}Rb D_2 ($5^2S_{1/2}\rightarrow5^2P_{3/2}$) Dipole Matrix Element for σ_+ transition ($F = 3, m_F \rightarrow F', m'_F = m_F + 1$), express as multiples of $\langle J = 1/2||er|J' = 3/2\rangle$.

	$m_F = -3$	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$	$m_F = 3$
$F' = 4$	$\sqrt{\frac{1}{56}}$	$\sqrt{\frac{3}{56}}$	$\sqrt{\frac{3}{28}}$	$\sqrt{\frac{5}{28}}$	$\sqrt{\frac{15}{56}}$	$\sqrt{\frac{3}{8}}$	$\sqrt{\frac{1}{2}}$
$F' = 3$	$\sqrt{\frac{5}{72}}$	$\sqrt{\frac{25}{216}}$	$\sqrt{\frac{5}{36}}$	$\sqrt{\frac{5}{36}}$	$\sqrt{\frac{25}{216}}$	$\sqrt{\frac{5}{72}}$	
$F' = 2$	$\sqrt{\frac{5}{63}}$	$\sqrt{\frac{10}{189}}$	$\sqrt{\frac{2}{63}}$	$\sqrt{\frac{1}{63}}$	$\sqrt{\frac{1}{189}}$		

Table A.6. ^{85}Rb D_2 ($5^2S_{1/2}\rightarrow5^2P_{3/2}$) Dipole Matrix Element for π transition ($F = 3, m_F \rightarrow F', m'_F = m_F$), express as multiples of $\langle J = 1/2||er|J' = 3/2\rangle$.

	$m_F = -3$	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$	$m_F = 3$
$F' = 4$	$-\sqrt{\frac{1}{8}}$	$-\sqrt{\frac{3}{14}}$	$-\sqrt{\frac{15}{56}}$	$-\sqrt{\frac{2}{7}}$	$-\sqrt{\frac{15}{56}}$	$-\sqrt{\frac{3}{14}}$	$-\sqrt{\frac{1}{8}}$
$F' = 3$	$-\sqrt{\frac{5}{24}}$	$-\sqrt{\frac{5}{54}}$	$-\sqrt{\frac{5}{216}}$	0	$\sqrt{\frac{5}{216}}$	$\sqrt{\frac{5}{54}}$	$\sqrt{\frac{5}{24}}$
$F' = 2$		$\sqrt{\frac{5}{189}}$	$\sqrt{\frac{8}{189}}$	$\sqrt{\frac{1}{21}}$	$\sqrt{\frac{8}{189}}$	$\sqrt{\frac{5}{189}}$	

Table A.7: ^{85}Rb D_2 ($5^2S_{1/2}\rightarrow5^2P_{3/2}$) Dipole Matrix Element for σ_- transition ($F = 3, m_F \rightarrow F', m'_F = m_F - 1$), express as multiples of $\langle J = 1/2||er|J' = 3/2\rangle$.

	$m_F = -3$	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$	$m_F = 3$
$F' = 4$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{3}{8}}$	$\sqrt{\frac{15}{56}}$	$\sqrt{\frac{5}{28}}$	$\sqrt{\frac{3}{28}}$	$\sqrt{\frac{3}{56}}$	$\sqrt{\frac{1}{56}}$
$F' = 3$		$-\sqrt{\frac{5}{72}}$	$-\sqrt{\frac{25}{216}}$	$-\sqrt{\frac{5}{36}}$	$-\sqrt{\frac{5}{36}}$	$-\sqrt{\frac{25}{216}}$	$-\sqrt{\frac{5}{72}}$
$F' = 2$			$\sqrt{\frac{1}{189}}$	$\sqrt{\frac{1}{63}}$	$\sqrt{\frac{2}{63}}$	$\sqrt{\frac{10}{189}}$	$\sqrt{\frac{5}{63}}$

Table A.8: ^{85}Rb D_2 ($5^2S_{1/2}\rightarrow5^2P_{3/2}$) Dipole Matrix Element for σ_+ transition ($F = 2, m_F \rightarrow F', m'_F = m_F + 1$), express as multiples of $\langle J = 1/2||er|J' = 3/2\rangle$.

	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$
$F' = 3$	$\sqrt{\frac{3}{135}}$	$\sqrt{\frac{2}{45}}$	$\sqrt{\frac{4}{45}}$	$\sqrt{\frac{4}{27}}$	$\sqrt{\frac{2}{9}}$
$F' = 2$	$\sqrt{\frac{7}{54}}$	$\sqrt{\frac{7}{36}}$	$\sqrt{\frac{7}{36}}$	$\sqrt{\frac{7}{54}}$	
$F' = 1$	$\sqrt{\frac{3}{10}}$	$\sqrt{\frac{3}{20}}$	$\sqrt{\frac{1}{20}}$		

Table A.9: ^{85}Rb D_2 ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$) Dipole Matrix Element for π transition ($F = 2, m_F \rightarrow F', m'_F = m_F$), express as multiples of $\langle J = 1/2 || er | J' = 3/2 \rangle$.

	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$
$F' = 3$	$-\sqrt{\frac{2}{27}}$	$-\sqrt{\frac{16}{135}}$	$-\sqrt{\frac{2}{15}}$	$-\sqrt{\frac{16}{135}}$	$-\sqrt{\frac{2}{27}}$
$F' = 2$	$-\sqrt{\frac{7}{27}}$	$-\sqrt{\frac{7}{108}}$	0	$\sqrt{\frac{7}{108}}$	$\sqrt{\frac{7}{27}}$
$F' = 1$		$\sqrt{\frac{3}{20}}$	$\sqrt{\frac{1}{5}}$	$\sqrt{\frac{3}{20}}$	

Table A.10: ^{85}Rb D_2 ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$) Dipole Matrix Element for σ_- transition ($F = 2, m_F \rightarrow F', m'_F = m_F - 1$), express as multiples of $\langle J = 1/2 || er | J' = 3/2 \rangle$.

	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$
$F' = 3$	$\sqrt{\frac{2}{9}}$	$\sqrt{\frac{4}{27}}$	$\sqrt{\frac{4}{45}}$	$\sqrt{\frac{2}{45}}$	$\sqrt{\frac{3}{135}}$
$F' = 2$		$-\sqrt{\frac{7}{54}}$	$-\sqrt{\frac{7}{36}}$	$-\sqrt{\frac{7}{36}}$	$-\sqrt{\frac{7}{54}}$
$F' = 1$			$\sqrt{\frac{1}{20}}$	$\sqrt{\frac{3}{20}}$	$\sqrt{\frac{3}{10}}$

Table A.11: ^{85}Rb D_1 ($5^2S_{1/2}\rightarrow5^2P_{1/2}$) Dipole Matrix Element for σ_+ transition ($F = 3, m_F \rightarrow F', m'_F = m_F + 1$), express as multiples of $\langle J = 1/2||er|J' = 1/2\rangle$.

	$m_F = -3$	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$	$m_F = 3$
$F' = 3$	$\sqrt{\frac{1}{9}}$	$\sqrt{\frac{5}{27}}$	$\sqrt{\frac{2}{29}}$	$\sqrt{\frac{2}{29}}$	$\sqrt{\frac{5}{27}}$	$\sqrt{\frac{1}{9}}$	
$F' = 2$	$\sqrt{\frac{5}{9}}$	$\sqrt{\frac{10}{27}}$	$\sqrt{\frac{2}{9}}$	$\sqrt{\frac{1}{9}}$	$\sqrt{\frac{1}{27}}$		

Table A.12: ^{85}Rb D_1 ($5^2S_{1/2}\rightarrow5^2P_{1/2}$) Dipole Matrix Element for π transition ($F = 3, m_F \rightarrow F', m'_F = m_F$), express as multiples of $\langle J = 1/2||er|J' = 1/2\rangle$.

	$m_F = -3$	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$	$m_F = 3$
$F' = 3$	$-\sqrt{\frac{1}{3}}$	$-\sqrt{\frac{4}{27}}$	$-\sqrt{\frac{1}{27}}$	0	$\sqrt{\frac{1}{27}}$	$\sqrt{\frac{4}{27}}$	$\sqrt{\frac{1}{3}}$
$F' = 2$		$\sqrt{\frac{5}{27}}$	$\sqrt{\frac{8}{27}}$	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{8}{27}}$	$\sqrt{\frac{5}{27}}$	

Table A.13: ^{85}Rb D_1 ($5^2S_{1/2}\rightarrow5^2P_{1/2}$) Dipole Matrix Element for σ_- transition ($F = 3, m_F \rightarrow F', m'_F = m_F - 1$), express as multiples of $\langle J = 1/2||er|J' = 1/2\rangle$.

	$m_F = -3$	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$	$m_F = 3$
$F' = 3$		$-\sqrt{\frac{1}{9}}$	$-\sqrt{\frac{5}{27}}$	$-\sqrt{\frac{2}{29}}$	$-\sqrt{\frac{2}{29}}$	$-\sqrt{\frac{5}{27}}$	$-\sqrt{\frac{1}{9}}$
$F' = 2$			$\sqrt{\frac{1}{27}}$	$\sqrt{\frac{1}{9}}$	$\sqrt{\frac{2}{9}}$	$\sqrt{\frac{10}{27}}$	$\sqrt{\frac{5}{9}}$

Table A.14: ^{85}Rb D_1 ($5^2S_{1/2}\rightarrow5^2P_{1/2}$) Dipole Matrix Element for σ_+ transition ($F = 2, m_F \rightarrow F', m'_F = m_F + 1$), express as multiples of $\langle J = 1/2||er|J' = 1/2\rangle$.

	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$
$F' = 3$	$-\sqrt{\frac{1}{27}}$	$-\sqrt{\frac{1}{9}}$	$-\sqrt{\frac{2}{9}}$	$-\sqrt{\frac{10}{27}}$	$-\sqrt{\frac{5}{9}}$
$F' = 2$	$-\sqrt{\frac{2}{27}}$	$-\sqrt{\frac{1}{9}}$	$-\sqrt{\frac{1}{9}}$	$-\sqrt{\frac{2}{27}}$	

Table A.15: ^{85}Rb D_1 ($5^2S_{1/2}\rightarrow5^2P_{1/2}$) Dipole Matrix Element for π transition ($F = 3, m_F \rightarrow F', m'_F = m_F$), express as multiples of $\langle J = 1/2||er|J' = 1/2\rangle$.

	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$
$F' = 3$	$\sqrt{\frac{5}{27}}$	$\sqrt{\frac{8}{27}}$	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{8}{27}}$	$\sqrt{\frac{5}{27}}$
$F' = 2$	$\sqrt{\frac{4}{27}}$	$\sqrt{\frac{1}{27}}$	0	$-\sqrt{\frac{1}{27}}$	$-\sqrt{\frac{4}{27}}$

Table A.16: ^{85}Rb D_1 ($5^2S_{1/2}\rightarrow5^2P_{1/2}$) Dipole Matrix Element for σ_- transition ($F = 2, m_F \rightarrow F', m'_F = m_F - 1$), express as multiples of $\langle J = 1/2||er|J' = 1/2\rangle$.

	$m_F = -2$	$m_F = -1$	$m_F = 0$	$m_F = 1$	$m_F = 2$
$F' = 3$	$-\sqrt{\frac{5}{9}}$	$-\sqrt{\frac{10}{27}}$	$-\sqrt{\frac{2}{9}}$	$-\sqrt{\frac{1}{9}}$	$-\sqrt{\frac{1}{27}}$
$F' = 2$		$\sqrt{\frac{2}{27}}$	$\sqrt{\frac{1}{9}}$	$\sqrt{\frac{1}{9}}$	$\sqrt{\frac{2}{27}}$

APPENDIX B

SIMULATION AND PROGRAMING

B.1 Temperature of single atoms

```
function Prob_recaptured=Release_recapture_fit1(T,Temperature)
global x1_randn x2_randn x3_randn x4_randn x5_randn x6_randn mass Kb wx P...
       omega_rad_theory omega_ax_theory N recapture_prob U0
%Calculate ICs
w0=wx;
xi=sqrt(Kb*Temperature/mass);
sigma_x=sqrt(-0.5*w0^2*log((-Kb*Temperature*log(0.05)+U0)/U0));
sigma_y=sigma_x;
sigma_z=sigma_x*10;
Init_cond=zeros(N,7);
x1_ic=x1_randn*sigma_x;                    %x initial position
x2_ic=xi*x2_randn;    %x initial velocity = Normally distributed with sd of sqrt(kt/m)
x3_ic=x3_randn*sigma_y;                    %y initial position
x4_ic=xi*x4_randn;                         %y initial velocity
x5_ic=x5_randn*sigma_z;                    %z initial position
x6_ic=xi*x6_randn;                         %z initial velocity
Init_cond(:,1)=x1_ic;
Init_cond(:,2)=x2_ic;
Init_cond(:,3)=x3_ic;
Init_cond(:,4)=x4_ic;
Init_cond(:,5)=x5_ic;
Init_cond(:,6)=x6_ic;
Init_cond(:,7)=sqrt(x2_ic.^2 + x4_ic.^2 + x6_ic.^2);  %initial SPEED^2
```

```
%% Test that single atoms are trapped befor RR
no_time_steps = length(T);
Prob_recaptured = zeros(1,no_time_steps);
atoms_in_trap_before = ones(1,N);
r=rand(N,1);
c1=find(0.5*mass*Init_cond(:,7).^2 >
abs(dipole_potential_3D(Init_cond(:,1),Init_cond(:,3),Init_cond(:,5))));
for i=1:length(c1)
    atoms_in_trap_before(c1(i))=0;
end
c2=find(r(:)>exp((abs((dipole_potential_3D(Init_cond(:,1),Init_cond(:,3),Init_cond(:,5
                                                    ))))+U0)./(Kb*Temperature)));
for j=1:length(c2)
    atoms_in_trap_before(c2(j))=0;
end
```

```
%% Turn off the trap and let the atoms fly out
for M = 1:no_time_steps;
    time_of_flight=T(M);
    new_conditions = zeros(N,7);
    new_conditions(:,1) = Init_cond(:,1) + Init_cond(:,2) .* time_of_flight - 9.8 .*
                                                          time_of_flight.^2 ./ 2;
    new_conditions(:,2) = Init_cond(:,2) - 9.8.* time_of_flight;
    new_conditions(:,3) = Init_cond(:,3) + Init_cond(:,4) .* time_of_flight;
    new_conditions(:,4) = Init_cond(:,4) ;
    new_conditions(:,5) = Init_cond(:,5) + Init_cond(:,6) .* time_of_flight;
```

```
    new_conditions(:,6) = Init_cond(:,6);
    new_conditions(:,7) = sqrt(new_conditions(:,2).^2 + new_conditions(:,4).^2 +
                                                        new_conditions(:,6).^2);
    % Test the atoms still be in the trap
    atoms_in_trap_after = ones(1,N);
    c3=find(0.5*mass*new_conditions(:,7).^2 > abs(dipole_potential_3D(new_conditions(:,
                                    1),new_conditions(:,3),new_conditions(:,5))));
    for k=1:length(c3)
        atoms_in_trap_after(c3(k))=0;
    end
    percent_recaptured = sum(atoms_in_trap_before .* atoms_in_trap_after) ./
                                                        sum(atoms_in_trap_before);
    Prob_recaptured(M) = percent_recaptured;
end
Prob_recaptured = Prob_recaptured(:)*recapture_prob; %(due to losing atoms in first
                                                                    picture)
end
```

B.2 Simulation of two-body collision induced by the blue-detuned light

```
clear all
close all
path(path,'\\Singleatomlab\matlab\fitting');
path(path,'\\Singleatomlab\matlab\Dipole_trap')
global wx P
```

```
%% Constants
detuning1=2*pi*4.3e6;                                   %MOT detuning from F=3 to F'=3 in the trap
detuning2=2*pi*(120+4);                                 %MOT detuning from F=3 to F'=4 in the trap
hbar=1.0546e-34;                                        %h bar
c=2.99792458e8;                                         %light speed (m/s)
mass=1.409993e-25;                                      %Rb mass (kg)
                    Kb=1.38065e-23;                                         %Boltzmann's constant (J/K)
gamma2=2*pi*6.066e6;                                    %1/exited state lifetime for D2 (s^-1)
gamma1=2*pi*5.750e6;                                    %1/exited state lifetime for D1 (s^-1)
lambda2=780.241368e-9;                                  %lambda for D2 (m)
lambda1=794.979014e-9;                                  %for D1 (m)
omega2=2*pi*384.230406373e12;                           %omega for D2 (s^-1)
omega1=2*pi*377.107385690e12;                           %for D1 (s^-1)
k_lambda2=2*pi/lambda2;
k_lambda1=2*pi/lambda1;
```

```
%% Trap parameters
wx=1.8e-6;                                              %waist of dipole beam (m)
P=30e-3;                                                %dipole power (W)
w0=wx;
I0=2*P/(pi*wx^2);                                       %intensity at waist(W/m^2)
lambda_trap=828e-9;                                     %lambda of dipole laser (m)
```

```
%% Beam parameters
Is=1.66932e-3/1e-4;                                     %saturated intensity of circular polarized light for D2(mF=+-3 to mF'=+-4)(W/m^2)
MOT_power=0.64e-3;                                      %MOT beam power (W)
MOT_d=4.8e-3;                                           %MOT beam diameter (m)
I_MOT=0.00065*2*MOT_power/(pi*(MOT_d/2)^2);             %0.007MOT beam intensity(W/m^2) 0.024
delta=-6e6;                                             %MOT detuning (Hz) from F=3 to F'=3 -8.9 -8.1
delta2=-124e6;                                          %MOT detuning (Hz) from F=3 to F'=4
```

```
%% Initail parameters
Temperature=280e-6;                                     %temperature of atom in dipole trap (K)
```

```
N=1000;                                          %number of single atom in the trap
dt=1e-7;                                         %time in each time step (s)
total_step=12e5;                                 %total number of steps
no_point=100;                                    %number of points to save data
cooling=1;
evo=1;
coll=1;
fig=0;
save_data=1;
if no_point< total_step
no_s=total_step/no_point;                        %number of step to save data
else
no_s=1;
end
%set number for check atom in trap after cooling and collision
if total_step>=1e6
    no_c=1e4;
else
    no_c=no_s;
end
```

```
%% Collision parameters
delta_coll=185e6;                                %Coll. detunning at the bottom of trap (Hz)
C3=58.0282*10^(-19)*10^(-30);                    %C3 of the potential
Rc=(C3/(delta_coll*hbar*2*pi))^(1/3);            %Condon radius (m)
Er=2*pi*hbar*delta_coll;                         %Coll. blue detunign = trap depth
I_over_Isat=5.2;                                 %I/Isat 7.6 for 11uW
```

```
%% Create single atoms in dipole trap from initial conditions
xpretty=1e-6*linspace(-5,5,500);
ypretty=xpretty;
zpretty=1e-6*linspace(-150,150,500);
[dUdX junk junk U0 zR]=grad_dipole_potential_3D(xpretty,0,0);
[junk dUdY junk U0 zR]=grad_dipole_potential_3D(0,ypretty,0);
[junk junk dUdZ U0 zR]=grad_dipole_potential_3D(0,0,zpretty);
%[junk junk dUdZ U0 zR]=grad_dipole_potential_3D(0,0,0);

p_min=exp(U0/(Kb*Temperature))+0.0001;
sigma_x=sqrt(-0.5*w0^2*log((-Kb*Temperature*(log(p_min))+U0)/U0));
sigma_y=sigma_x;
sigma_z=zR*sqrt(U0/(-Kb*Temperature*log(p_min+0.003)+U0)-1);
xi=sqrt(Kb*Temperature/mass);
atom_ic=zeros(N,7);
atom_counter=0;
while atom_counter<N
    %Random position and velocity
```

```
    x1_ic=zeros(N ,1);                                  %x initial position
    x2_ic=xi*randn(N,1);                                %x initial velocity  = Normally distributed with a st dev of sqrt(kt/m)
    x3_ic=zeros(N,1);                                   %y initial position
    x4_ic=xi*randn(N,1);                                %y initial velocity
    x5_ic=zeros(N,1);                                   %z initial position
    x6_ic=xi*randn(N,1);                                %z initial velocity
atoms_in_trap_before= zeros(N,1);
    %create spatial distribution by p(x,y,z)=exp(U(x,y,z)/KbT)/exp(U0/KbT)
    for counter=1:N
        while atoms_in_trap_before(counter)==0
            x1_ic(counter)=(2*rand-1)*sigma_x;
            x3_ic(counter)=(2*rand-1)*sigma_y;
            x5_ic(counter)=(2*rand-1)*sigma_z;
            if rand<exp((abs((dipole_potential_3D(x1_ic(counter),x3_ic(counter),x5_ic(counter))))+U0)./(Kb*Temperature))
                atoms_in_trap_before(counter)=1;
            end
        end
    end
    Init_cond=zeros(N,7);
    Init_cond(:,1)=x1_ic;
    Init_cond(:,2)=x2_ic;
    Init_cond(:,3)=x3_ic;
    Init_cond(:,4)=x4_ic;
    Init_cond(:,5)=x5_ic;
    Init_cond(:,6)=x6_ic;
    Init_cond(:,7)=sqrt(x2_ic.^2 + x4_ic.^2 + x6_ic.^2);    %initial SPEED (as opposed to velocity)
%Atom is in trap or not, by Ek(v^2)<=U(x,y,z)
    c2=find(0.5*mass*Init_cond(:,7).^2 <= abs(dipole_potential_3D(Init_cond(:,1),Init_cond(:,3),Init_cond(:,5))));
    for i=1:min(length(c2),N-atom_counter)
        atom_ic(i+atom_counter,:)=Init_cond(c2(i),:);
    end
    atom_counter=atom_counter+min(length(c2),N-atom_counter);
end
Initial_T=mass*mean(atom_ic(:,7).^2)/(3*Kb);
```

```
%% Evolution of each atom in trap

%create initial value of all parameter
k1=zeros(N,6);k2=zeros(N,6);k3=zeros(N,6);k4=zeros(N,6);
atom_fc=zeros(N,7);
atom_E=zeros(N,total_step/no_s,3);
ii=1;
abs_rate=zeros(N,6);
Final_T=zeros(total_step/no_s+1,1);
Final_T(1)=Initial_T;
atom_mU=zeros(total_step/no_s+1,1);
```

```
atom_mU(1)=mean(dipole_potential_3D(atom_ic(:,1),atom_ic(:,3),atom_ic(:,5)));
atom_s=zeros(N,7,total_step/no_s);
atom_N=zeros(total_step/no_s+1,1);
atom_N(1)=N;
atom_delta=zeros(N/2,7);
atom_delta_dt=zeros(N/2,7);
coll_counter=zeros(N/2,3);
alpha=zeros(N/2,1);
single_atom_lost=0;
pair_lost=0;
no_atom_lost=0;
atom_in_trap_after=ones(N,2);
atom_in_trap_after(:,2)=0;
last_coll=zeros(N/2,1);
tic
for no_step=1:total_step
    %calcurate photon absorbtion rate of atom
    if cooling==1
    %for F=3 to F'=3
    abs_rate(:,1)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta-2*pi./lambda2*atom_ic(:,2))./gamma2).^2); %for photon +x direction
    abs_rate(:,2)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta+2*pi./lambda2*atom_ic(:,2))./gamma2).^2); %for photon -x direction
    abs_rate(:,3)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta-2*pi./lambda2*atom_ic(:,4))./gamma2).^2); %for photon +y direction
    abs_rate(:,4)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta+2*pi./lambda2*atom_ic(:,4))./gamma2).^2); %for photon -y direction
    abs_rate(:,5)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta-2*pi./lambda2*atom_ic(:,6))./gamma2).^2); %for photon +z direction
    abs_rate(:,6)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta+2*pi./lambda2*atom_ic(:,6))./gamma2).^2); %for photon -z direction
    abs_rand=rand(N,6);                                %create random matrix for checking propabilty of absorbtion each photon
    %fine atoms that absorb photon, index of atoms be contain in abs_1
    %also check atom out of trap
    %also check if only single atom left in trap after coll. keep it without cooling
    abs_1=find(abs_rand(:,1)<=abs_rate(:,1) & atom_in_trap_after(:,1)==1 & coll_counter([1:N/2 1:N/2],2)==0);    %+x direction
    abs_2=find(abs_rand(:,2)<=abs_rate(:,2) & atom_in_trap_after(:,1)==1 & coll_counter([1:N/2 1:N/2],2)==0);
    abs_3=find(abs_rand(:,3)<=abs_rate(:,3) & atom_in_trap_after(:,1)==1 & coll_counter([1:N/2 1:N/2],2)==0);
    abs_4=find(abs_rand(:,4)<=abs_rate(:,4) & atom_in_trap_after(:,1)==1 & coll_counter([1:N/2 1:N/2],2)==0);
    abs_5=find(abs_rand(:,5)<=abs_rate(:,5) & atom_in_trap_after(:,1)==1 & coll_counter([1:N/2 1:N/2],2)==0);
    abs_6=find(abs_rand(:,6)<=abs_rate(:,6) & atom_in_trap_after(:,1)==1 & coll_counter([1:N/2 1:N/2],2)==0);
    %atom absorb and emit photon for photon +x direction
    for abs_1i=1: length(abs_1)                                                    %atoms that absorb photon change velocity
        atom_ic(abs_1(abs_1i),2)=atom_ic(abs_1(abs_1i),2)+hbar*k_lambda2/mass;     %atoms change velocity in x direction
        emit=rand(2,1);                                                            %random direction for emitting photon
        emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
        emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
        emit_norm(3)=cos(pi*emit(2));
        atom_ic(abs_1(abs_1i),2)=atom_ic(abs_1(abs_1i),2)-emit_norm(1)*hbar*k_lambda2/mass;  %atoms change velocity in x direction
        atom_ic(abs_1(abs_1i),4)=atom_ic(abs_1(abs_1i),4)-emit_norm(2)*hbar*k_lambda2/mass;  %atoms change velocity in y direction
        atom_ic(abs_1(abs_1i),6)=atom_ic(abs_1(abs_1i),6)-emit_norm(3)*hbar*k_lambda2/mass;  %atoms change velocity in z direction
    end
```

```
%atom absorb and emit photon for photon -x direction
for abs_2i=1: length(abs_2)
    atom_ic(abs_2(abs_2i),2)=atom_ic(abs_2(abs_2i),2)-hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_2(abs_2i),2)=atom_ic(abs_2(abs_2i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_2(abs_2i),4)=atom_ic(abs_2(abs_2i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_2(abs_2i),6)=atom_ic(abs_2(abs_2i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon +y direction
for abs_3i=1: length(abs_3)
    atom_ic(abs_3(abs_3i),4)=atom_ic(abs_3(abs_3i),4)+hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_3(abs_3i),2)=atom_ic(abs_3(abs_3i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_3(abs_3i),4)=atom_ic(abs_3(abs_3i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_3(abs_3i),6)=atom_ic(abs_3(abs_3i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon -y direction
for abs_4i=1: length(abs_4)
    atom_ic(abs_4(abs_4i),4)=atom_ic(abs_4(abs_4i),4)-hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_4(abs_4i),2)=atom_ic(abs_4(abs_4i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_4(abs_4i),4)=atom_ic(abs_4(abs_4i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_4(abs_4i),6)=atom_ic(abs_4(abs_4i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon +z direction
for abs_5i=1: length(abs_5)
    atom_ic(abs_5(abs_5i),6)=atom_ic(abs_5(abs_5i),6)+hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_5(abs_5i),2)=atom_ic(abs_5(abs_5i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_5(abs_5i),4)=atom_ic(abs_5(abs_5i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_5(abs_5i),6)=atom_ic(abs_5(abs_5i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon -z direction
for abs_6i=1: length(abs_6)
```

```
    atom_ic(abs_6(abs_6i),6)=atom_ic(abs_6(abs_6i),6)-hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_6(abs_6i),2)=atom_ic(abs_6(abs_6i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_6(abs_6i),4)=atom_ic(abs_6(abs_6i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_6(abs_6i),6)=atom_ic(abs_6(abs_6i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
end
%evolution of atom 1 by using the fourth-order RungeñKutta method
if evo==1
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1),atom_ic(:,3),atom_ic(:,5));    %dUdX = (dU/dx)/mass+9.8
k1(:,1)=dt*atom_ic(:,2);
k1(:,2)=dt*(-dUdX);
k1(:,3)=dt*atom_ic(:,4);
k1(:,4)=dt*(-dUdY);
k1(:,5)=dt*atom_ic(:,6);
k1(:,6)=dt*(-dUdZ);
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1)+k1(:,1)./2,atom_ic(:,3)+k1(:,3)./2,atom_ic(:,5)+k1(:,5)./2);
k2(:,1)=dt*(atom_ic(:,2)+k1(:,2)./2);
k2(:,2)=dt*(-dUdX);
k2(:,3)=dt*(atom_ic(:,4)+k1(:,4)./2);
k2(:,4)=dt*(-dUdY);
k2(:,5)=dt*(atom_ic(:,6)+k1(:,6)./2);
k2(:,6)=dt*(-dUdZ);
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1)+k2(:,1)./2,atom_ic(:,3)+k2(:,3)./2,atom_ic(:,5)+k2(:,5)./2);
k3(:,1)=dt*(atom_ic(:,2)+k2(:,2)./2);
k3(:,2)=dt*(-dUdX);
k3(:,3)=dt*(atom_ic(:,4)+k2(:,4)./2);
k3(:,4)=dt*(-dUdY);
k3(:,5)=dt*(atom_ic(:,6)+k2(:,6)./2);
k3(:,6)=dt*(-dUdZ);
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1)+k3(:,1),atom_ic(:,3)+k3(:,3),atom_ic(:,5)+k3(:,5));
k4(:,1)=dt*(atom_ic(:,2)+k3(:,2));
k4(:,2)=dt*(-dUdX);
k4(:,3)=dt*(atom_ic(:,4)+k3(:,4));
k4(:,4)=dt*(-dUdY);
k4(:,5)=dt*(atom_ic(:,6)+k3(:,6));
k4(:,6)=dt*(-dUdZ);
atom_fc(:,1:6)=atom_ic(:,1:6)+(k1+2*k2+2*k3+k4)./6;
end
%Check collision event
if coll==1 && evo==1
atom_delta(:,[1 3 5])=atom_ic(1:N/2,[1 3 5])-atom_ic((N/2+1):N,[1 3 5]);
atom_delta(:,[2 4 6])=(atom_fc(1:N/2,[1 3 5])-atom_ic(1:N/2,[1 3 5]))./dt-(atom_fc((N/2+1):N,[1 3 5])-atom_ic((N/2+1):N,[1 3
```

```
                                                                                                    5]))./dt;  %extimate that atom
atom_delta(:,7)=sqrt(atom_delta(:,2).^2+atom_delta(:,4).^2+atom_delta(:,6).^2);
atom_delta_R_sqr=atom_delta(:,1).^2+atom_delta(:,3).^2+atom_delta(:,5).^2;
atom_delta_RdotV=atom_delta(:,1).*atom_delta(:,2)+atom_delta(:,3).*atom_delta(:,4)+atom_delta(:,5).*atom_delta(:,6);
t_Rmin=-atom_delta_RdotV./atom_delta(:,7).^2;
atom_delta_dt(:,1:6)=atom_fc(1:N/2,1:6)-atom_fc((N/2+1):N,1:6);
atom_delta_dt_R_sqr=atom_delta_dt(:,1).^2+atom_delta_dt(:,3).^2+atom_delta_dt(:,5).^2;
%check collision conditions
c9=find((t_Rmin>0) & ((atom_delta_R_sqr-t_Rmin.^2.*atom_delta(:,7).^2)<=Rc^2) & ((t_Rmin<=dt)|(atom_delta_dt_R_sqr<=Rc^2)));
if ~isempty(c9)
%check that atom was not check in the last time step & atoms still in trap
c3=find((no_step>last_coll(c9)+1) & (atom_in_trap_after(c9,1).*atom_in_trap_after(c9+N/2,1)==1));
last_coll(c9)=no_step;
c9=c9(c3);
if ~isempty(c9)
    t_coll=(-2*atom_delta_RdotV(c9)-sqrt((2*atom_delta_RdotV(c9)).^2-4*atom_delta(c9,7).^2.*(atom_delta_R_sqr(c9)-
                                                                Rc^2)))./(2*atom_delta(c9,7).^2);  %time that collision happen
    %shift time and atom parameter to time that collision happen
    for j=1:length(c9)
        atom_ic(c9(j),:)=atom_ic(c9(j),:)+t_coll(j)*(atom_fc(c9(j),:)-atom_ic(c9(j),:))./dt;
        atom_ic(c9(j)+N/2,:)=atom_ic(c9(j)+N/2,:)+t_coll(j)*(atom_fc(c9(j)+N/2,:)-atom_ic(c9(j)+N/2,:))./dt;
    end
    atom_delta(c9,:)=atom_ic(c9,:)-atom_ic(c9+N/2,:);                          %relative R and v at R=Rc
    %calculate propability that inelastic collision happen
    atom_delta_RdotV=atom_delta(c9,1).*atom_delta(c9,2)+atom_delta(c9,3).*atom_delta(c9,4)+atom_delta(c9,5).*atom_delta(c9,6);
    atom_delta_R_sqr=atom_delta(c9,1).^2+atom_delta(c9,3).^2+atom_delta(c9,5).^2;
    atom_delta_speed=-atom_delta_RdotV./sqrt(atom_delta_R_sqr);                %relative speed in relative R direction
    gamma=I_over_Isat*hbar*Rc^4*gamma1^2./(2*pi*6*C3*atom_delta_speed);        %I_coll/I_sat=20.78 4.07
    P_coll=2*exp(-gamma).*(1-exp(-gamma));                                     %Propability for inelastic collision of each pair
    P_rand=rand(length(P_coll),1);
    c6=find(P_rand<=P_coll);                                                   %check whitch pairs have an inelastic coll.
    c9=c9(c6);                                                                 %assign new index that coll. happen
    if ~isempty(c9)
    atom_delta_R_sqr(c9)=atom_delta(c9,1).^2+atom_delta(c9,3).^2+atom_delta(c9,5).^2;
    atom_delta_RdotV(c9)=atom_delta(c9,1).*atom_delta(c9,2)+atom_delta(c9,3).*atom_delta(c9,4)+atom_delta(c9,5).*atom_delta(c9,6);
    alpha=(-atom_delta_RdotV(c9)+sqrt(4*Er*atom_delta_R_sqr(c9)./mass+atom_delta_RdotV(c9).^2))./(2*atom_delta_R_sqr(c9));
    atom_fc([c9 c9+N/2],[1 3 5])=atom_ic([c9 c9+N/2],[1 3 5]);                 %set new position after collision for both atom
    coll_counter(c9,1)=coll_counter(c9,1)+1;
    for j=1:length(c9)
        %set new velocity
        atom_fc(c9(j),[2 4 6])=atom_ic(c9(j),[2 4 6])+alpha(j)*atom_delta(c9(j),[1 3 5]);          %the 1st atoms
        atom_fc(c9(j)+N/2,[2 4 6])=atom_ic(c9(j)+N/2,[2 4 6])-alpha(j).*atom_delta(c9(j),[1 3 5]);  %the 2nd atoms
        atom_fc([c9(j) c9(j)+N/2],7)=sqrt(atom_fc([c9(j) c9(j)+N/2],2).^2+atom_fc([c9(j) c9(j)+N/2],4).^2+atom_fc([c9(j)
                                                                                    c9(j)+N/2],6).^2); %calculate new speed
        c8=find(0.5*mass*atom_fc([c9(j) c9(j)+N/2],7).^2 > abs(dipole_potential_3D(atom_fc([c9(j) c9(j)+N/2],1),atom_fc([c9(j)
                                                                                c9(j)+N/2],3),atom_fc([c9(j) c9(j)+N/2],5))));
```

```
        if isempty(c8)
            no_atom_lost=no_atom_lost+1;
        elseif length(c8)==2
            pair_lost=pair_lost+1;
            coll_counter(c9(j),3)=1;
            atom_in_trap_after([c9(j) c9(j)+N/2],1)=0;
            atom_in_trap_after([c9(j) c9(j)+N/2],2)=no_step;
        elseif length(c8)==1
            single_atom_lost=single_atom_lost+1;
            coll_counter(c9(j),2)=1;
            index=[c9(j) c9(j)+N/2];
            atom_in_trap_after(index(c8),1)=0;
            atom_in_trap_after(index(c8),2)=no_step;
        end
    end
    end
end
end
end
if evo==1
    atom_ic=atom_fc;
else
    atom_fc=atom_ic;
end
%check that atom still be in trap
if mod(no_step,no_c)==0
    atom_fc(:,7)=sqrt(atom_fc(:,2).^2+atom_fc(:,4).^2+atom_fc(:,6).^2);
    c10=find(0.5*mass*atom_fc(:,7).^2 > abs(dipole_potential_3D(atom_fc(:,1),atom_fc(:,3),atom_fc(:,5))) &
                                                                                    atom_in_trap_after(:,1)==1);
    atom_in_trap_after(c10,1)=0;
    atom_in_trap_after(c10,2)=no_step;
end
%save parameter at each no_s steps
if ii==no_step/no_s
    atom_fc(:,7)=sqrt(atom_fc(:,2).^2+atom_fc(:,4).^2+atom_fc(:,6).^2);
    %save energy of each atom
    atom_E(:,ii,1)=0.5*mass*atom_fc(:,7).^2 ;
    atom_E(:,ii,2)=dipole_potential_3D(atom_fc(:,1),atom_fc(:,3),atom_fc(:,5));
    atom_E(:,ii,3)=atom_E(:,ii,1)+atom_E(:,ii,2);
    %save mean enery of atoms
    c11=find(atom_in_trap_after(:,1)==1);
    Final_T(ii+1)=mass*mean(atom_fc(c11,7).^2)/(3*Kb);
    atom_N(ii+1)=length(c11);
    atom_s(:,:,ii)=atom_fc;
    ii=ii+1;
end
```

```
end
toc
```

```
%% Plot parameter for checking
if fig==1
t=linspace(0,total_step*dt,total_step/no_s+1);
figure;
plot(t,Final_T,'k')
```

```
%% Check atoms in trap or not
two_atoms=zeros(no_step/no_s+1,1);
one_atom=zeros(no_step/no_s+1,1);
zero_atom=zeros(no_step/no_s+1,1);
two_atoms(1)=N/2;
for kk=1:no_step/no_s
    for k=1:N/2
        c5=find(atom_in_trap_after([k k+N/2],1)==1 | (atom_in_trap_after([k k+N/2],2)./no_s>kk | atom_in_trap_after([k k+N/2],2)==0));
        if isempty(c5)
            zero_atom(kk+1)=zero_atom(kk+1)+1;
        elseif length(c5)==1
            one_atom(kk+1)=one_atom(kk+1)+1;
        elseif length(c5)==2
            two_atoms(kk+1)=two_atoms(kk+1)+1;
        end
    end
end
figure;
plot(t,two_atoms.*2./N,'b.')
hold on
plot(t,one_atom.*2./N,'r.')
hold on
plot(t,zero_atom.*2./N,'g.')
end
```

```
%% Save data
if save_data==1
clk=clock;
save_name=sprintf('%s-%d-%d-N%dpairs-T%duK-dt%dns-cooling%d-Detunning%dMHz-
                                100IovIsat%1.0f',date,clk(4),clk(5),N/2,Temperature*1e6,dt*1e9,cooling,delta_coll/1e6,I_over_Isat*100);
save(save_name);
end
```

B.3 Simulation of two-body collision induced by the red-detuned light

```
clear all
close all
path(path,'/Users/mimmim248/Documents/WORK/Program/fitting');
path(path,'/Users/mimmim248/Documents/WORK/Program/Dipole_trap');
global wx P
```

```
%% Constants
detuning1=2*pi*4.3e6;                          %MOT detuning from F=3 to F'=3 in the trap
detuning2=2*pi*(120+4);                        %MOT detuning from F=3 to F'=4 in the trap
hbar=1.0546e-34;                               %h bar
c=2.99792458e8;                                %light speed (m/s)
mass=1.409993e-25;                             %Rb mass (kg)
Kb=1.38065e-23;                                %Boltzmann's constant (J/K)
gamma2=2*pi*6.066e6;                           %1/exited state lifetime for D2 (s^-1)
gamma1=2*pi*5.750e6;                           %1/exited state lifetime for D1 (s^-1)
lambda2=780.241368e-9;                         %lambda for D2 (m)
lambda1=794.979014e-9;                         %for D1 (m)
omega2=2*pi*384.230406373e12;                  %omega for D2 (s^-1)
omega1=2*pi*377.107385690e12;                  %for D1 (s^-1)
k_lambda2=2*pi/lambda2;
k_lambda1=2*pi/lambda1;
```

```
%% Trap parameters
wx=1.8e-6;                                     %waist of dipole beam (m)
P=30e-3;                                       %dipole power (W)
w0=wx;
I0=2*P/(pi*wx^2);                              %intensity at waist(W/m^2)
lambda_trap=828e-9;                            %lambda of dipole laser (m)
```

```
%% Beam parameters
Is=1.66932e-3/1e-4;                            %saturated intensity of circular polarized light for D2(mF=+-3 to mF'=+-4)(W/m^2)
MOT_power=0.35e-3;                             %MOT beam power (W)
MOT_d=4.8e-3;                                  %MOT beam diameter (m)
I_MOT=0.023*2*MOT_power/(pi*(MOT_d/2)^2); %MOT beam intensity(W/m^2) 0.027
delta=-9e6;                                    %MOT detuning (Hz) from F=3 to F'=3 -9.2 10.5
delta2=-124e6;                                 %MOT detuning (Hz) from F=3 to F'=4
```

```
%% Initail parameters
```

```
Temperature=280e-6;                                 %temperature of atom in dipole trap (K)
N=1000;                                             %number of single atom in the trap
dt=1e-7;                                            %time in each time step (s)
total_step=1e6;                                     %total number of steps
no_point=100;
cooling=1;
evo=1;
coll=1;
fig=0;
save_data=1;
if no_point< total_step
no_s=total_step/no_point;%number of step to save data
else
no_s=1;
end
%set number for check atom in trap after cooling and collision
if total_step>=1e6
    no_c=1e4;
else
    no_c=no_s;
end
```

```
%% Collision parameters
delta_coll=-45e6;                                   %Coll. detunning at the bottom of trap (Hz)
delta_E_coll=delta_coll*hbar*2*pi;
C3_au=20.13;                                        %C3 in a.u. unit
C3=C3_au*27.2*0.53^3*1.60210e-19*1e-30;
Rc=(C3/(abs(delta_coll)*hbar*2*pi))^(1/3);          %Condon radius (m)
I_over_Isat=0.42*6.7;                               %I_coll/I_sat=0.4175 *6.7 for 221nW -45MHz
```

```
%% Create sigle atoms in dipole trap from initial conditions
xpretty=1e-6*linspace(-5,5,500);
ypretty=xpretty;
zpretty=1e-6*linspace(-150,150,500);
[dUdX junk junk U0 zR]=grad_dipole_potential_3D(xpretty,0,0);
[junk dUdY junk U0 zR]=grad_dipole_potential_3D(0,ypretty,0);
[junk junk dUdZ U0 zR]=grad_dipole_potential_3D(0,0,zpretty);
%[junk junk dUdZ U0 zR]=grad_dipole_potential_3D(0,0,0);
p_min=exp(U0/(Kb*Temperature))+0.0001;
sigma_x=sqrt(-0.5*w0^2*log((-Kb*Temperature*(log(p_min))+U0)/U0));
sigma_y=sigma_x;
sigma_z=zR*sqrt(U0/(-Kb*Temperature*log(p_min+0.003)+U0)-1);
xi=sqrt(Kb*Temperature/mass);
atom_ic=zeros(N,7);
atom_counter=0;
while atom_counter<N
```

```
%Random position and velocity
    x1_ic=zeros(N ,1);                                  %x initial position
    x2_ic=xi*randn(N,1);                                %x initial velocity  = Normally distributed with a st dev of sqrt(kt/m)
    x3_ic=zeros(N,1);                                   %y initial position
    x4_ic=xi*randn(N,1);                                %y initial velocity
    x5_ic=zeros(N,1);                                   %z initial position
    x6_ic=xi*randn(N,1);                                %z initial velocity
%create spatial distribution by p(x,y,z)=exp(U(x,y,z)/KbT)/exp(U0/KbT)
    atoms_in_trap_before= zeros(N,1);
    for counter=1:N
        while atoms_in_trap_before(counter)==0
            x1_ic(counter)=(2*rand-1)*sigma_x;
            x3_ic(counter)=(2*rand-1)*sigma_y;
            x5_ic(counter)=(2*rand-1)*sigma_z;
            if rand<exp((abs((dipole_potential_3D(x1_ic(counter),x3_ic(counter),x5_ic(counter))))+U0)./(Kb*Temperature))
                atoms_in_trap_before(counter)=1;
            end
        end
    end
    Init_cond=zeros(N,7);
    Init_cond(:,1)=x1_ic;
    Init_cond(:,2)=x2_ic;
    Init_cond(:,3)=x3_ic;
    Init_cond(:,4)=x4_ic;
    Init_cond(:,5)=x5_ic;
    Init_cond(:,6)=x6_ic;
    Init_cond(:,7)=sqrt(x2_ic.^2 + x4_ic.^2 + x6_ic.^2);  %initial SPEED (as opposed to velocity)
%Atom is in trap or not, by Ek(v^2)<=U(x,y,z)
    c2=find(0.5*mass*Init_cond(:,7).^2 <= abs(dipole_potential_3D(Init_cond(:,1),Init_cond(:,3),Init_cond(:,5))));
    for i=1:min(length(c2),N-atom_counter)
        atom_ic(i+atom_counter,:)=Init_cond(c2(i),:);
    end
    atom_counter=atom_counter+min(length(c2),N-atom_counter);
end
Initial_T=mass*mean(atom_ic(:,7).^2)/(3*Kb);
```

```
%% Evolution of each atom in trap
%create initial value of all parameter
k1=zeros(N,6);k2=zeros(N,6);k3=zeros(N,6);k4=zeros(N,6);
atom_fc=zeros(N,7);
atom_E=zeros(N,total_step/no_s,3);
ii=1;
abs_rate=zeros(N,6);
Final_T=zeros(total_step/no_s+1,1);
Final_T(1)=Initial_T;
atom_mU=zeros(total_step/no_s+1,1);
```

```
atom_mU(1)=mean(dipole_potential_3D(atom_ic(:,1),atom_ic(:,3),atom_ic(:,5)));
atom_s=zeros(N,7,total_step/no_s);
atom_N=zeros(total_step/no_s+1,1);
atom_N(1)=N;
atom_delta=zeros(N/2,7);
atom_delta_dt=zeros(N/2,7);
coll_counter=zeros(N/2,4);
alpha=zeros(N/2,1);
single_atom_lost=0;
pair_lost=0;
no_atom_lost=0;
atom_in_trap_after=ones(N,2);
atom_in_trap_after(:,2)=0;
last_coll=zeros(N/2,1);
delta_released_max=500e6+abs(delta_coll);              %set maximum energy that can released
Rmin=(C3/((delta_released_max*hbar*2*pi))^(1/3);       %calculat R relative with E_released_max
N_R=1000;                                              %number of step to devide R from Rc to Rmin
R_released=linspace(Rc,Rmin,N_R)';
dR=zeros(N_R,1);
dR(2:N_R)=R_released(1)-R_released(2);
tic
for no_step=1:total_step
%calcurate photon absorbtion rate of atom
    if cooling==1
    %for F=3 to F'=3
    abs_rate(:,1)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta-2*pi./lambda2*atom_ic(:,2))./gamma2).^2); %for photon +x direction
    abs_rate(:,2)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta+2*pi./lambda2*atom_ic(:,2))./gamma2).^2); %for photon -x direction
    abs_rate(:,3)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta-2*pi./lambda2*atom_ic(:,4))./gamma2).^2); %for photon +y direction
    abs_rate(:,4)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta+2*pi./lambda2*atom_ic(:,4))./gamma2).^2); %for photon -y direction
    abs_rate(:,5)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta-2*pi./lambda2*atom_ic(:,6))./gamma2).^2); %for photon +z direction
    abs_rate(:,6)=dt*0.5*gamma2*(I_MOT/Is)./(1+I_MOT/Is+(2*(2*pi*delta+2*pi./lambda2*atom_ic(:,6))./gamma2).^2); %for photon -z direction
    abs_rand=rand(N,6);                                %creat random matrix for checking propabilty of absorbtion each photon
    %fine atoms that absorb photon, index of atoms be contain in abs_1
    %also check atom out of trap
    abs_1=find(abs_rand(:,1)<=abs_rate(:,1) & atom_in_trap_after(:,1)==1 );
    abs_2=find(abs_rand(:,2)<=abs_rate(:,2) & atom_in_trap_after(:,1)==1 );
    abs_3=find(abs_rand(:,3)<=abs_rate(:,3) & atom_in_trap_after(:,1)==1 );
    abs_4=find(abs_rand(:,4)<=abs_rate(:,4) & atom_in_trap_after(:,1)==1 );
    abs_5=find(abs_rand(:,5)<=abs_rate(:,5) & atom_in_trap_after(:,1)==1 );
    abs_6=find(abs_rand(:,6)<=abs_rate(:,6) & atom_in_trap_after(:,1)==1 );
    %atom absorb and emit photon for photon +x direction
    %let atoms that absorb photon change velocity
    for abs_1i=1: length(abs_1)
        atom_ic(abs_1(abs_1i),2)=atom_ic(abs_1(abs_1i),2)+hbar*k_lambda2/mass;%atoms change velocity in x direction cause of absorbtion
        emit=rand(2,1);                                %random direction for emitting photon
        emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
```

```
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    %atoms change velocity in x direction cause of emittion photon
    atom_ic(abs_1(abs_1i),2)=atom_ic(abs_1(abs_1i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    %atoms change velocity in y direction cause of emittion photon
    atom_ic(abs_1(abs_1i),4)=atom_ic(abs_1(abs_1i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    %atoms change velocity in z direction cause of emittion photon
    atom_ic(abs_1(abs_1i),6)=atom_ic(abs_1(abs_1i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon -x direction
for abs_2i=1: length(abs_2)
    atom_ic(abs_2(abs_2i),2)=atom_ic(abs_2(abs_2i),2)-hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_2(abs_2i),2)=atom_ic(abs_2(abs_2i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_2(abs_2i),4)=atom_ic(abs_2(abs_2i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_2(abs_2i),6)=atom_ic(abs_2(abs_2i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon +y direction
for abs_3i=1: length(abs_3)
    atom_ic(abs_3(abs_3i),4)=atom_ic(abs_3(abs_3i),4)+hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_3(abs_3i),2)=atom_ic(abs_3(abs_3i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_3(abs_3i),4)=atom_ic(abs_3(abs_3i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_3(abs_3i),6)=atom_ic(abs_3(abs_3i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon -y direction
for abs_4i=1: length(abs_4)
    atom_ic(abs_4(abs_4i),4)=atom_ic(abs_4(abs_4i),4)-hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_4(abs_4i),2)=atom_ic(abs_4(abs_4i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_4(abs_4i),4)=atom_ic(abs_4(abs_4i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_4(abs_4i),6)=atom_ic(abs_4(abs_4i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon +z direction
for abs_5i=1: length(abs_5)
    atom_ic(abs_5(abs_5i),6)=atom_ic(abs_5(abs_5i),6)+hbar*k_lambda2/mass;
    emit=rand(2,1);
```

```
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_5(abs_5i),2)=atom_ic(abs_5(abs_5i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_5(abs_5i),4)=atom_ic(abs_5(abs_5i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_5(abs_5i),6)=atom_ic(abs_5(abs_5i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
%atom absorb and emit photon for photon -z direction
for abs_6i=1: length(abs_6)
    atom_ic(abs_6(abs_6i),6)=atom_ic(abs_6(abs_6i),6)-hbar*k_lambda2/mass;
    emit=rand(2,1);
    emit_norm(1)=sin(pi*emit(2))*cos(2*pi*emit(1));
    emit_norm(2)=sin(pi*emit(2))*sin(2*pi*emit(1));
    emit_norm(3)=cos(pi*emit(2));
    atom_ic(abs_6(abs_6i),2)=atom_ic(abs_6(abs_6i),2)-emit_norm(1)*hbar*k_lambda2/mass;
    atom_ic(abs_6(abs_6i),4)=atom_ic(abs_6(abs_6i),4)-emit_norm(2)*hbar*k_lambda2/mass;
    atom_ic(abs_6(abs_6i),6)=atom_ic(abs_6(abs_6i),6)-emit_norm(3)*hbar*k_lambda2/mass;
end
end

%evolution of atom 1 by using the fourth-order RungeñKutta method
if evo==1
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1),atom_ic(:,3),atom_ic(:,5));    %dUdX = (dU/dx)/mass+9.8 dUdY=(dU/dy)/mass
k1(:,1)=dt*atom_ic(:,2);
k1(:,2)=dt*(-dUdX);
k1(:,3)=dt*atom_ic(:,4);
k1(:,4)=dt*(-dUdY);
k1(:,5)=dt*atom_ic(:,6);
k1(:,6)=dt*(-dUdZ);
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1)+k1(:,1)./2,atom_ic(:,3)+k1(:,3)./2,atom_ic(:,5)+k1(:,5)./2);
k2(:,1)=dt*(atom_ic(:,2)+k1(:,2)./2);
k2(:,2)=dt*(-dUdX);
k2(:,3)=dt*(atom_ic(:,4)+k1(:,4)./2);
k2(:,4)=dt*(-dUdY);
k2(:,5)=dt*(atom_ic(:,6)+k1(:,6)./2);
k2(:,6)=dt*(-dUdZ);
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1)+k2(:,1)./2,atom_ic(:,3)+k2(:,3)./2,atom_ic(:,5)+k2(:,5)./2);
k3(:,1)=dt*(atom_ic(:,2)+k2(:,2)./2);
k3(:,2)=dt*(-dUdX);
k3(:,3)=dt*(atom_ic(:,4)+k2(:,4)./2);
k3(:,4)=dt*(-dUdY);
k3(:,5)=dt*(atom_ic(:,6)+k2(:,6)./2);
k3(:,6)=dt*(-dUdZ);
[dUdX dUdY dUdZ U0 zR]=grad_dipole_potential_3D(atom_ic(:,1)+k3(:,1),atom_ic(:,3)+k3(:,3),atom_ic(:,5)+k3(:,5));
k4(:,1)=dt*(atom_ic(:,2)+k3(:,2));
k4(:,2)=dt*(-dUdX);
```

```
k4(:,3)=dt*(atom_ic(:,4)+k3(:,4));
k4(:,4)=dt*(-dUdY);
k4(:,5)=dt*(atom_ic(:,6)+k3(:,6));
k4(:,6)=dt*(-dUdZ);
atom_fc(:,1:6)=atom_ic(:,1:6)+(k1+2*k2+2*k3+k4)./6;
end

%Check collision event
if coll==1 && evo==1
atom_delta(:,[1 3 5])=atom_ic(1:N/2,[1 3 5])-atom_ic((N/2+1):N,[1 3 5]);
atom_delta(:,[2 4 6])=(atom_fc(1:N/2,[1 3 5])-atom_ic(1:N/2,[1 3 5]))./dt-(atom_fc((N/2+1):N,[1 3 5])-atom_ic((N/2+1):N,[1 3
                                                                                                                    5]))./dt;  %estimate that atom
atom_delta(:,7)=sqrt(atom_delta(:,2).^2+atom_delta(:,4).^2+atom_delta(:,6).^2);
atom_delta_R_sqr=atom_delta(:,1).^2+atom_delta(:,3).^2+atom_delta(:,5).^2;
atom_delta_RdotV=atom_delta(:,1).*atom_delta(:,2)+atom_delta(:,3).*atom_delta(:,4)+atom_delta(:,5).*atom_delta(:,6);
t_Rmin=-atom_delta_RdotV./atom_delta(:,7).^2;
atom_delta_dt(:,1:6)=atom_fc(1:N/2,1:6)-atom_fc((N/2+1):N,1:6);
atom_delta_dt_R_sqr=atom_delta_dt(:,1).^2+atom_delta_dt(:,3).^2+atom_delta_dt(:,5).^2;
%collision conditions
c9=find((t_Rmin>0) & ((atom_delta_R_sqr-t_Rmin.^2.*atom_delta(:,7).^2)<=Rc^2) & ((t_Rmin<=dt)|(atom_delta_dt_R_sqr<=Rc^2)));
if ~isempty(c9)
%check that atom was not check in the last time step & atoms still in trap
c3=find((no_step>last_coll(c9)+1) & (atom_in_trap_after(c9,1).*atom_in_trap_after(c9+N/2,1)==1));
    %check that atom did not collide in previous time step
    last_coll(c9)=no_step;
    c9=c9(c3);
if ~isempty(c9)
    t_coll=(-2*atom_delta_RdotV(c9)-sqrt((2*atom_delta_RdotV(c9)).^2-4*atom_delta(c9,7).^2.*(atom_delta_R_sqr(c9)-
                                                                Rc^2)))./(2*atom_delta(c9,7).^2);  %time that collision happen
    %shift time and atom parameter to time that collision happen
    for j=1:length(c9)
        atom_ic(c9(j),:)=atom_ic(c9(j),:)+t_coll(j)*(atom_fc(c9(j),:)-atom_ic(c9(j),:))./dt;
        atom_ic(c9(j)+N/2,:)=atom_ic(c9(j)+N/2,:)+t_coll(j)*(atom_fc(c9(j)+N/2,:)-atom_ic(c9(j)+N/2,:))./dt;
    end
    atom_delta(c9,:)=atom_ic(c9,:)-atom_ic(c9+N/2,:);                                   %relative R and v at R=Rc
    %calculate propability that inelastic collision happen
    atom_delta_RdotV=atom_delta(c9,1).*atom_delta(c9,2)+atom_delta(c9,3).*atom_delta(c9,4)+atom_delta(c9,5).*atom_delta(c9,6);
    atom_delta_R_sqr=atom_delta(c9,1).^2+atom_delta(c9,3).^2+atom_delta(c9,5).^2;
    atom_delta_speed=-atom_delta_RdotV./sqrt(atom_delta_R_sqr);                         %relative speed in relative R direction
    gamma=I_over_Isat*hbar*Rc^4*gamma1^2./(2*pi*6*C3*atom_delta_speed);
    P_a=1-exp(-gamma);
    P_coll=P_a + P_a.*exp(-gamma).^2.*(1+P_a.^2+P_a.^4+P_a.^6+P_a.^8+P_a.^10+P_a.^12+P_a.^14+P_a.^16+P_a.^18+P_a.^20);
    P_rand=rand(length(P_coll),1);
    c6=find(P_rand<=P_coll);                                                    %check whitch pairs have an inelastic coll
    if ~isempty(c6)
        c9=c9(c6);                                                              %assign new index that coll. happen
```

```
        atom_delta_speed=atom_delta_speed(c6);                          %assign new radial relative speed of pairs that collide
        %calculate the released energy
        Er=zeros(length(c9),1);
        atom_delta(c9,7)=sqrt(atom_delta(c9,2).^2+atom_delta(c9,4).^2+atom_delta(c9,6).^2);
        l=sqrt(atom_delta(c9,7).^2-atom_delta_speed.^2).*Rc.*mass.*0.5;                  %initail angular momentum
        for k=1:length(c9)
            U_R_eff=-C3./R_released.^3+l(k)^2./(mass.*R_released.^2);                    %U(R)+centrifugal potential
            S_tau=cumsum(dR./sqrt(atom_delta_speed(k).^2-2./(0.5*mass).*(U_R_eff-U_R_eff(1))));
            S_tau(imag(S_tau)~=0)=inf;
            S=exp(-2.*gamma1.*S_tau);                                                    %survival prop.
            Er(k)=C3/(R_released(find(S>rand,1,'last'))^3)-abs(delta_E_coll);             %released energy from atom roll down U(R)
        end
        atom_delta_R_sqr=atom_delta(c9,1).^2+atom_delta(c9,3).^2+atom_delta(c9,5).^2;
        atom_delta_RdotV=atom_delta(c9,1).*atom_delta(c9,2)+atom_delta(c9,3).*atom_delta(c9,4)+atom_delta(c9,5).*atom_delta(c9,6);
        alpha=(atom_delta_RdotV+sqrt(4*Er.*atom_delta_R_sqr./mass+atom_delta_RdotV.^2))./(2*atom_delta_R_sqr);
        atom_fc([c9 c9+N/2],[1 3 5])=atom_ic([c9 c9+N/2],[1 3 5]);                  %set new position after collision for both atom
        coll_counter(c9,1)=coll_counter(c9,1)+1;
        for j=1:length(c9)
            %set new velocity after collision
            atom_fc(c9(j),[2 4 6])=atom_ic(c9(j),[2 4 6])-alpha(j)*atom_delta(c9(j),[1 3 5]);          %for 1st atom
            atom_fc(c9(j)+N/2,[2 4 6])=atom_ic(c9(j)+N/2,[2 4 6])+alpha(j).*atom_delta(c9(j),[1 3 5]);  %for 2nd atom
            atom_fc([c9(j) c9(j)+N/2],7)=sqrt(atom_fc([c9(j) c9(j)+N/2],2).^2+atom_fc([c9(j) c9(j)+N/2],4).^2+atom_fc([c9(j)
                                                                                c9(j)+N/2],6).^2); %calculate new speed
            c8=find(0.5*mass*atom_fc([c9(j) c9(j)+N/2],7).^2 > abs(dipole_potential_3D(atom_fc([c9(j) c9(j)+N/2],1),atom_fc([c9(j)
                                                                              c9(j)+N/2],3),atom_fc([c9(j) c9(j)+N/2],5))));

            if isempty(c8)
                no_atom_lost=no_atom_lost+1;
            elseif length(c8)==2
                pair_lost=pair_lost+1;
                coll_counter(c9(j),3)=Er(j);
                coll_counter(c9(j),4)=atom_delta(c9(j),7);
                atom_in_trap_after([c9(j) c9(j)+N/2],1)=0;
                atom_in_trap_after([c9(j) c9(j)+N/2],2)=no_step;
            elseif length(c8)==1
                single_atom_lost=single_atom_lost+1;
                coll_counter(c9(j),2)=Er(j);
                coll_counter(c9(j),4)=atom_delta(c9(j),7);
                index=[c9(j) c9(j)+N/2];
                atom_in_trap_after(index(c8),1)=0;
                atom_in_trap_after(index(c8),2)=no_step;
            end
        end
    end
end
end
end
```

```
    if evo==1
        atom_ic=atom_fc;
    else
        atom_fc=atom_ic;
    end
    %check that atom still be in trap
    if mod(no_step,no_c)==0
        atom_fc(:,7)=sqrt(atom_fc(:,2).^2+atom_fc(:,4).^2+atom_fc(:,6).^2);
        c10=find(0.5*mass*atom_fc(:,7).^2 > abs(dipole_potential_3D(atom_fc(:,1),atom_fc(:,3),atom_fc(:,5))) &
                                                                                    atom_in_trap_after(:,1)==1);
        atom_in_trap_after(c10,1)=0;
        atom_in_trap_after(c10,2)=no_step;
    end
    %save parameter at each no_s steps
    if ii==no_step/no_s
        atom_fc(:,7)=sqrt(atom_fc(:,2).^2+atom_fc(:,4).^2+atom_fc(:,6).^2);
        %save energy of each atom
        atom_E(:,ii,1)=0.5*mass*atom_fc(:,7).^2 ;
        atom_E(:,ii,2)=dipole_potential_3D(atom_fc(:,1),atom_fc(:,3),atom_fc(:,5));
        atom_E(:,ii,3)=atom_E(:,ii,1)+atom_E(:,ii,2);
        %save mean enery of atoms
        c11=find(atom_in_trap_after(:,1)==1);
        Final_T(ii+1)=mass*mean(atom_fc(c11,7).^2)/(3*Kb);
        atom_N(ii+1)=length(c11);
        atom_s(:,:,ii)=atom_fc;
        ii=ii+1;
    end
end
toc
```

```
%% Plot parameter for checking
if fig==1
t=linspace(0,total_step*dt,total_step/no_s+1);
figure;
plot(t,Final_T,'k')
```

```
%% Check atoms in trap or not
two_atoms=zeros(no_step/no_s+1,1);
one_atom=zeros(no_step/no_s+1,1);
zero_atom=zeros(no_step/no_s+1,1);
two_atoms(1)=N/2;
for kk=1:no_step/no_s
    for k=1:N/2
        c5=find(atom_in_trap_after([k k+N/2],1)==1 | (atom_in_trap_after([k k+N/2],2)./no_s>kk | atom_in_trap_after([k k+N/2],2)==0));
        if isempty(c5)
```

```
            zero_atom(kk+1)=zero_atom(kk+1)+1;
        elseif length(c5)==1
            one_atom(kk+1)=one_atom(kk+1)+1;
        elseif length(c5)==2
            two_atoms(kk+1)=two_atoms(kk+1)+1;
        end
    end
end
figure;
plot(t,two_atoms.*2./N,'b.')
hold on
plot(t,one_atom.*2./N,'r.')
hold on
plot(t,zero_atom.*2./N,'g.')
end
```

```
%% Save data
if save_data==1
    clk=clock;
    save_name=sprintf('%s-%d-%d-N%dpairs-T%duK-dt%dns-cooling=%d-
                                                    Detunning%dMHz',date,clk(4),clk(5),N/2,Temperature*1e6,dt*1e9,cooling,delta_coll/1e6);
    save(save_name);
end
```

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Scholarship

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Presentation

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Publications

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5. N. Thaicharoen, A Chayakul, **P. Sompet**, N. Chattrapiban, and W. Anukool, "The First Magneto-Optical Trap in Thailand and Beyond," Proceeding of the 1st ASEAN Plus Three Graduate Research Congress, Chiang Mai, Thailand (2012).