

## DENSITY EFFECTS FOR BINARY COLLISIONS OF COOLED TRAPPED ATOMS

R.Z. Vitlina, V.S. Bagnato, G.I. Surdutovich and J. Weiner\*

Instituto de Física de São Carlos, Universidade de São Paulo  
Caixa Postal 369, 13560-970 São Carlos, SP, Brazil

\* Department of Chemistry and Biochemistry, University of Maryland  
Maryland 20742, USA

### ABSTRACT

It is demonstrated that with increase of the cooled atoms density the intermediate between paired and multi-particles processes start to play a predominant role even under conditions of small gas parameter  $\beta = nf^3 \ll 1$ , where  $n$  is the trapped atom density and  $f$  is the scattering amplitude of the binary collision. The influence of the environment, i.e. background gas density effects, on the process of excitation transfer between atoms is illustrated through the example of the Rb isotopes. The condition on the trapped, cooled atoms density for observation of such effects is deduced.

### 1. INTRODUCTION

The advances made during the last years in laser cooling and trapping of neutral atoms open new possibilities of investigation of atomic collisions. Unlike thermal collisions these processes have some particular features: (i) the duration of the collision is longer or comparable with lifetime of excited state; and (ii) the kinetic energy  $E$  of the relative motion is on the order of the natural linewidth.

Collisional loss processes are very important for determination of the particle residence time in an optical trap [1]. For the calculation of the collisional parameters (probability and cross section) we limit ourselves to binary collisions. However, with decrease of the kinetic energy of the particles a new "collisional channel" opens. This collisional process is an intermediate one between binary and multi-particle processes and has been dis-

cussed, for example, in the case of charge exchange and excitation transfer at conventional temperatures [2,3]. Thus, for example, in case where the condition of binary collisions is satisfied for the resonant charge exchange process, the interaction between colliding particles and surrounding background gas may transform the potential terms of the colliding pair and convert this process to a nonresonant one. On the other hand, for a nonresonant two-body process, the interaction with surrounding particles may diminish the effective detuning  $\Delta$  and convert this process into the resonant one. Obviously, the influence of the environment becomes important for not-so-low densities only.

### 2. THEORETICAL MODEL

Here we investigate the process of the excitation transfer between cooled isotopes of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ . This system is especially suitable due to comparable ratio (3:1) of the natural isotope concentrations. Differences in ground state hyperfine structure of the Rb isotopes result in a shift of the optical transitions of the order of a few GHz. At typical temperatures for magneto-optical traps of a few hundred microkelvins the process of two-body excitation transfer has an exponentially small cross section. If one of the hyperfine levels  $5P_{1/2}$  of  $^{85}\text{Rb}$  is excited (see Fig. 1), then the dipole - dipole interaction forms the quasimolecule ( $^{85}\text{Rb} + ^{85}\text{Rb}^*$ ). An excited level of  $^{87}\text{Rb}$  becomes degenerate with one of the terms of this quasimolecule at some quasimolecular internuclear distance  $r_0$  (see Fig. 2). The probability of the excitation transfer between quasimolecule ( $^{85}\text{Rb} + ^{85}\text{Rb}^*$ ) and atom  $^{87}\text{Rb}$  is determined by the Landau - Zener formula in which coupling matrix elements depend on the

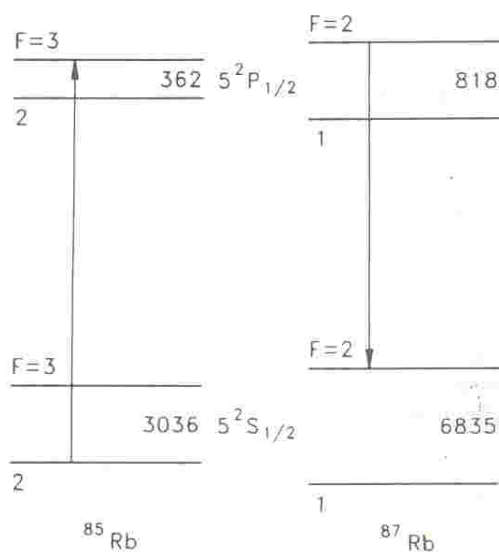
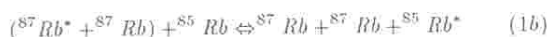
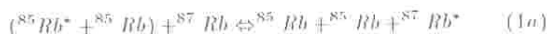


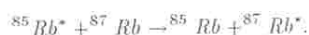
Fig. 1 - A scheme of the  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  isotopes levels.

distance  $R$  between the atom and the quasimolecule. It may be shown that typical values of  $R$  are larger than the characteristic internuclear distance of the quasimolecule  $r_0$ . In other words, in the vicinity of the atom  $^{87}\text{Rb}$ , the binary collisions of the atoms  $^{85}\text{Rb}$  and  $^{85}\text{Rb}^*$  take place and the colliding atoms with the impact parameter  $\rho$  smaller than the critical parameter  $\rho_0$  excite isotope  $^{87}\text{Rb}$ . Denote the Landau-Zener probability of the excitation transfer process as  $W(\rho, \vec{R}, v)$ , where  $v$  is the relative velocity of the collision. Here and further we restrict the term *collision* to motion of atoms forming the quasimolecule, although from the process of excitation transfer is the result of interaction ("collision") of this quasimolecule with isotope  $^{87}\text{Rb}$  atom. Further we imply that all Rb atoms have the same kinetic energy  $E$ . At the considered optical trap conditions the detuning  $\Delta$  is larger than the kinetic energy ( $\Delta \gg E$ ) and the only possible processes are ones where the level of  $^{87}\text{Rb}$  is situated lower than all excited level of  $^{87}\text{Rb}$  (see Fig.2).

We discuss two possible processes with participation of the Rb isotopes:



The competitive binary process is:



The cross section of this latter process is determined by the Stückelberg formula [4]. For  $\Delta \gg (\hbar v)^{3/2}/d$ , where  $d$  is the dipole matrix element of the transition, the cross section is exponentially small. In our case we take  $d \approx 3.2$  a.u.,  $T = 300 \mu\text{K}$ ,  $v = 30 \text{ cm.s}^{-1}$  and  $\Delta = 4 \text{ GHz}$ . The resulting exponent is equal to  $2.10^3$ . Therefore, a direct transfer of the excitation due to the binary process (1c) is extremely improbable and may be neglected.

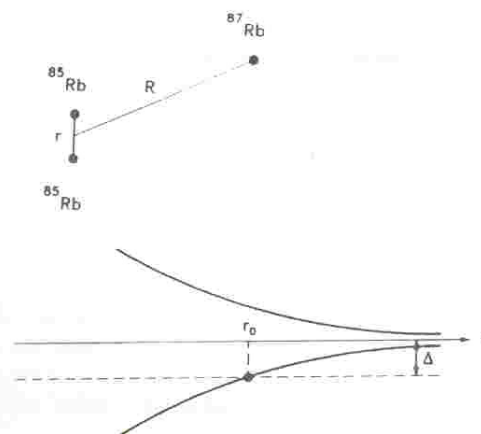


Fig. 2 - The schematic pattern of crossing of the quasimolecular ( $^{85}\text{Rb} + ^{87}\text{Rb}^*$ ) term with the  $^{87}\text{Rb}$  level without taking into account of the splitting  $\Sigma, \Pi$ .

### 3. CALCULATION OF THE RELAXATION FREQUENCY

The concept of the cross section is not useful for the processes (1a), (1b) but they may be characterized by the *excitation relaxation frequency* [3,5]. This frequency is equal to the rate of formation of quasimolecular pair collisions  $^{85}\text{Rb}^* + ^{85}\text{Rb}$  occurring in a unit time around the atom  $^{87}\text{Rb}$ , i.e.

$$\gamma = n^* n v \int W(\rho, \vec{R}, v) \exp\{-\Gamma_M t\} 2\pi \rho d\rho d^3 \vec{R} \quad (2)$$

$$W = 2e^{-\delta}(1 - e^{-\delta})$$

$$\delta = \frac{2\pi d^2}{v_r(r_0)|F_2 - F_1|_{r_0}}, \quad V^2 = d^4 \Phi^2 R^{-6}$$

The meaning of equation (2) is the following. The factor  $W(\rho, \vec{R}, v)$  in the integrand describes the probability of excitation transfer to the atom  $^{87}\text{Rb}$  at the distance  $R$  after passage by the pair of colliding  $^{85}\text{Rb}$  atoms at two Landau-Zener (LZ) points. The exponential factor describes the probability survival against spontaneous emission during time of the collision, and  $1/\Gamma_M$  is the lifetime of a quasimolecule due to the spontaneous radiation. Here  $n^*$ ,  $n$  are the densities of the excited and ground state  $^{85}\text{Rb}$  atoms,  $\Phi$  is the unitless angular function depending on the orientation of the vectors  $\vec{R}$  and  $\vec{d}$ ,  $E$  is the kinetic energy and  $v_r$  is modulo of the radial component of the relative velocity of the collision.

$$v_r = v \sqrt{1 + \frac{2d^2}{Er^3} - \rho^2/r^2}$$

At the (LZ) point  $\frac{2d^2}{r_0^3} = \Delta$  we get  $r_0 = \left(\frac{2d^2}{\Delta}\right)^{1/3}$  and then

$$v_r(r_0) = v \sqrt{1 + \frac{\Delta}{E} - \rho^2/r_0^2} \simeq v \sqrt{\frac{\Delta}{E} - \rho^2/r_0^2} \quad (3)$$

The difference of slopes of the terms in LZ point is equal to

$$|F_2 - F_1|_{r_0} = \frac{3\Delta^{1/3}}{2^{1/3}d^{2/3}}$$

In the calculation of the coupling matrix element of the interaction  $V$  between atom and quasimolecule we take the dipole moment of the quasimolecule equal to twice the atomic dipole moment. Finally time  $t$  in Eq.(2) is a classical time spent by atom in moving from a turning point  $\tilde{r}$ , where  $v_r(\tilde{r}) = 0$ , through two LZ-points

$$t = \int_{\tilde{r}}^{\tilde{r}} \frac{dr}{v_r} + \int_0^{\tilde{r}} \frac{dr}{v_r} \quad (4)$$

In distinction to the case considered in Ref. [1], for the present situation the distances between LZ point  $r_0$  and turning point  $\tilde{r}$  is comparable. Then similar to Ref.[3] calculations give for the excitation relaxation frequency  $\gamma$  the following result:

$$\gamma = 160n^*u \sqrt{\frac{v}{h}} \frac{d^{11/3}}{\Delta^{4/3}} \left\{ \left( \frac{\Delta}{E} \right)^{3/4} I(\alpha) \right\} \quad (5)$$

$$I(\alpha) = \int_0^1 \frac{y dy}{(1-y^2)^{1/4}} \exp \left\{ -\frac{\alpha}{y^5} \left[ \frac{3\pi}{4} + \varphi(y) \right] \right\}$$

$$\alpha = \frac{\Gamma_M r_0}{2} \frac{v}{v} \sqrt{\frac{E}{\Delta}}$$

$$\varphi(y) = -y^3 \sqrt{1-y^2} - \frac{3}{2} y \sqrt{1-y^2} + \frac{3}{2} \arcsin y$$

The factor in the curly brackets in Eq.(5) is large for cooled colliding atoms only. For thermal atoms it reduces to the constant  $2/3$ . The physical reason for this distinction is evident from Eq.(3): under small kinetic energy  $E$  and fixed detuning  $\Delta$  formation of a quasimolecule takes place with larger impact parameter  $\rho$ , than for thermal atoms.

#### 4. DISCUSSION

We present here some numerical estimations: for  $T = 300 \mu K$ ,  $v = 30 \text{ cm.s}^{-1}$ ,  $\Delta = 4 \text{ GHz}$ ,  $d = 3.2 \text{ a.u.}$ ,  $\Gamma_M = 2\Gamma_A = 7.4 \cdot 10^7 \text{ s}^{-1}$ , where  $\Gamma_A$  is the atomic linewidth. As a result from Eq.(5) we obtain  $\alpha \simeq 0.08$  and  $\gamma \simeq 2.6 \cdot 10^{-23} \text{ nm}^* \text{ s}^{-1}$ .

The formulas (2), (5) do not take into account the possibility of multiple oscillations of atoms in quasimolecule during the excited states lifetime, as was considered in Ref.[1]. However, the proper allowance of this effect gives only an additional factor  $C > 1$  in formula (5). It may be shown that this factor varies within the limits  $1.5 < C < 3$ .

The probability of such process during lifetime of excitation in quasimolecule is equal to  $\gamma \cdot \Gamma_M^{-1}$ . We must compare this

probability with the competitive process of the excitation of  $^{87}\text{Rb}$  atoms by the wing of the fluorescent linewidth of  $^{85}\text{Rb}$  transition. For Lorentzian form of line we obtain for the probability  $q$  of the competitive excitation

$$q = \frac{1}{2\pi} \left( \frac{\Gamma_A}{\Delta} \right)^2, \text{ for } \Delta \gg \Gamma_A (\Gamma_A = \Gamma_M/2). \quad (6)$$

Thus we come to the condition for observation of the considered effect

$$\gamma \cdot \Gamma_M^{-1} > \frac{1}{2\pi} \left( \frac{\Gamma_A}{\Delta} \right)^2 \quad (7)$$

Inequality (7) may be considered as a lower limit on the densities of the excited and unexcited atoms. For the given parameters it takes the form:

$$nn^* > 10^{24} \text{ cm}^{-6} \quad (8)$$

#### 5. CONCLUSION

In the Fig. 3 the optical transitions of Rb isotopes with the excited  $5P_{1/2}$  is shown [6]. A possible scheme for observation of the effect may be the following. Referring to Fig.3, we may excite A or B-lines of the  $^{85}\text{Rb}$  isotope. Then we will see only

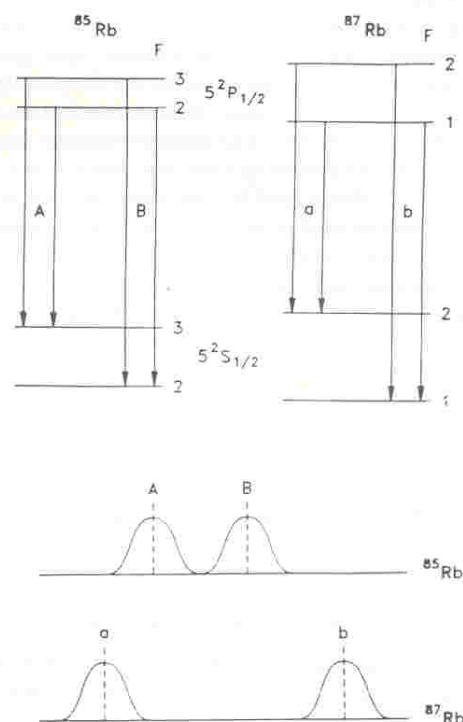


Fig. 3 - The pattern of the optical transitions in the rubidium isotopes.

fluorescence from the red-shifted  $a$ -line of  $^{87}\text{Rb}$ , arising from the process of Eq.(1a). However, if we excite  $b$ -line of  $^{87}\text{Rb}$  it gives the possibility to observe  $A$  and  $B$ -lines of  $^{87}\text{Rb}$ , arising from the process of Eq.(1b). In contrast excitation of the  $a$ -line of  $^{87}\text{Rb}$  does not allow possibility to observe any of the  $^{85}\text{Rb}$  isotopes lines. Eq.(8) shows that such a vivid distinction of the fluorescence patterns under excitation of the different isotope lines may be observed experimentally at densities  $n \sim 10^{12} \text{ cm}^{-3}$ . For smaller densities this distinction would be difficult to reveal. We considered here one of the examples when the environment not only influences on the binary processes but opens the possibilities for observation of the new processes. Such an influence of the environment may manifest itself in a form of the field from nearest neighbour atom, as in the considered case, or in the situation when contribution of all the environment, i.e. collective effects, is important, as in a case of the resonance charge exchange [2]. What is the physical reason of such a distinction? Due to the symmetry considerations it is evident that an average force from the random gas medium acting on the colliding pair of atoms is equal zero. If for any given configuration to separate this force into two parts as a force from the nearest neighbour and all the rest atoms then the corresponding average energies of interaction any of these parts will be equal. In other words, the distribution functions of the detunings for the nearest neighbour and collective effects models must be similar. Therefore, for any nonresonance process with sufficiently large detuning its compensation due to interaction with the environment may be fairly described in the limits of the nearest neighbour model, as it was done here. However, for essentially resonance processes, when not average form of the distribution function but its behaviour namely at small detunings is important, the situation changes in a cardinal manner. Since small detunings arise due to the symmetrical or nearly symmetrical spacial distributions of atoms around the colliding pair such distributions cannot spring

up due to the interaction with sole neighbour atom. Therefore distribution functions at small detunings in those models turn out to be very different and the nearest neighbour model might not be applied and so namely collective effects model is suitable. These general arguments totally correspond to the fluctuating gravitation force in the stellar dynamics processes where nearest neighbour model cannot provide satisfactory accuracy at small detunings and must be replaced for more general collective model (the Holtzmark's distribution function).

## 6. ACKNOWLEDGMENTS

The work is supported by FAPESP and CNPq foundation, Brazil.

## References

1. Gallagher, A and Pritchard, D.E. "Exoergic collisions of cold  $\text{Na}^* - \text{Na}$ "; *Phys. Rev. Lett.* **63**(9), 957-60, 1989.
2. Vitlina, R.Z. and Dykhne, A.M.: "Resonance charge exchange in high density gas"; *Sov. Phys. JETP* **37**(2), 260-62, 1973; Vitlina, R.Z. and Chaplik, A.V.: "Nonresonant charge exchange in dense gases"; *Sov. Phys. JETP* **43**(2), 280-82, 1976.
3. Vitlina, R.Z. and Chaplik, A.V.: "Excitation transfer in slow collisions in a dense gas"; *Sov. Phys. JETP* **44**(1), 83-86, 1976.
4. Mott, N.F. and Massey, H.S.W.: "The theory of atomic collisions"; Clarendon, Oxford, 650, 1987.
5. Kazantsev, A.P.: "Excitation of exciton type in a gas"; *Sov. Phys. JETP Lett.* **5**(1), 8-11, 1967.
6. Corney, A.: "Atomic and Laser Spectroscopy"; Clarendon, Oxford, 684, 1977.