Cold and Warm Atomic Physics

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Happy Birthday, Tony!
Thanks for everything!

Outline

- Definition of cold and warm AMO
- Working with Tony
- Qualitative features of cold-atom interactions

Cold and warm AMO

- Warm AMO
  - AMO working under Tony
- Cold AMO
  - AMO in the real world

Cold AMO
(My Life after Nebraska)

Cold AMO
(My Life after Nebraska)

Struggle!

Working hard,

but not getting anywhere

… with children like these

… it has not been easy!

Warm AMO
(Working under Tony)

Warm AMO
(Working under Tony)

Fun, love, and learning!

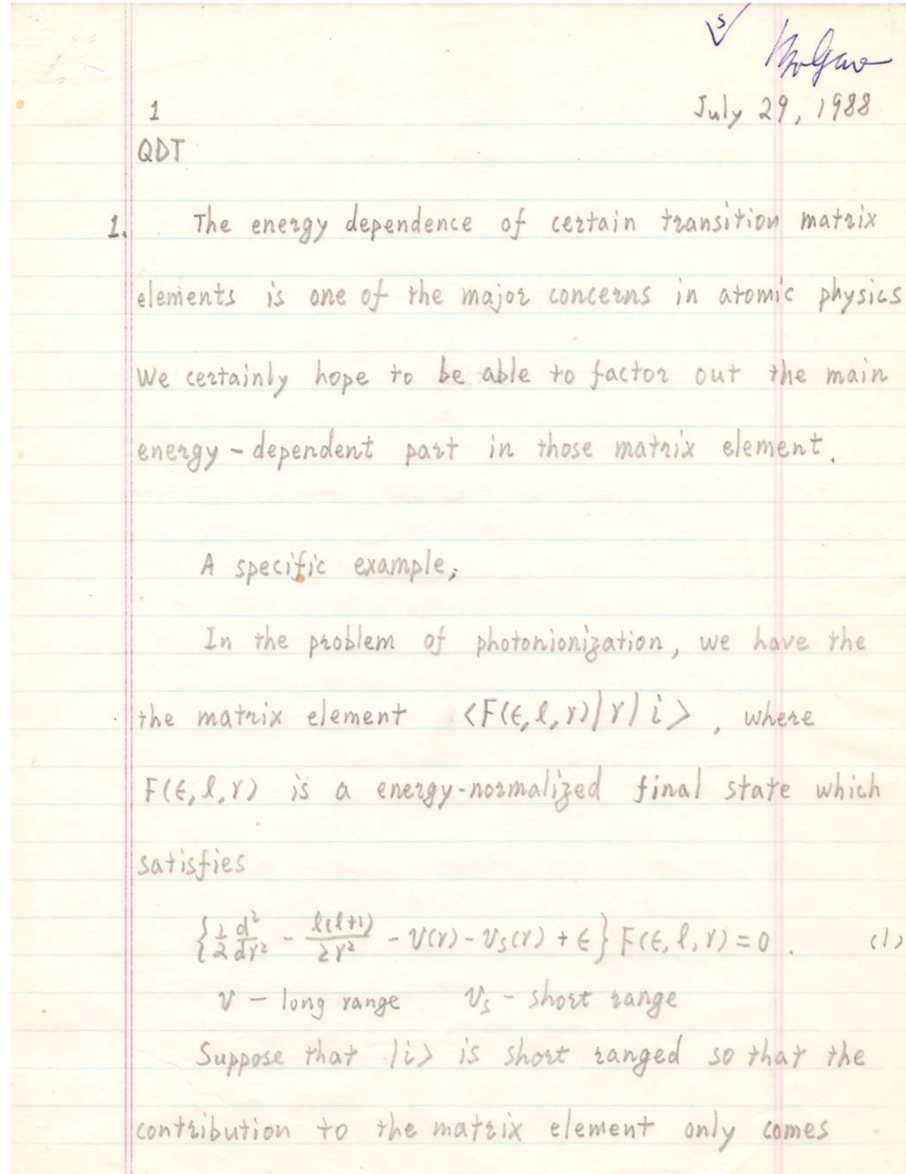
Fun

Love


Happy Silver Anniversary, Maria.
I love you!

… and learning

- There was no pressure.
- And it was not just for publications!



1 July 29, 1988

QDT

1. The energy dependence of certain transition matrix elements is one of the major concerns in atomic physics. We certainly hope to be able to factor out the main energy-dependent part in those matrix element.

A specific example;

In the problem of photonionization, we have the the matrix element $\langle F(\epsilon,l,r)|r|i\rangle$, where $F(\epsilon,l,r)$ is a energy-normalized final state which satisfies

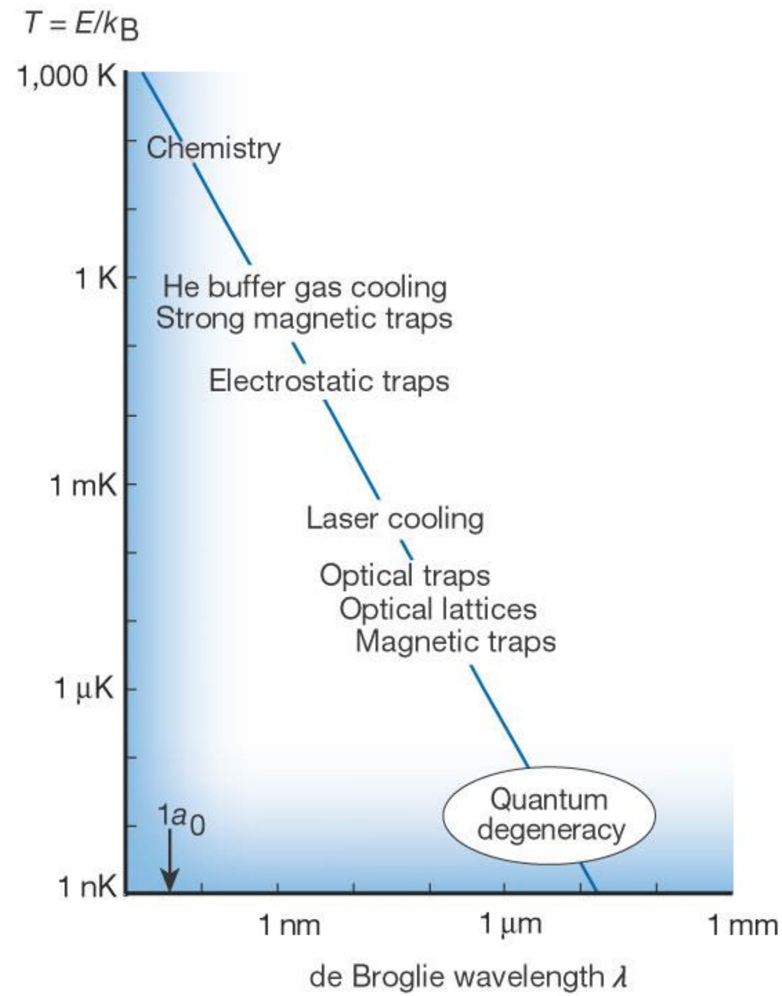
$$\left\{\frac{1}{2}\frac{d^2}{dr^2}-\frac{l(l+1)}{2r^2}-V(r)-V_s(r)+\epsilon\right\}F(\epsilon,l,r)=0 . \quad (1)$$

V — long range $\quad V_s$ - short range

Suppose that $|i\rangle$ is short ranged so that the contribution to the matrix element only comes

Major change since Nebraska days

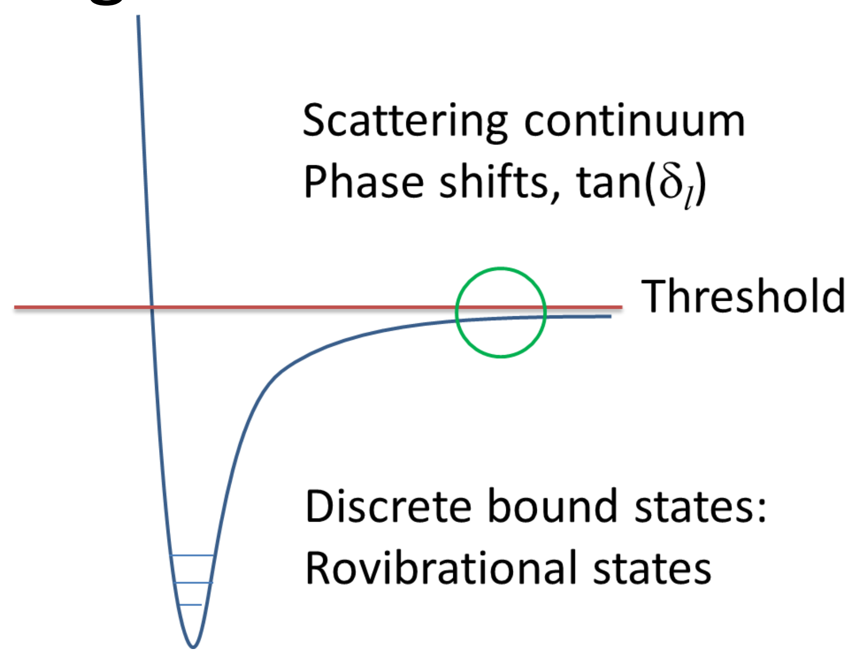
Various cooling schemes have achieved temperature scales far below the room temperature.



Understanding atomic interaction

- Bound states: molecular rovibrational states including vibrationally highly excited states
- Atom-atom scattering

±10 K (±1 meV) around the threshold.



Qualitative picture

1. What is the order of magnitude for the atomic scattering cross section?
2. And on what energy scale does it change?

1. Order of magnitude for atomic scattering cross section?

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Recall cross section is an area describing the effective size of an atom.

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Recall cross section is an area describing the effective size of an atom.

$$a_0^2$$

$a_0 \approx 0.53$ angstrom

Surprise #1

The effective size of an atom (ion) grows substantially at low temperatures!

Specifically,

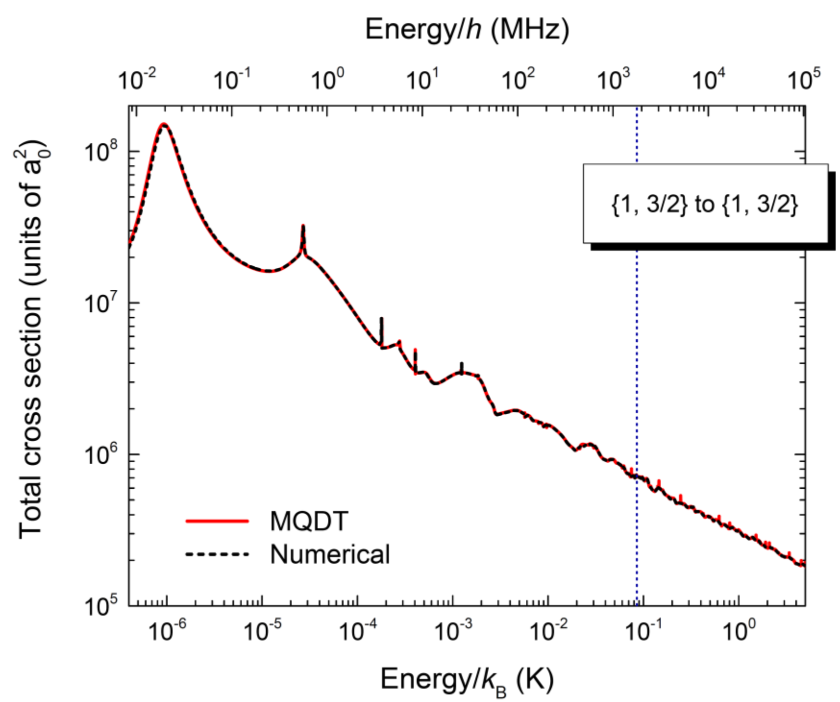
It grows to

- $\sim 10^4\ a_0^2$ for atom-atom
- $\sim 10^7\ a_0^2$ for ion-atom

in the limit of zero temperature.

Very substantial change!

Na+Na$^+$



Gao, PRL **104**, 213201 (2010),
Li, You, and Gao, PRA **89**, 052704 (2014).

Why?

Why?

The long-range interaction, which may be little felt at high temperatures, becomes very important at low temperatures.

- Neutral-neutral

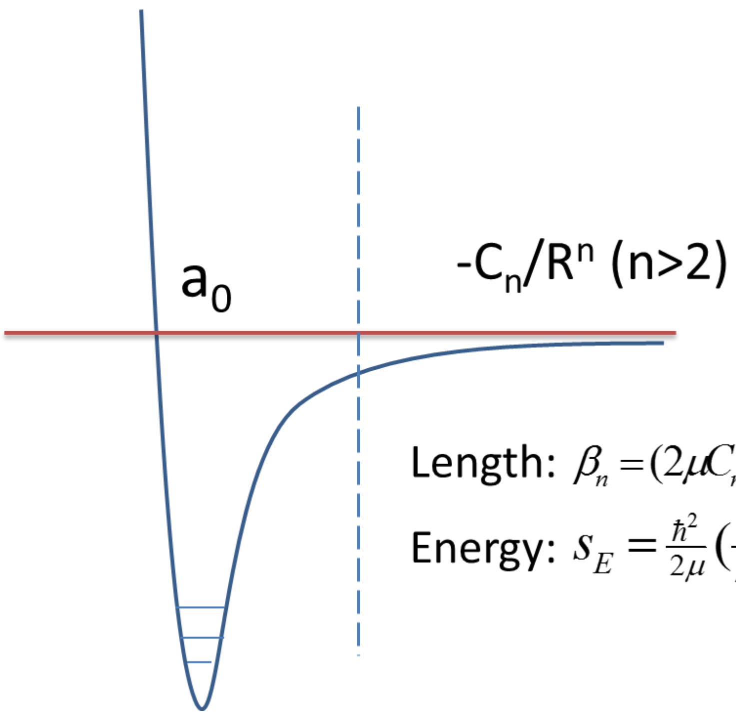
$$V \sim -C_6 / R^6$$

- Charge-neutral

$$V \sim -C_4 / R^4$$

The cross section grows to $\pi\beta_n^2$ with

$\beta_6 \sim 100\ a_0$
$\beta_4 \sim 1000\ a_0$



Length: $\beta_n = (2\mu C_n / \hbar^2)^{1/(n-2)}$

Energy: $s_E = \frac{\hbar^2}{2\mu}\left(\frac{1}{\beta_n}\right)^2$

2. On what energy scale does the interaction change?

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The vibrational energy scale of 100 K?

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The vibrational energy scale of 100 K?

Or the rotational energy scale of 1 K?

If any of these were true, …

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Theory of slow-atom collisions

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A general theory of slow-atom collisions is presented with special emphasis on the effects of nuclear statistics and atomic fine and/or hyperfine structures. Symmetry properties of the collision complex and correlations between the molecular states and the separated-atom states are carefully examined. The frame transformations between various angular momentum coupling schemes are derived, which, in combination with the multichannel quantum defect theory, provides a solid foundation for the computation and the physical interpretation of slow-atom collision processes. The theory reduces to those of Stoof *et al.* [Phys. Rev. B **38**, 4688 (1988)] and Zygelman *et al.* [Phys. Rev. A **49**, 2587 (1994); **50**, 3920 (1994)] in their respective ranges of validity. [S1050-2947(96)02108-7]

Hyperfine structure (0.1 K),

Nuclear statistics

Multichannel generalization of the ERT

Surprise #2

There is a rapid energy dependence, and tremendous amount of structure around the threshold.

Rapid energy dependence

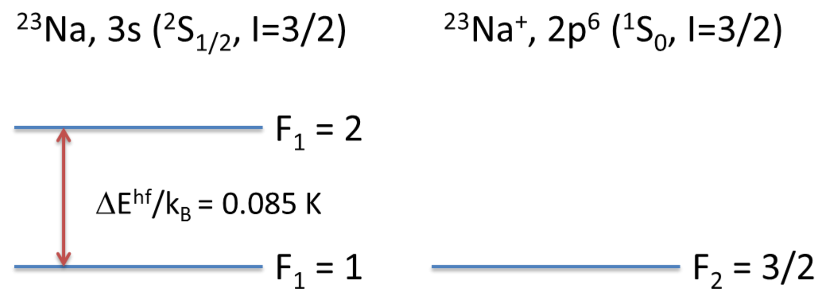
$Na(F_{1i}M_{1i})+Na^+(F_2M_{2i})$
$\rightarrow Na(F_{1j}M_{1j})+Na^+(F_2M_{2j})$

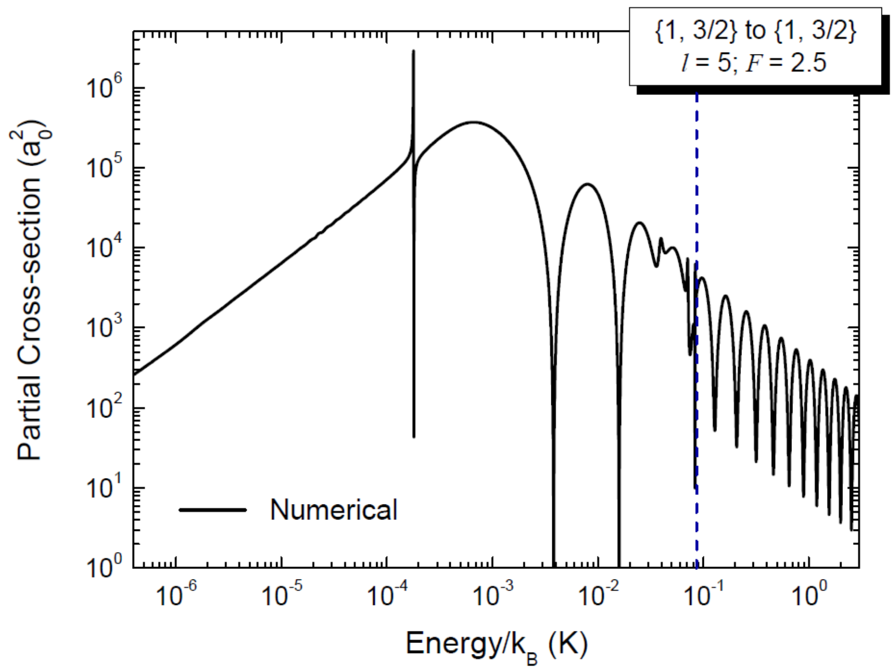
$F_2 = 3/2$ (Na^+, $2p^6\ {}^1S_0$, I=3/2)
$F_1 = 1, 2$ (Na, 3s $^2S_{1/2}$, I=3/2,
$\Delta E^{hf}/k_B = 0.085$ K)

Partial elastic cross section in channel F=5/2, *l*=5. ($\mathbf{F} = \mathbf{F}_1+\mathbf{F}_2$)

Many resonances (7) within a hyperfine interval.

Li, You, and Gao, PRA **89**, 052704 (2014).

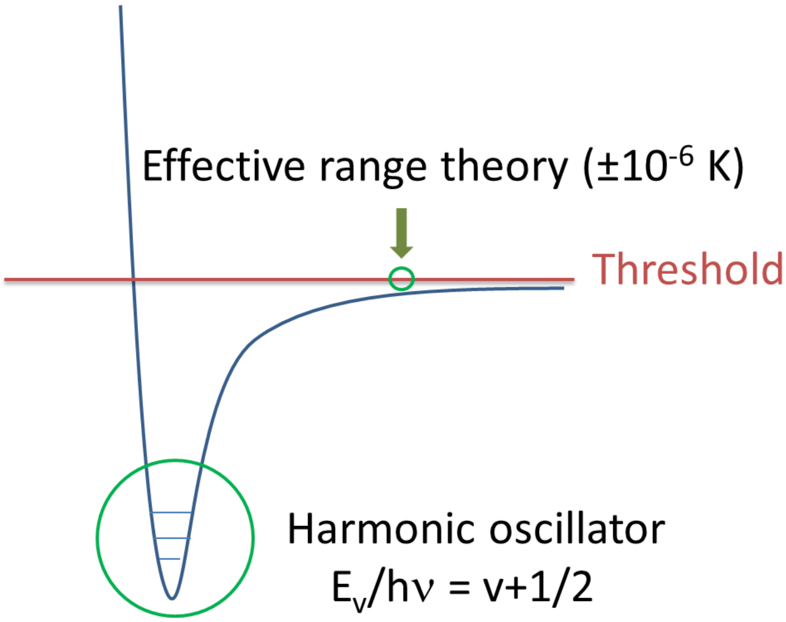




What has QDT accomplished

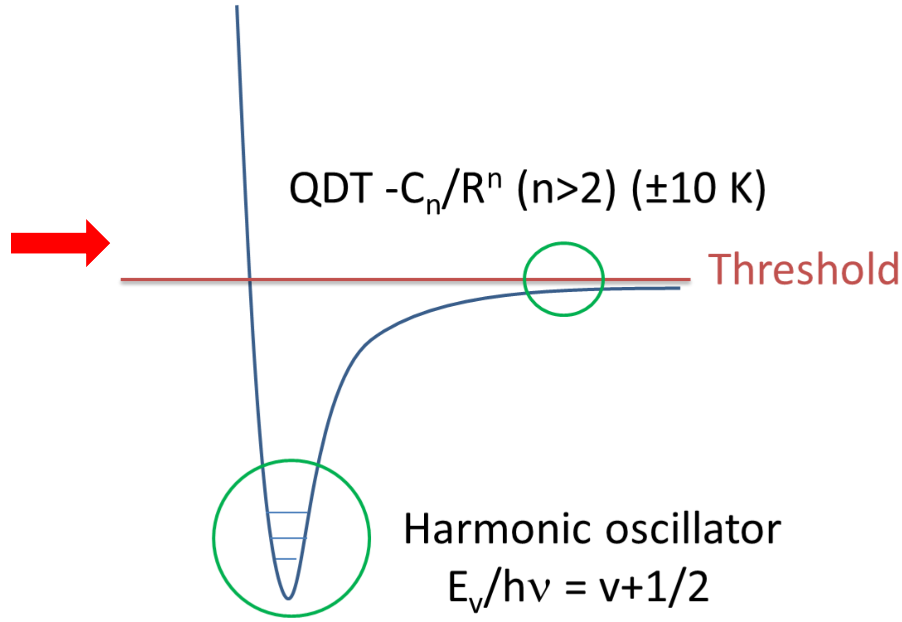
Before QDT

REGIONS OF UNIVERSAL BEHAVIOR



With QDT

REGIONS OF UNIVERSAL BEHAVIOR



Conclusion

- There is so much more to learn from Tony!

Be a happy and healthy physicist!