FESHBACH RESONANCE

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Feshbach resonances in ultracold gases

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Feshbach resonances are the essential tool to control the interaction between atoms in ultracold quantum gases. They have found numerous experimental applications, opening up the way to important breakthroughs. This review broadly covers the phenomenon of Feshbach resonances in ultracold gases and their main applications. This includes the theoretical background and models for the description of Feshbach resonances, the experimental methods to find and characterize the resonances, a discussion of the main properties of resonances in various atomic species and mixed atomic species systems, and an overview of key experiments with atomic Bose-Einstein condensates, degenerate Fermi gases, and ultracold molecules.

DOI: 10.1103/RevModPhys.82.1225 PACS number(s): 03.75.−b, 34.50.Cx, 67.85.−d

Átomos frios

Radiação microondas de fundo ~ 2.7K

Átomos frios ~ 400μK

Baixa energia cinética

Átomos neutros: ^{6}Li, ^{7}Li, ^{40}K, ^{87}Rb

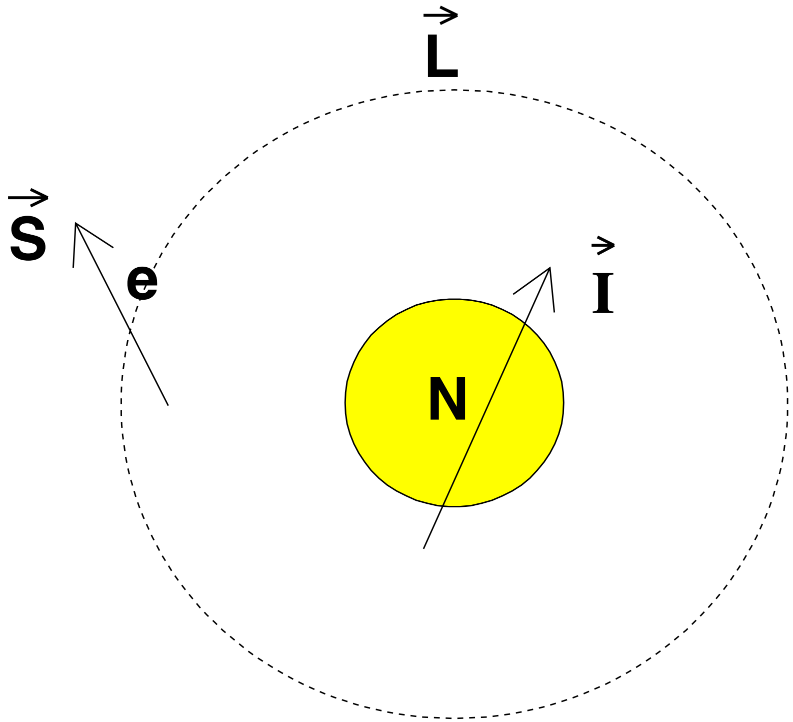
Spin

$^{6}Li = 3p + 3e + 3n$

Spin total semi-inteiro
(fermion)

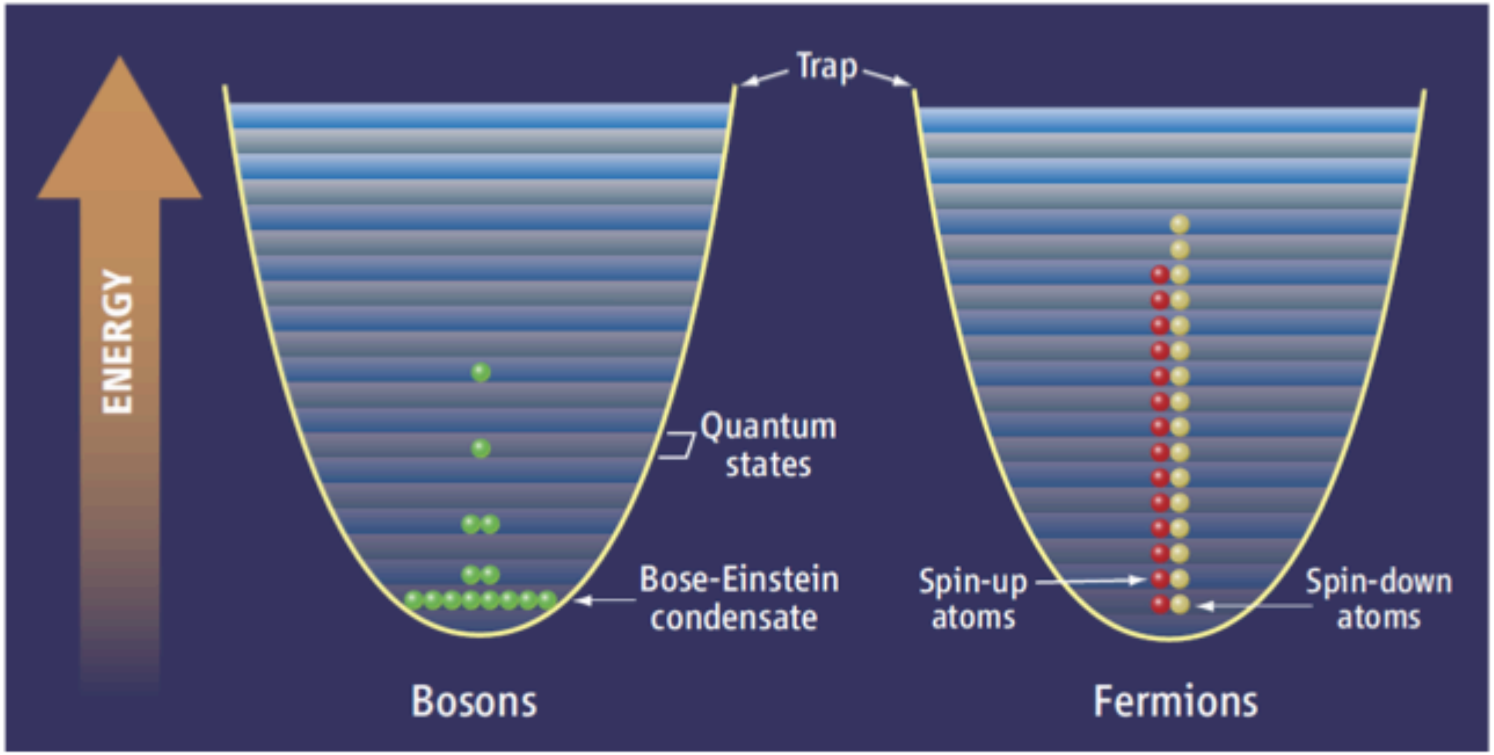
$^{7}Li = 3p + 3e + 4n$

Spin total inteiro
(boson)



$$\vec{f} = \vec{L} + \vec{S} + \vec{I}$$

Bósons x Férmions

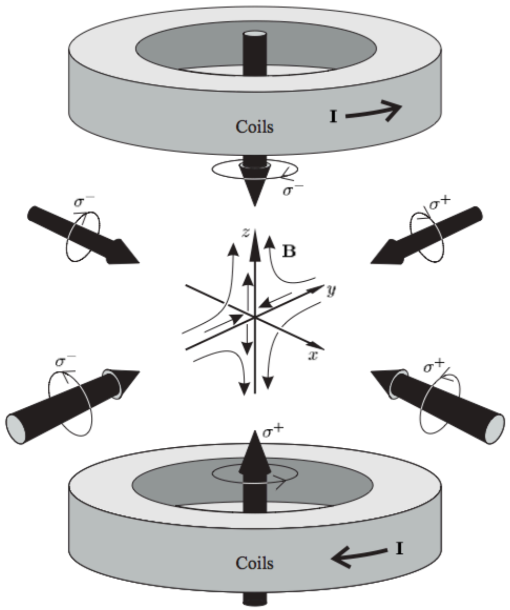


^{7}Li, ^{87}Rb

^{6}Li, ^{40}K

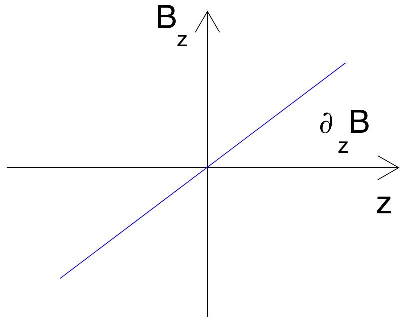
Confinamento atômico

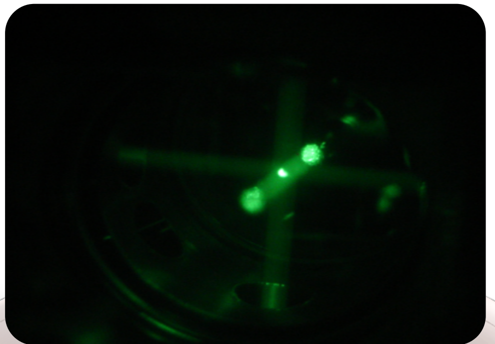
- Temperatura ~ 400uK
- Pressão ~ 10^{-7} Torr
- Átomos ~ 10 milhões
- Raio da nuvem ~ 3mm



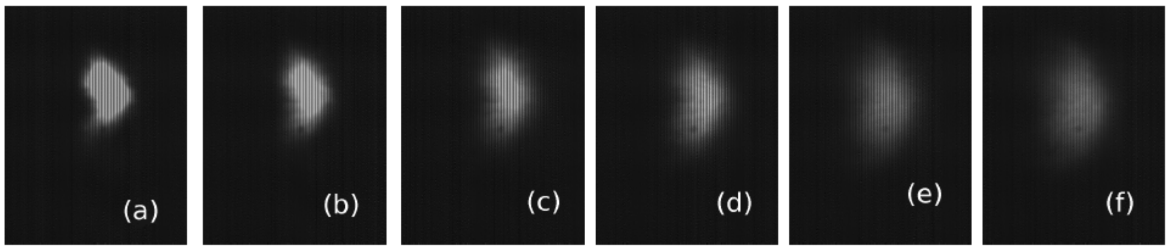
Vapor Rb

Vladimir A. Sautenkov *et al* PRA, **72** ,065801 (2005).





Armadilha Magneto-Ótica (MOT)



Ressonância de Feshbach

- Átomos possuem spin
- Diferentes simetrias dos estados ligados com relação ao estado de colisão
- Diferentes canais
- Canal aberto: estado de espalhamento
- Canal fechado: estados ligados, moléculas

Ressonância nuclear & atômica

Unified Theory of Nuclear Reactions*

HERMAN FESHBACH

Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

A new formulation of the theory of nuclear reactions based on the properties of a generalized "optical" potential is presented. The real and imaginary part of this potential satisfy a dispersion type relation while its poles give rise to resonances in nuclear reactions. A new derivation of the Breit-Wigner formula is given in which the concept of channel radius is not employed. This derivation is extended to the case of overlapping resonances. These results can then

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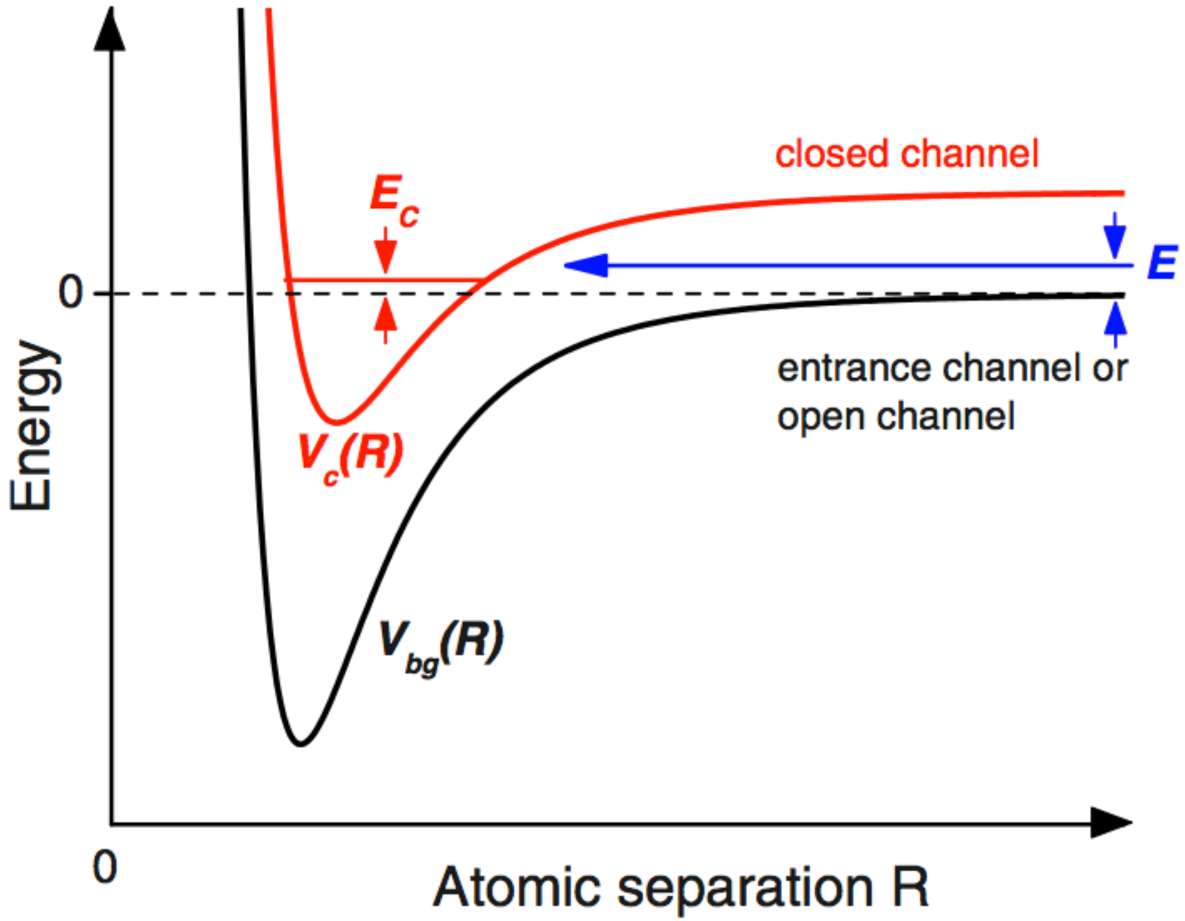
Effects of Configuration Interaction on Intensities and Phase Shifts*

U. FANO
National Bureau of Standards, Washington, D. C.
(Received July 14, 1961)

The interference of a discrete autoionized state with a continuum gives rise to characteristically asymmetric peaks in excitation spectra. The earlier qualitative interpretation of this phenomenon is extended and revised. A theoretical formula is fitted to the shape of the $2s2p\ ^1P$ resonance of He observed in the inelastic scattering of electrons. The fitting determines the parameters of the $2s2p\ ^1P$ resonance as follows: $E=60.1$ ev, $\Gamma\sim0.04$ ev, $f\sim2$ to 4×10^{-3}. The theory is extended to the interaction of one discrete level with two or more continua and of a set of discrete levels with one continuum. The theory can also give the position and intensity shifts produced in a Rydberg series of discrete levels by interaction with a level of another configuration. The connection with the nuclear theory of resonance scattering is indicated.

Ressonância de Feshbach



Chin, Cheng, et al. "Feshbach resonances in ultracold gases." *Reviews of Modern Physics* 82.2 (2010): 1225.

Comprimento de espalhamento

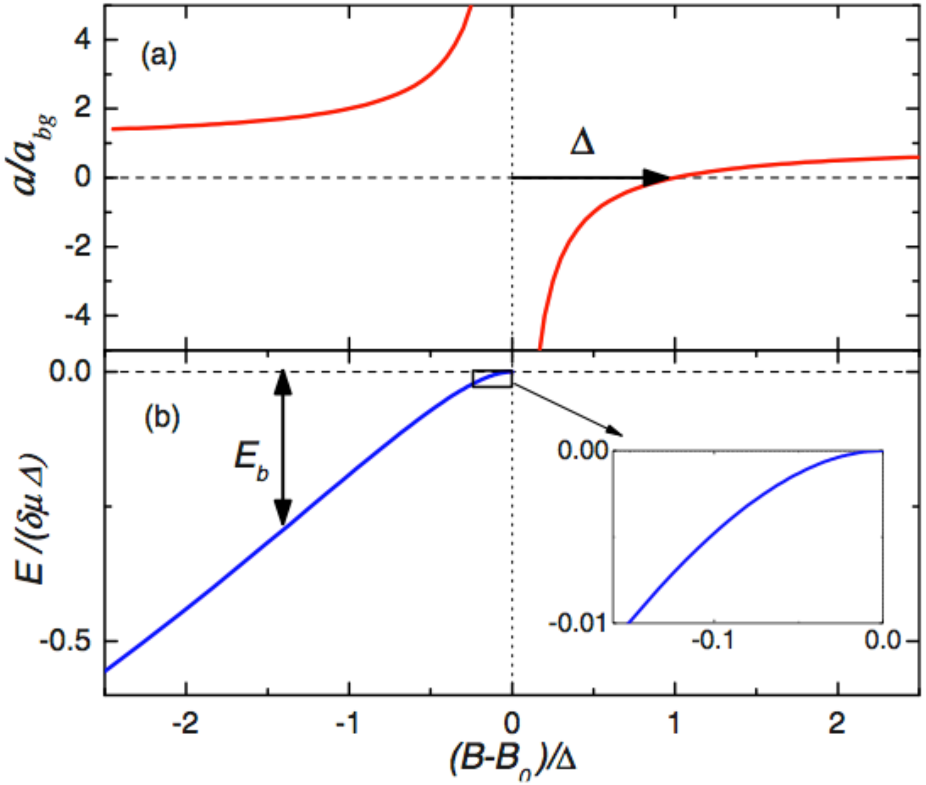


FIG. 2. (Color online) Feshbach resonance properties. (a) Scattering length a and (b) molecular state energy E near a magnetically tuned Feshbach resonance. The binding energy is defined to be positive, $E_b = -E$. The inset shows the universal regime near the point of resonance where a is very large and positive.

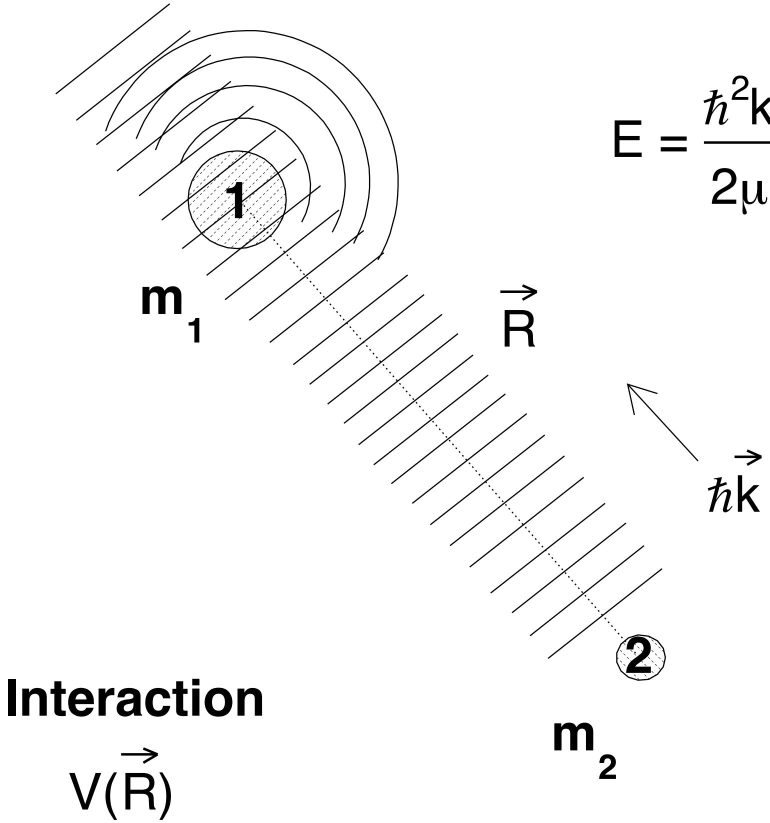
Moerdijk, A. J., B. J. Verhaar, and A. Axelsson. "Resonances in ultracold collisions of Li 6, Li 7, and Na 23." *Physical Review A* 51.6 (1995): 4852.

$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

$$E_b = \frac{\hbar^2}{2\mu a^2}$$

Física das colisões

- Colisão de dois corpos:



$$E = \frac{\hbar^2 k^2}{2\mu}$$

Partial wave expansion:

$$-\frac{\hbar^2}{2\mu}\frac{d^2\phi_l(R)}{dR^2} + V_l(R)\phi_l(R) = E\,\phi_l(R)$$

Bound state $\Rightarrow |\, nl \rangle$

Scattering state:

$$\phi_l(R,E) \rightarrow c\,\frac{\sin[kR - \pi l/2 + \eta_l(E)]}{\sqrt{k}}\,e^{i\eta_l(E)}$$

Cold neutral atoms collisions:

(s-wave)

$$k \cot \eta_0(E) = -1/a + \frac{1}{2} r_0 k^2$$

Low energy: (a-parameter)

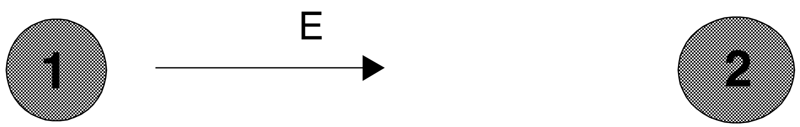
$$E_b = \frac{\hbar^2}{2\mu\, a^2}$$

Braaten, Eric, and H-W. Hammer. "Universality in few-body systems with large scattering length." *Physics Reports* 428.5 (2006): 259-390.

Canal de colisão

Cold collision with spin structure

$q_1 \rightarrow m_1 f_1$ $\qquad$ $q_2 \rightarrow m_2 f_2$



$E(q_1)$ $\qquad$ $E(q_2)$

$$\vec{f}_i = \vec{L}_i + \vec{S}_i + \vec{I}_i$$

Elastic collision

$q_1, q_2 = q_1', q_2'$ $\qquad$ $|\alpha\rangle = |q_1 q_2\rangle \, |l\, m_l\rangle$

$\vec{B}$ magnetic field

$M = m_1 + m_2 + m_l$

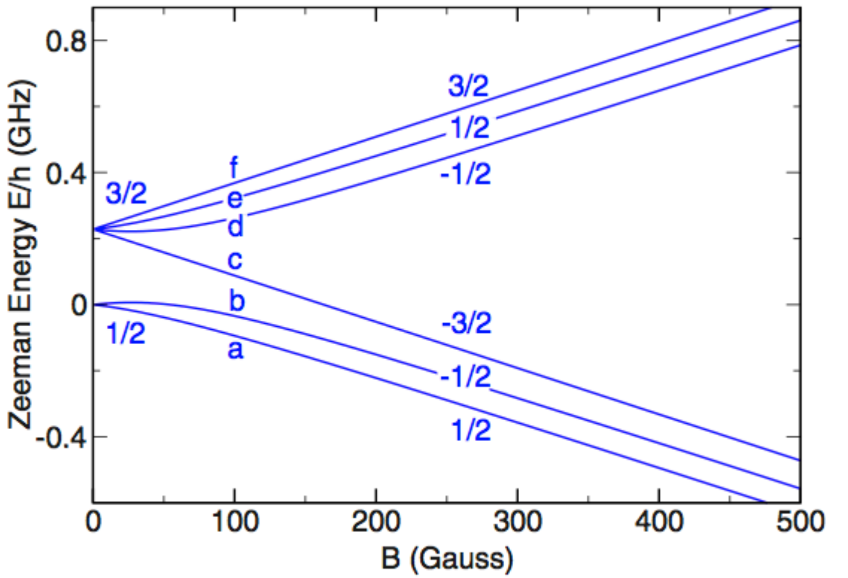
$\{q_1 q_2\, l\, M\}$

s-wave

$l = m_l = 0$

$\{q_1 q_2\}$

^{6}Li atom $\Rightarrow L = 0,\ S = 1/2,\ I = 1$, and $f = 1/2$ and $3/2$



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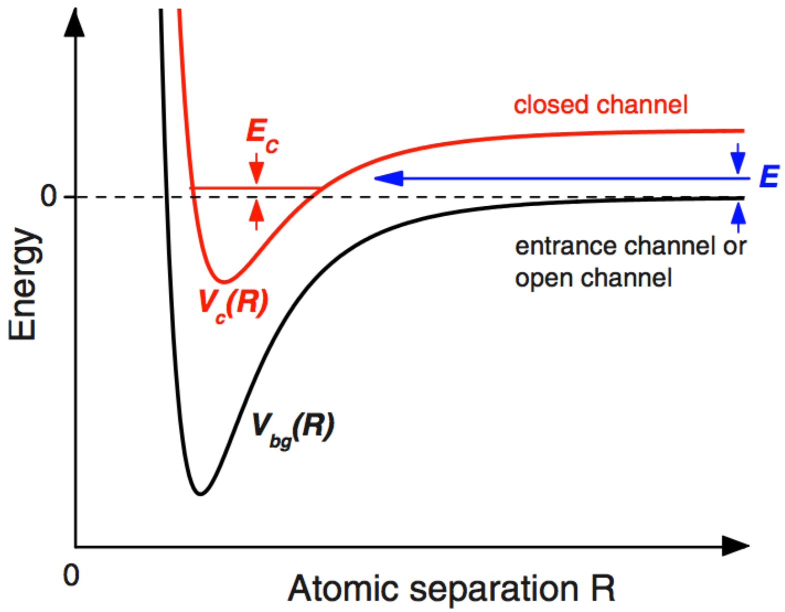
Energy

$$E_{tot} = E(q_1) + E(q_2) + E$$

$E_\beta \leq E_{tot}$ open channel

$E_\beta > E_{tot}$ closed channel

Ressonância de espalhamento



open channel: $|E\rangle = \phi_{bg}(R,E)\,|bg\rangle$

closed channel: $|C\rangle = \phi_c(R)\,|c\rangle$

Hamiltonian coupling $\Rightarrow$ **W(R)**

$$\eta(E) = \eta_{bg}(E) + \eta_{res}(E)$$

$$\eta_{res}(E) = -\tan^{-1}\left(\frac{\frac{1}{2}\Gamma(E_c)}{E - E_c - \delta E(E_c)}\right)$$

The theory of atomic collisions

Mott and Massey, 1965

$$E_c = \delta\mu\,(B - B_c)$$

$$a(B) = a_{bg} - a_{bg}\Delta / (B - B_0),$$

onde

$$\Delta = \Gamma_0 / \delta\mu \quad e \quad B_0 = B_c + \delta B$$

s-wave and the limit k $\rightarrow$ 0

$$\frac{1}{2}\Gamma(E) = \pi\,|\langle C|\,W(R)\,|E\rangle|^2 \rightarrow (ka_{bg})\Gamma_0$$

$$E_c + \delta E(E) = P\int_{-\infty}^{\infty} \frac{|\langle C|\,W(R)\,|E'\rangle|^2}{E - E'} dE' \rightarrow E_0$$

Resultado experimental

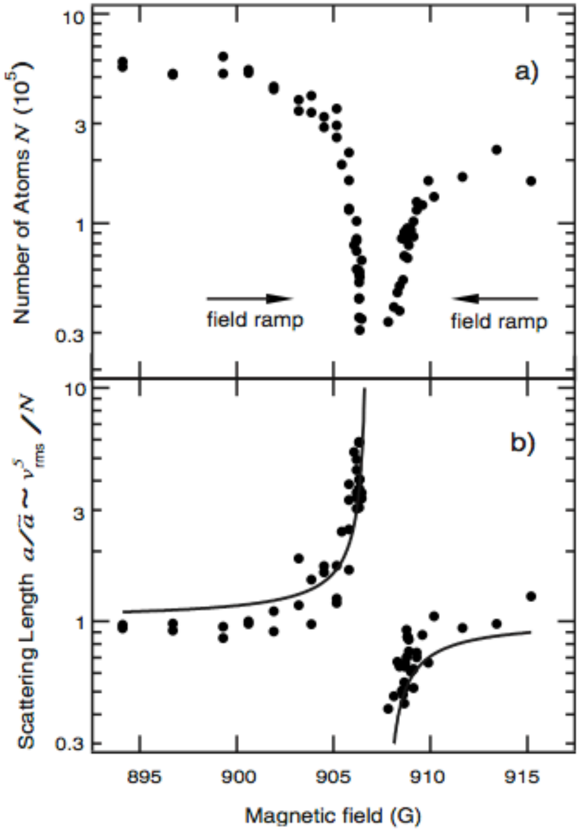


FIG. 3. Observation of a magnetically tuned Feshbach resonance in an optically trapped BEC of Na atoms. The upper panel shows a strong loss of atoms near the resonance, which is due to enhanced three-body recombination. The lower panel shows the dispersive shape of the scattering length a near the resonance, as determined from measurements of the mean-field interaction by expansion of the condensate after release from the trap; here a is normalized to the background value a_{bg}. From Inouye *et al.*, 1998.

Chin, Cheng, et al. "Feshbach resonances in ultracold gases." *Reviews of Modern Physics* 82.2 (2010): 1225.

Considerações gerais

- Qual o campo magnético necessário?

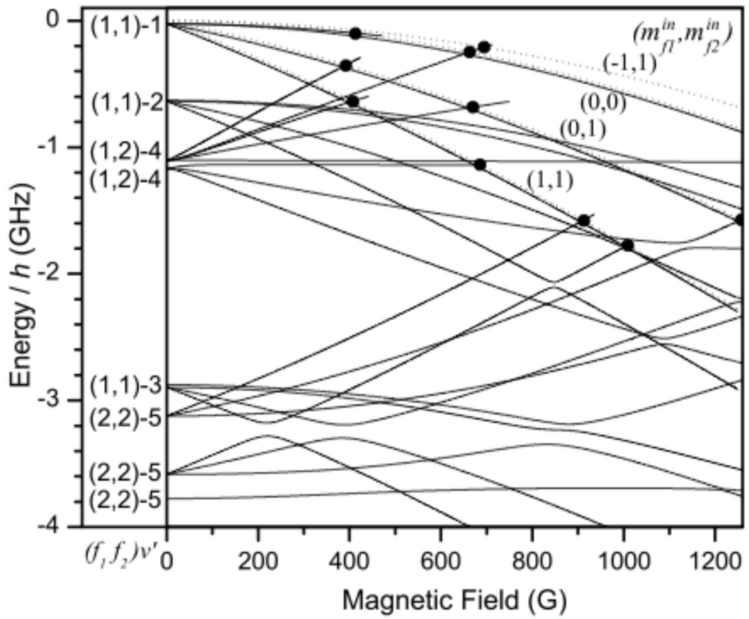


FIG. 1. $l = 0$ Feshbach resonances in a coupled-channel calculation. Bound-state energies (solid lines) are shown as a function of magnetic field with quantum numbers $(f_1, f_2)v'$ assigned at $B = 0$. Additionally, dissociation threshold energies (dotted lines) are shown for four different entrance channels $(m_{f1}^{in}, m_{f2}^{in})$. A Feshbach resonance (•) occurs, when a bound state with quantum number m_F crosses a dissociation threshold with the same m_F.

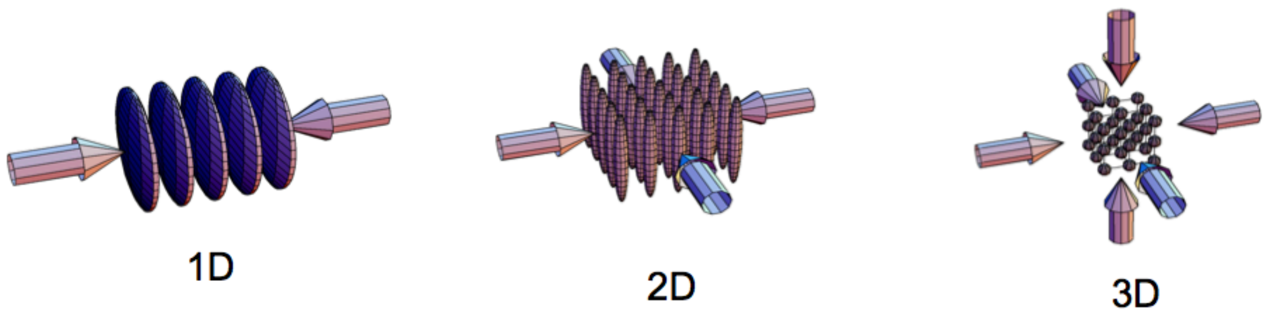
Marte, A., et al. "Feshbach resonances in rubidium 87: Precision measurement and analysis." *Physical Review Letters* 89.28 (2002): 283202.

Considerações gerais

- Resolução do campo magnético:
  - Depende fortemente da largura da ressonância, em muitos casos superior a 1 G.
- Temperatura típica:
  - Inferior a 1uK.

Aplicações

- Estudar supercondutores em átomos frios.
- Emular com átomos frios sistemas fortemente correlacionados que não é possível resolver exatamente.
- Estudar materiais fortemente correlacionados.
- Estudar átomos frios em redes óticas.



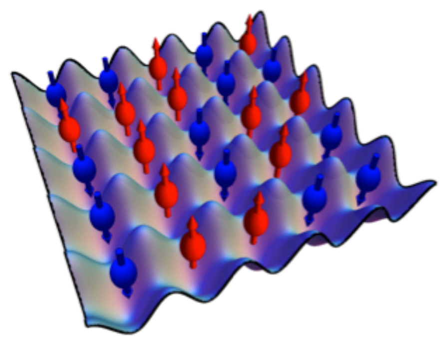


Figura cedida pela Profa. Thereza Paiva, UFRJ

Fim,
Obrigado.