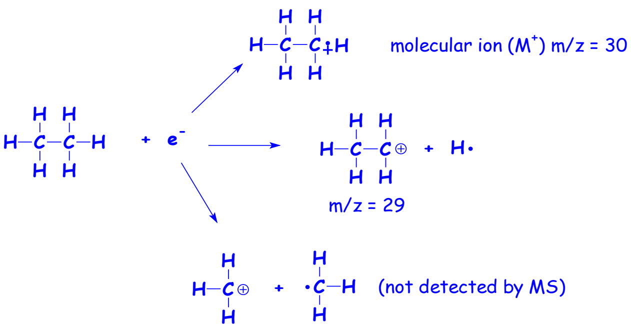
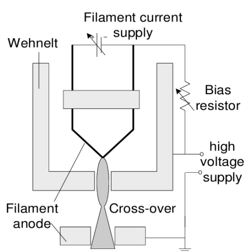
Mass spectroscopy - ionization methods

1. Electron ionization



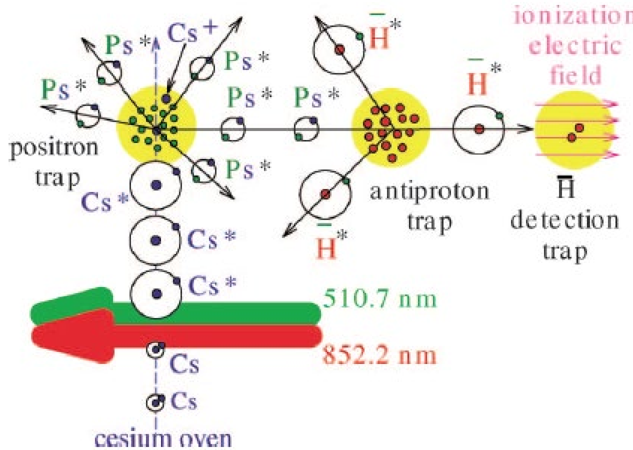


2. Chemical ionization:

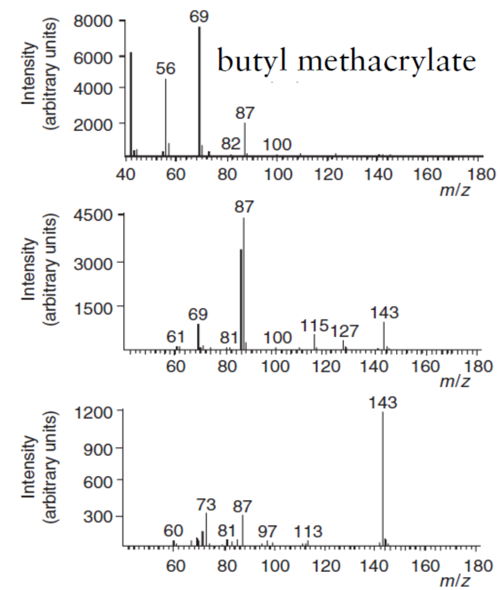
a) Charge transfer

$$Xe + e^- \longrightarrow Xe^{\bullet+} + 2e^-$$

$$Xe^{\bullet+} + M \longrightarrow M^{\bullet+} + Xe$$

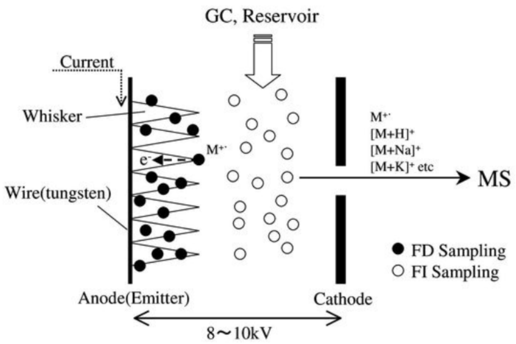


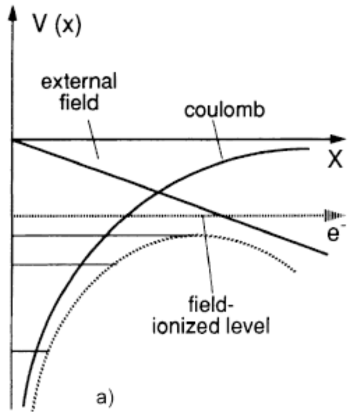
b) proton transfer



Mass spectroscopy - ionization methods

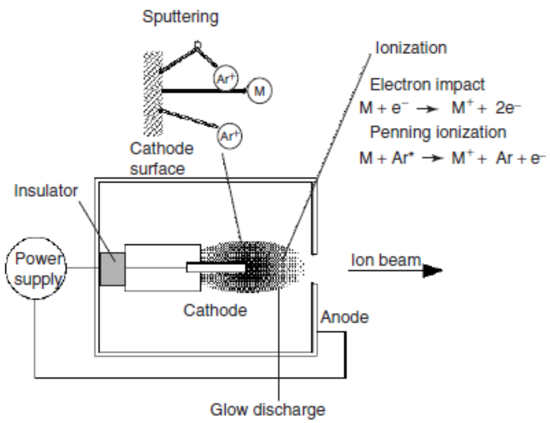
3. Field ionization



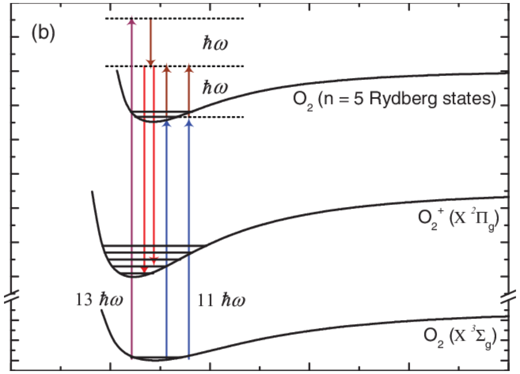


$$IP_{\rm eff} = IP - \sqrt{\frac{Z_{\rm eff} e^3 E_0}{\pi \epsilon_0}}$$

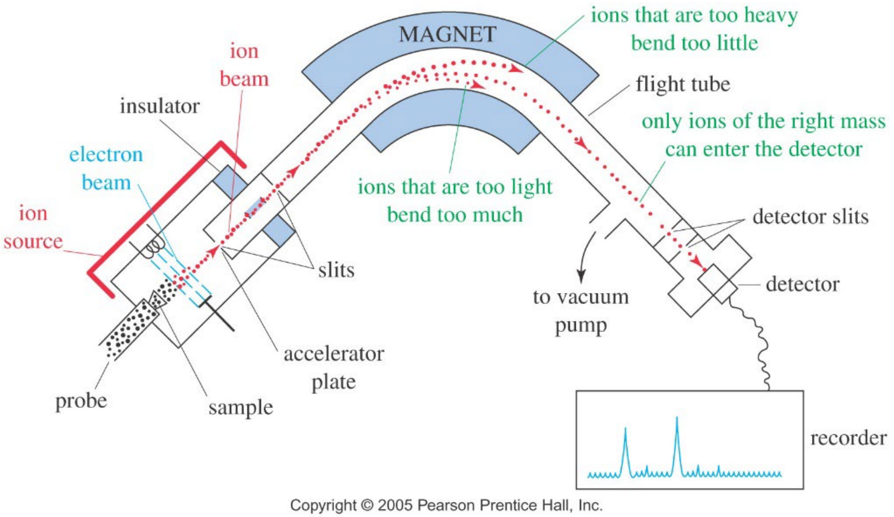
4. Glow discharge source

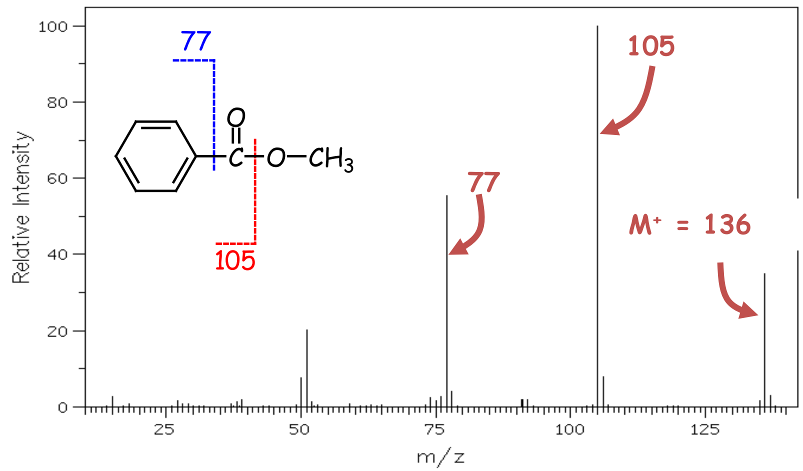


5. Photoionization



Mass spectroscopy



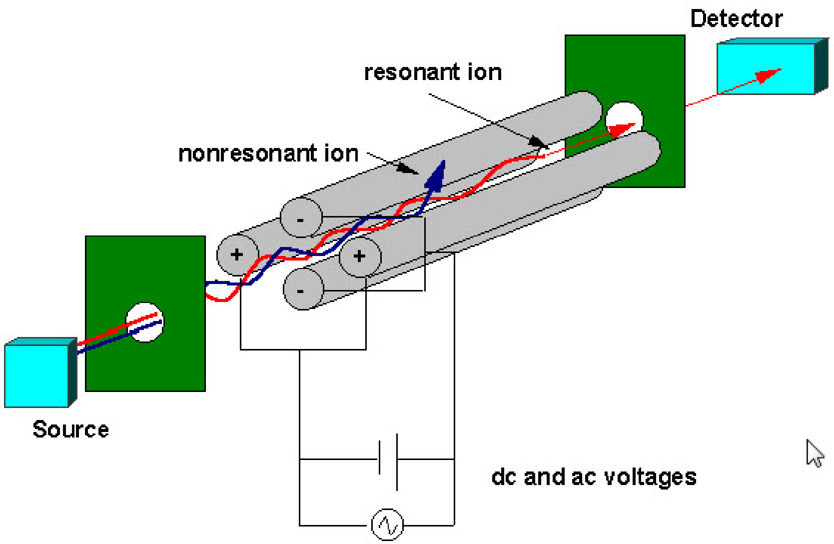


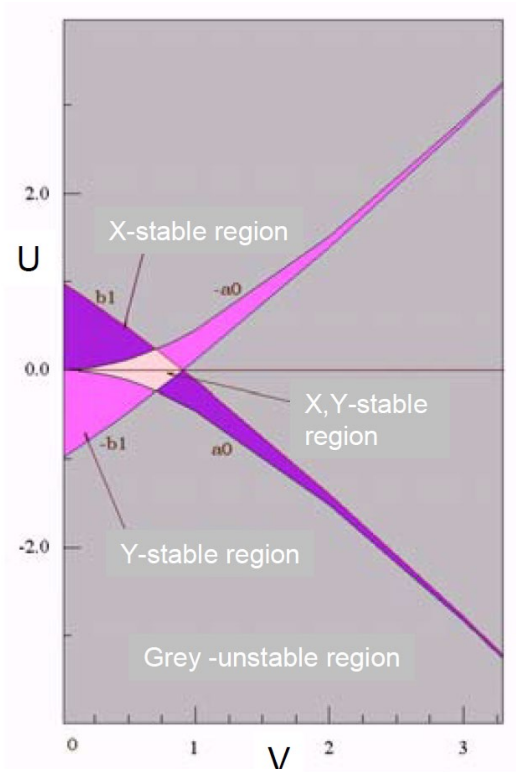
$$qvB = \frac{mv^2}{r} \quad \text{or} \quad mv = qBr \qquad \frac{m}{q} = \frac{r^2B^2}{2V_s}$$

Most elements occur naturally as a mixture of isotopes.

- The presence of significant amounts of heavier isotopes leads to small peaks that have masses that are higher than the parent ion peak.
- M+1 = a peak that is one mass unit higher than M^+
- M+2 = a peak that is two mass units higher than M^+

Quadrupole Mass Filter





Mathieu's equations

$$\frac{d^2x}{dt^2} = -\left(\frac{e}{m}\right)\frac{[U + V\cos(\omega t)]}{r_0^2}x,$$

$$\frac{d^2y}{dt^2} = \left(\frac{e}{m}\right)\frac{[U + V\cos(\omega t)]}{r_0^2}y,$$

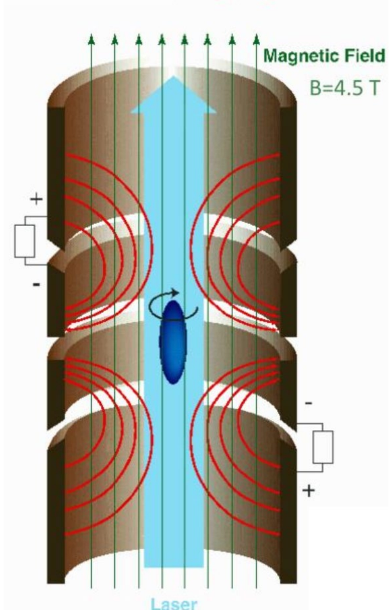
$$\frac{d^2z}{dt^2} = 0.$$

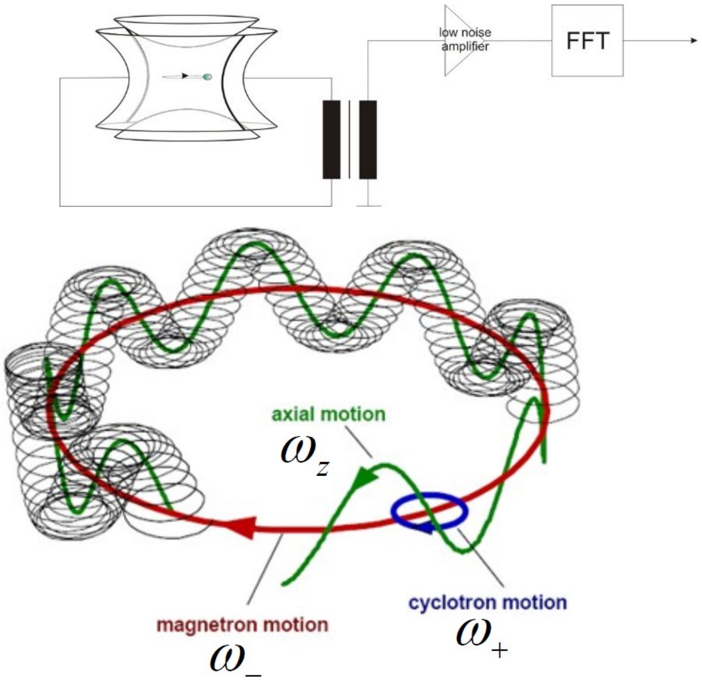
$$\frac{\mathrm{d}^2u}{\mathrm{d}\xi^2} + (a_u - 2q_u\cos 2\xi)\,u = 0$$

$$a_u = a_x = -a_y = \frac{8zeU}{m\omega^2 r_0^2}$$

$$q_u = q_x = -q_y = \frac{4zeV}{m\omega^2 r_0^2}$$

Penning trap mass spectrometry





$$\omega_c = \frac{q}{m} B$$

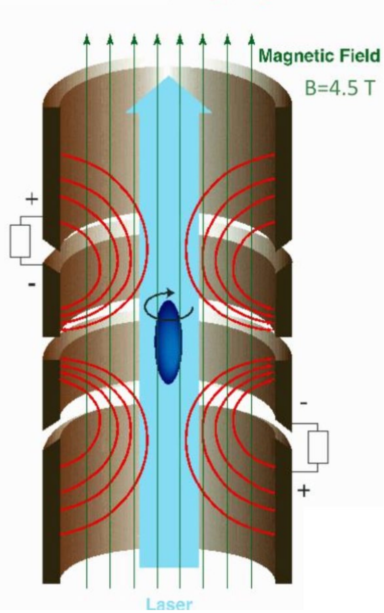
$$\omega_z = \sqrt{\frac{qU_{dc}}{md^2}},$$

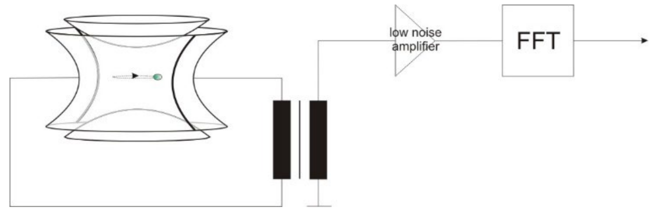
$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

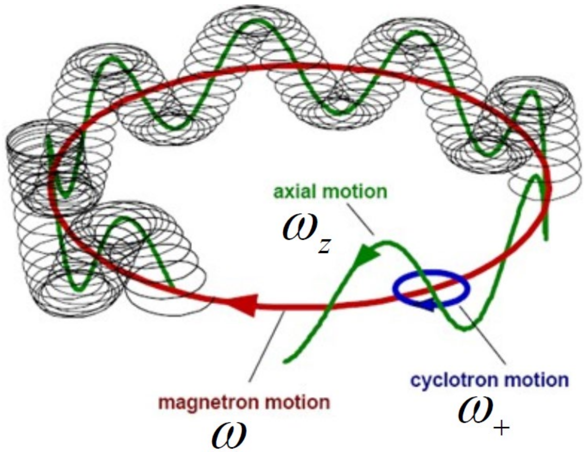
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

$$\frac{|q|}{m} B^2 > 2\frac{|U_{dc}|}{d^2} \text{ and } qU_{dc} > 0$$

Penning trap mass spectrometry







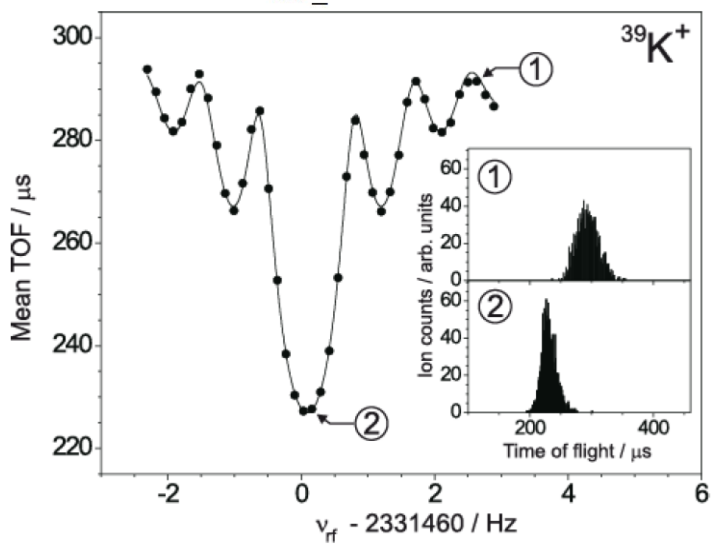
$$\omega_c = \frac{q}{m} B$$

$$\omega_z = \sqrt{\frac{qU_{dc}}{md^2}},$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

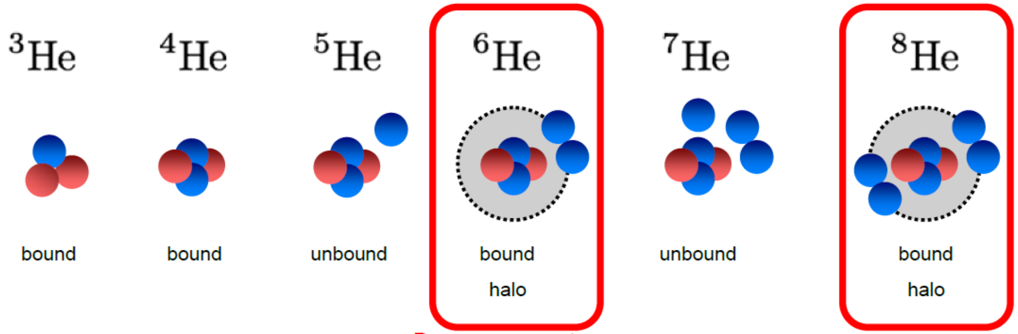
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

$$\frac{|q|}{m} B^2 > 2\frac{|U_{dc}|}{d^2} \text{ and } qU_{dc} > 0$$



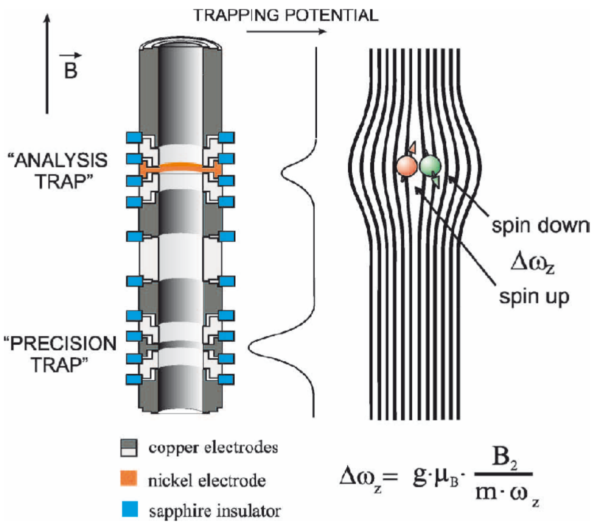
Penning trap mass spectrometry

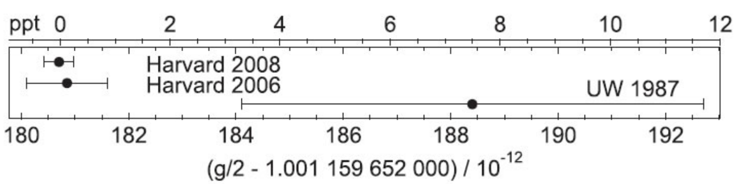
Binding energy measurements



Borromean system

Most exotic nucleus "on earth"

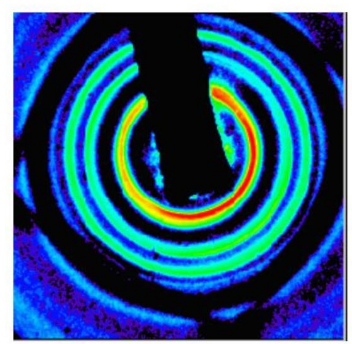




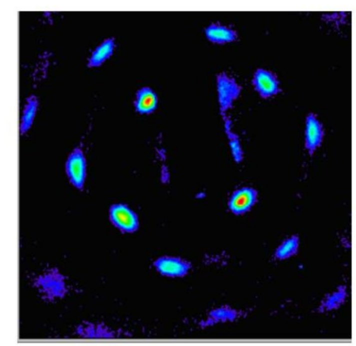
$$g/2 = 1.001\,159\,652\,180\,73(28) \quad [0.28\ \text{ppt}].$$

Electron/proton g-factor measurements

time averaged Bragg scattering



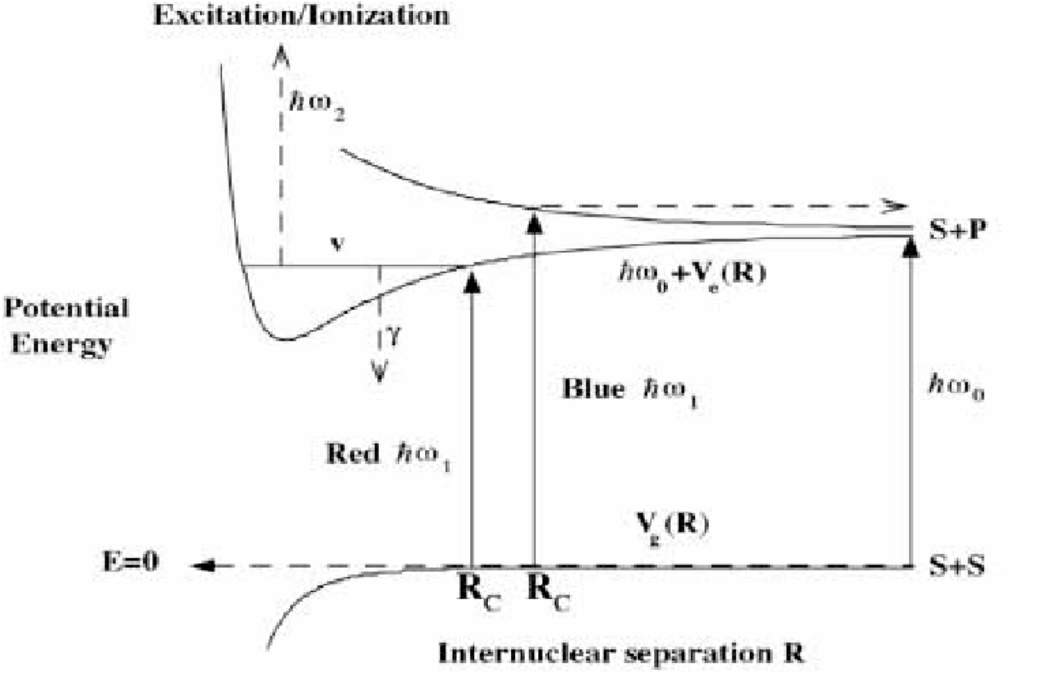
camera strobed by the rotating wall



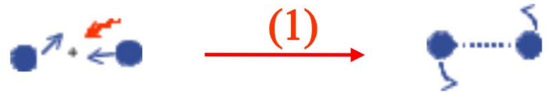
- **determine if crystal pattern due to 1 or multiple crystals**
- **enables real space imaging of ion crystals**

Photoassociation spectroscopy

$$Cs(6s,F)+Cs(6s,F)+h\nu_L \rightarrow Cs_2^* (\Omega(6s+6p_j);v,J)$$

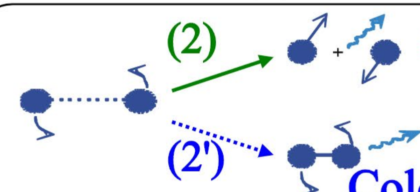


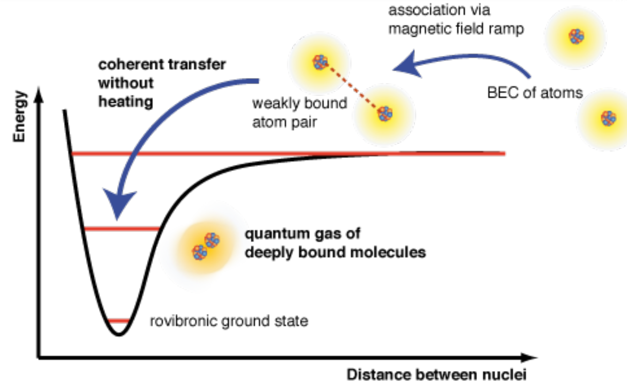
Photoassociation



Resonant photon absorption by two cold atoms (T~10uK)

Deexcitation

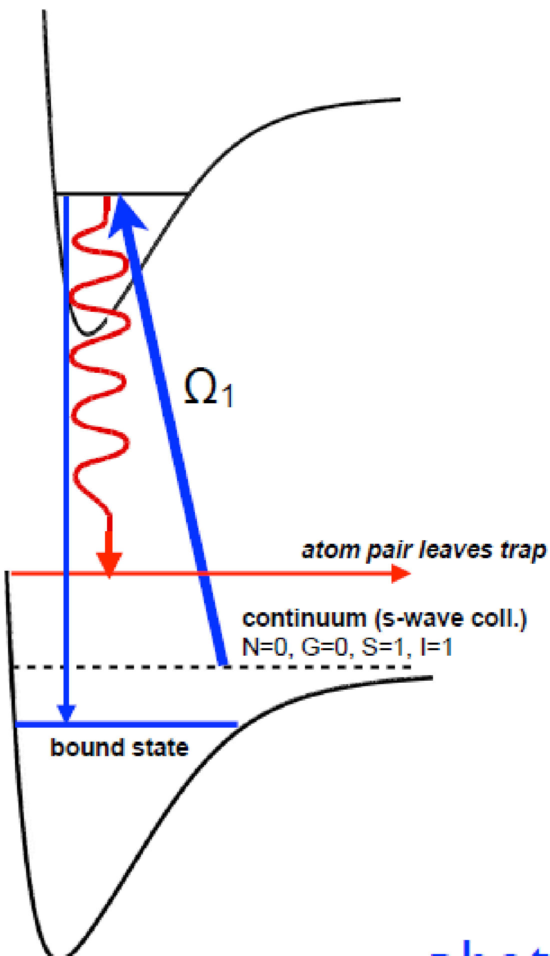




Photoassociation spectroscopy

Obtaining spectroscopic signal

“one-color PA”



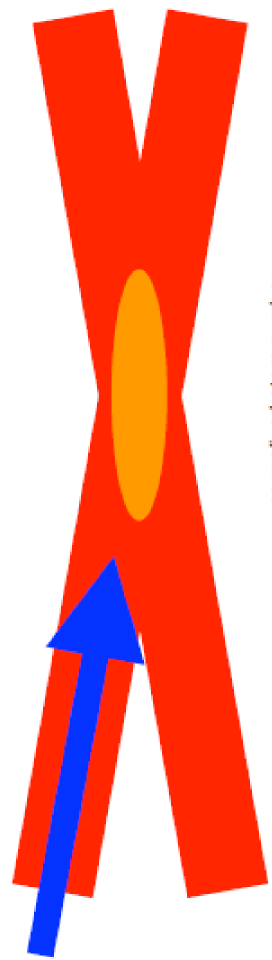
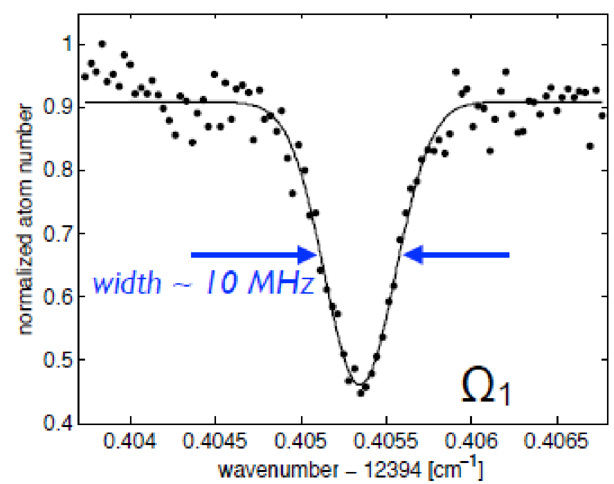


photo-association light

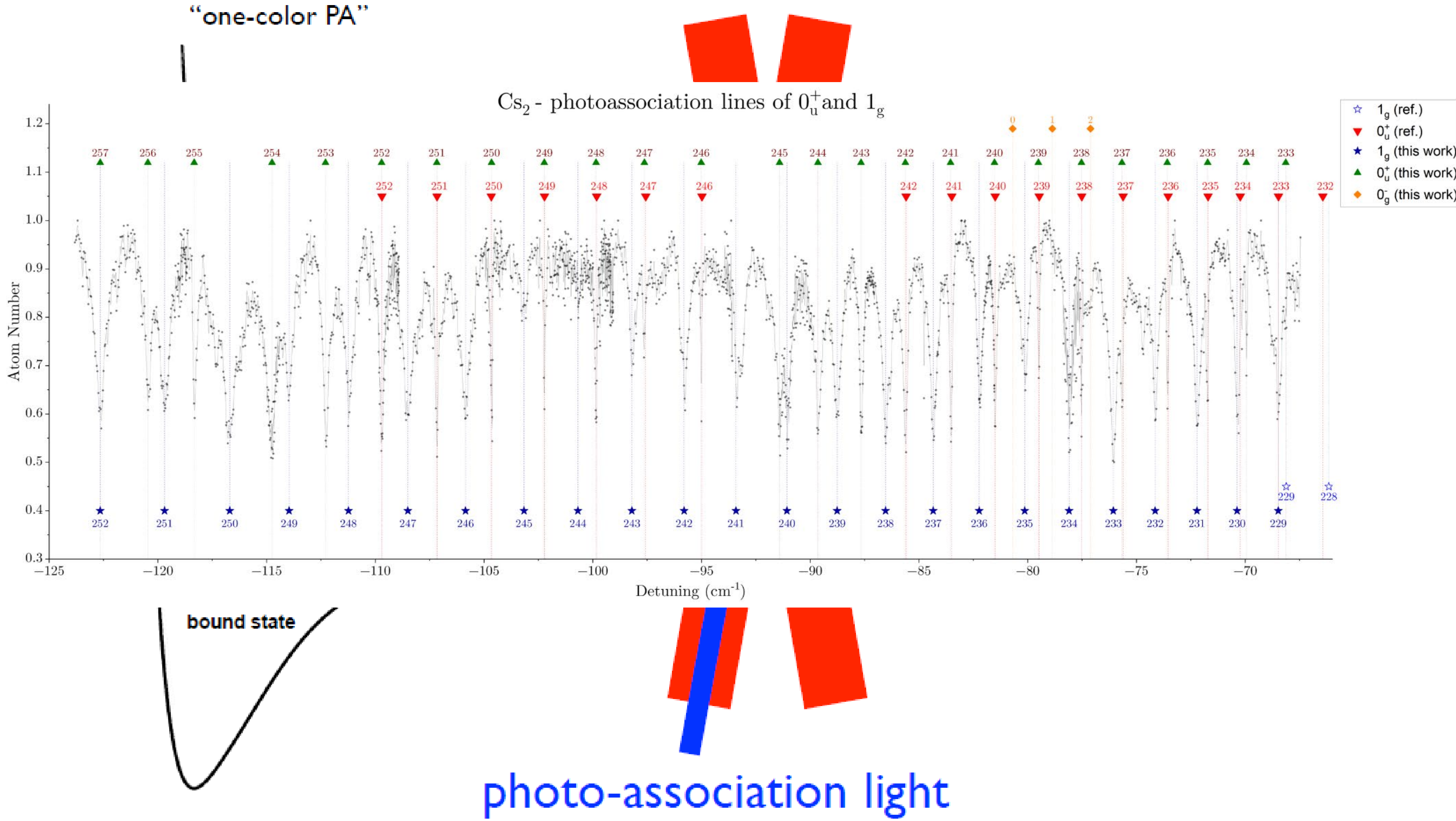
atom loss



width set by excited state lifetime

Photoassociation spectroscopy

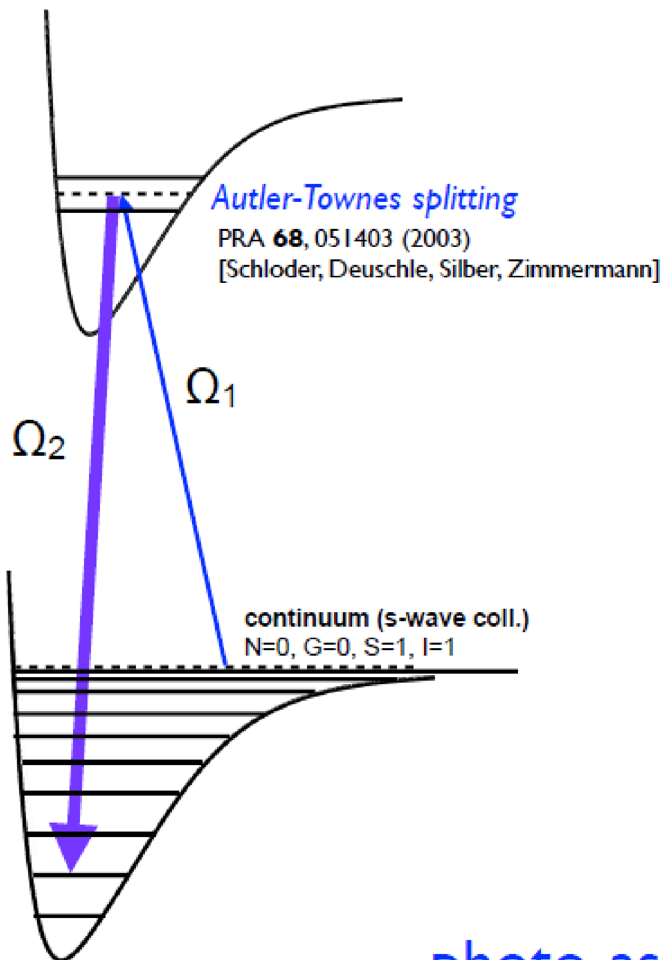
Obtaining spectroscopic signal

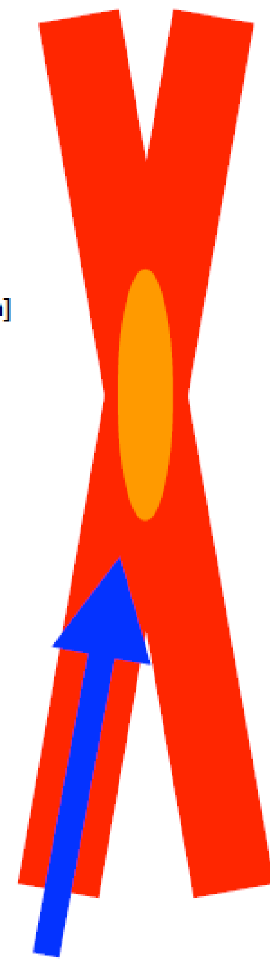


Photoassociation spectroscopy

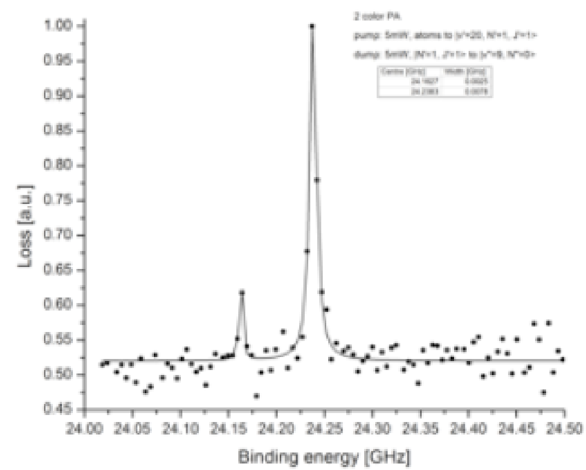
Obtaining spectroscopic signal

“two-color PA”





atom loss suppressed

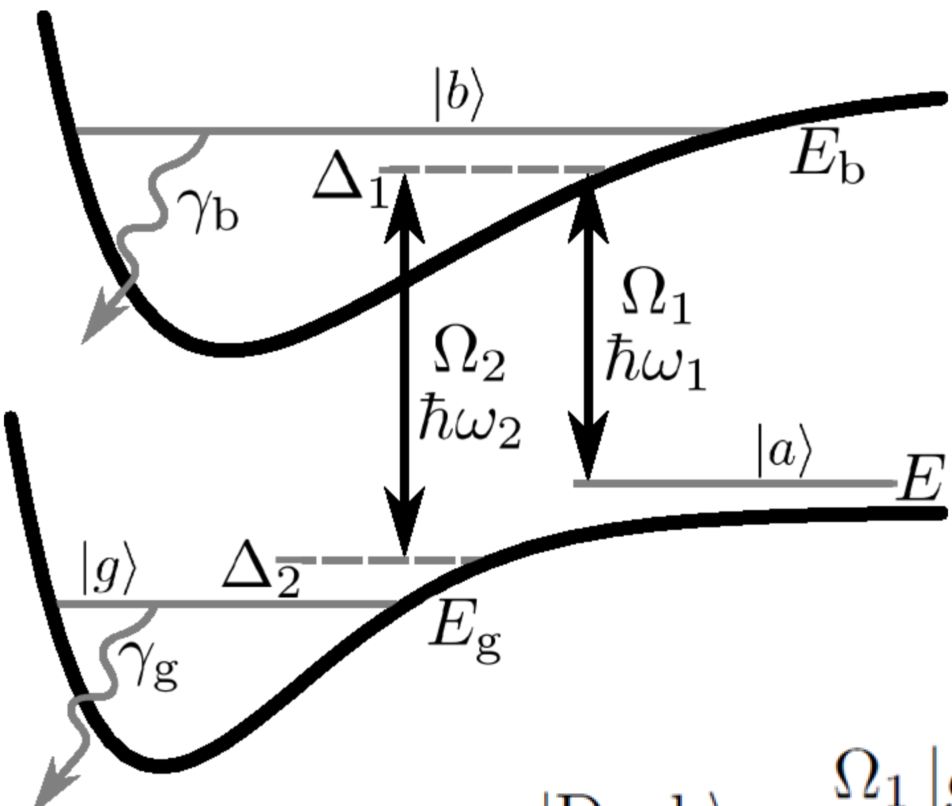


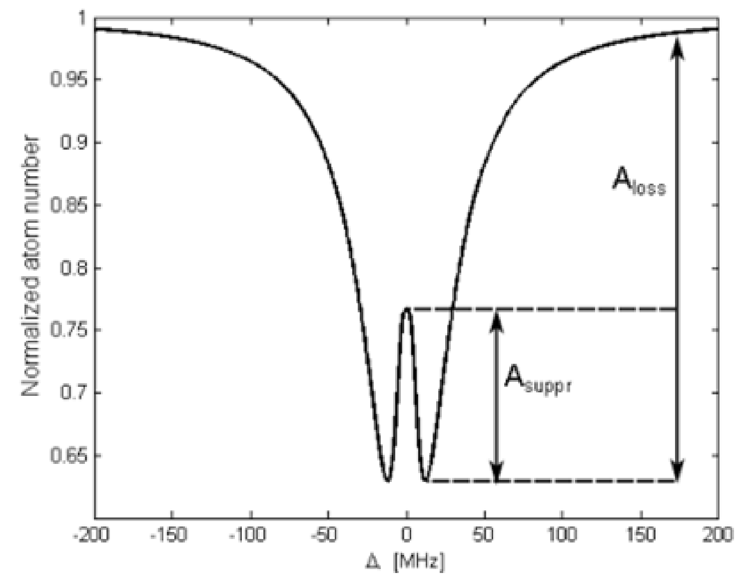
$\Omega_2 - \Omega_1$

width set by coupling induced by Ω_2

photo-association light

Photoassociation spectroscopy





$$|\mathrm{Dark}\rangle = \frac{\Omega_1 |g\rangle - \Omega_2 |a\rangle}{\sqrt{\Omega_1^2 + \Omega_2^2}}$$

Photoassociation spectroscopy

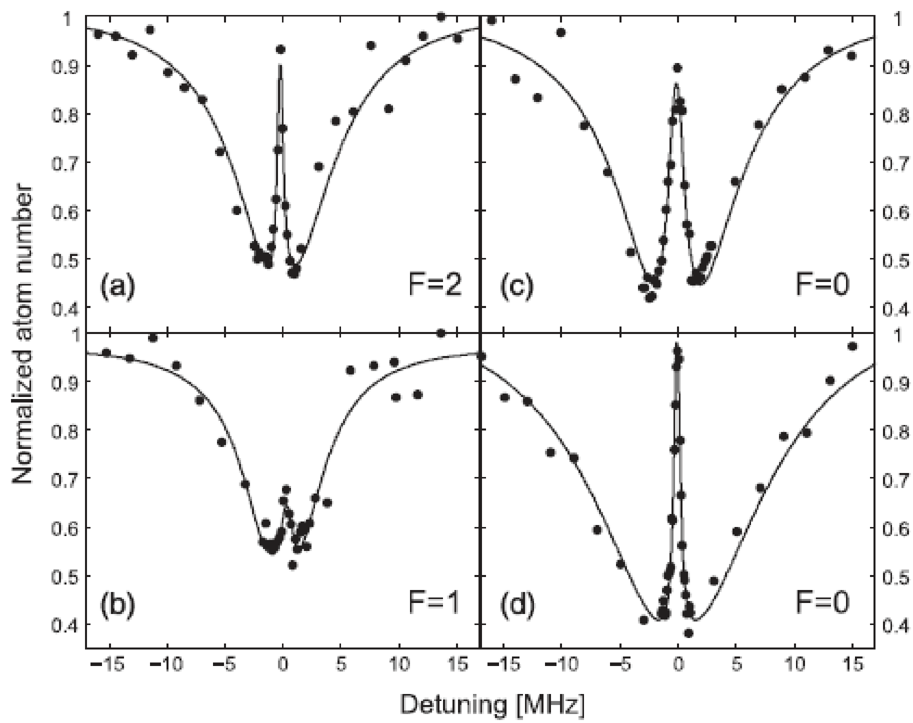
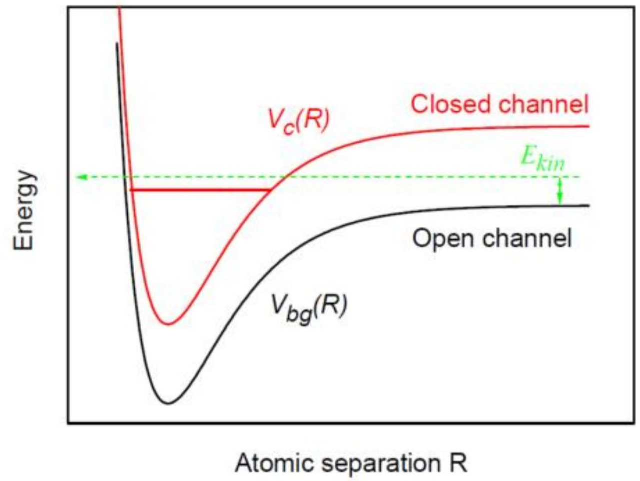
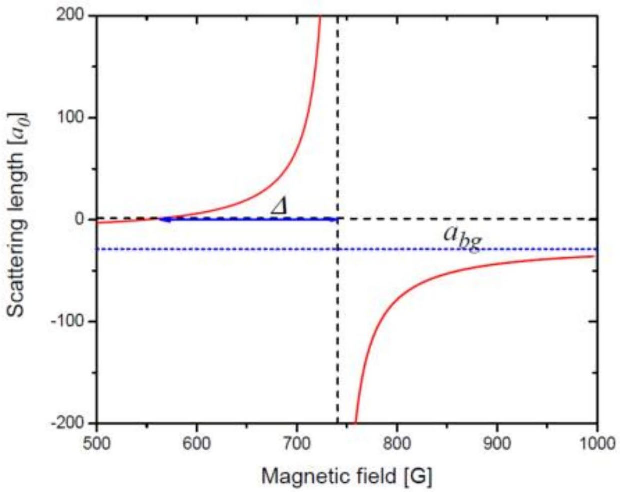


FIG. 2. Dark states in a Fermi gas at 0 G. The atom number is plotted versus the detuning of the probe frequency from the two-photon resonance, where the photon energy difference $h(\nu_2 - \nu_1)$ equals the difference between the energy of the initial free atom state and a bound molecular level and the atom number exhibits a maximum revival. (a)–(c) Corresponding different molecular hyperfine levels ($F'' = 2, 1, 0$) of the $v'' = 9$, $N'' = 0$ level in the $a(1^3\Sigma_u^+)$ potential. We were not able to find parameters that would improve the revival of $F'' = 1$ to above 50%. Spectrum (d) corresponds to the $v'' = 38$, $N'' = I'' = F'' = 0$ level of the $X(1^1\Sigma_g^+)$ potential.

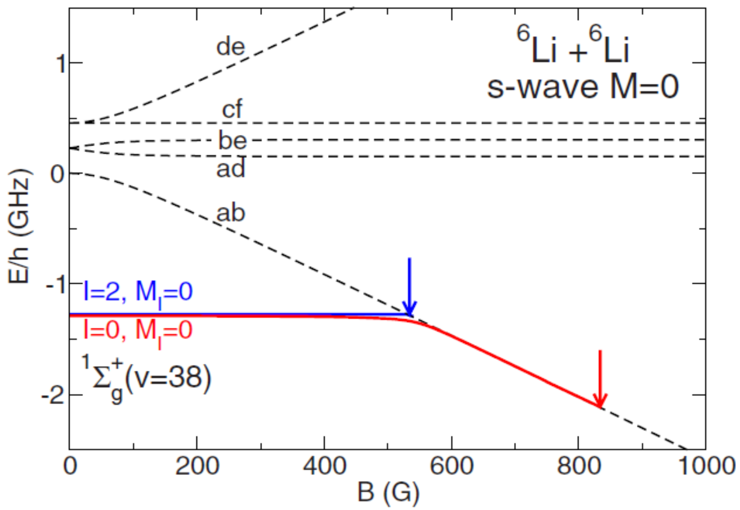
Feshbach spectroscopy

Feshbach resonance



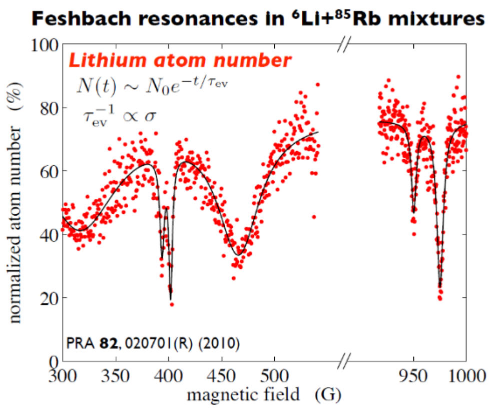


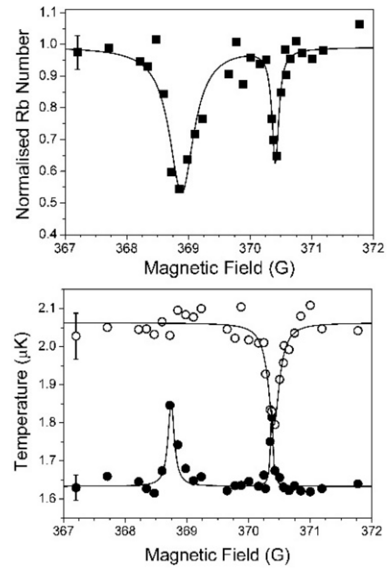
$$a = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

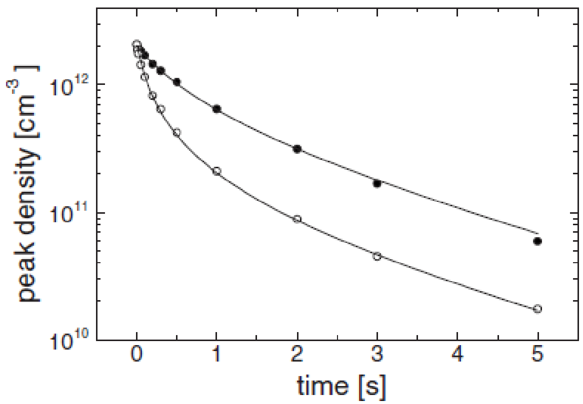


Feshbach spectroscopy

Inelastic loss spectroscopy

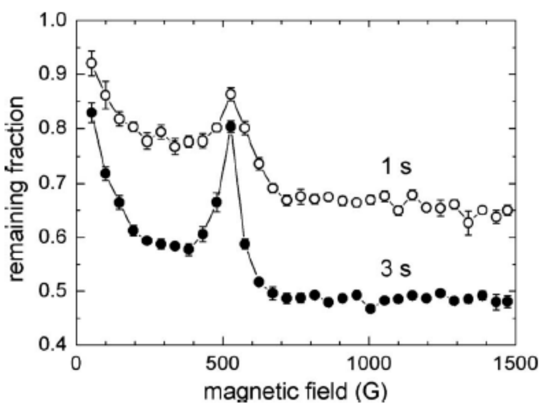




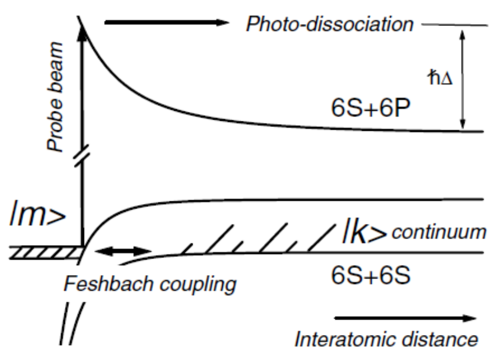


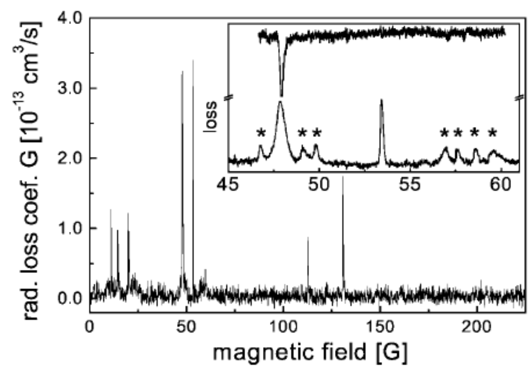
$$\dot{\bar{n}}(t) = -\frac{\bar{n}(t)}{\tau} - L_2\bar{n}(t)^2 - (4/3)^{3/2}L_3\bar{n}(t)^3$$

Elastic loss spectroscopy

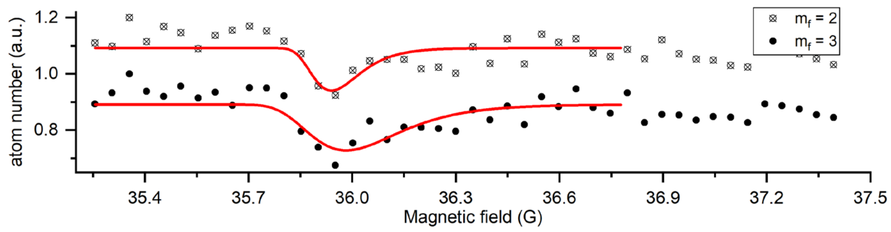


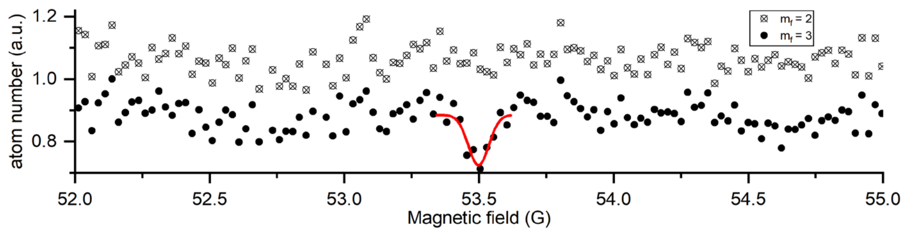
Radiative loss spectroscopy

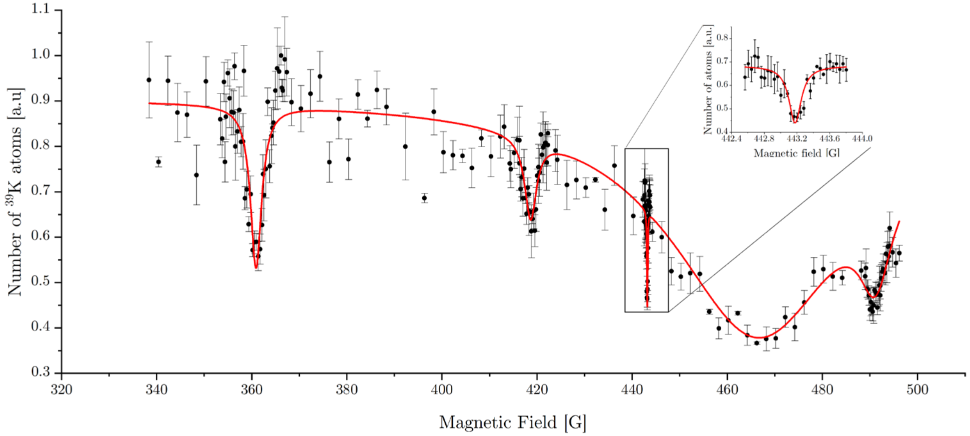


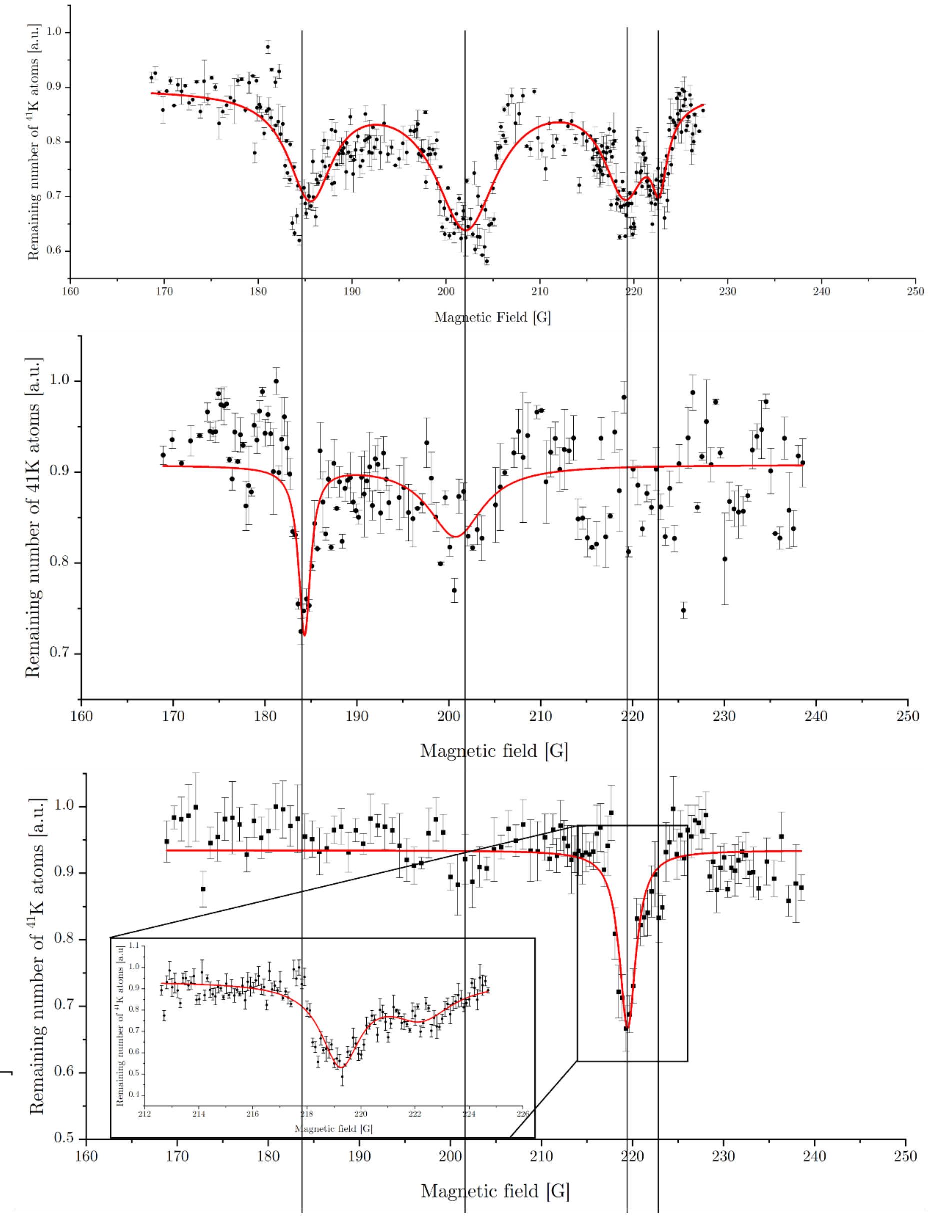


Feshbach spectroscopy

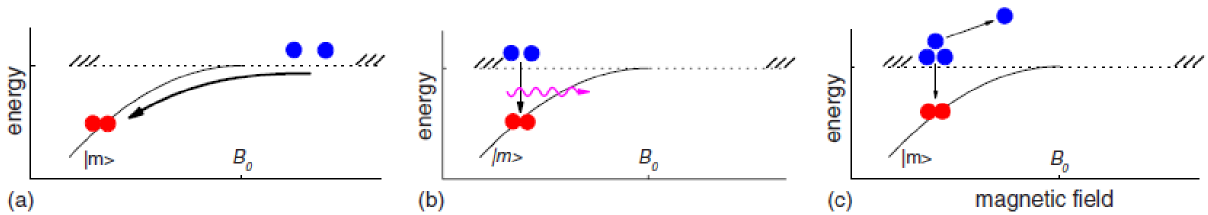


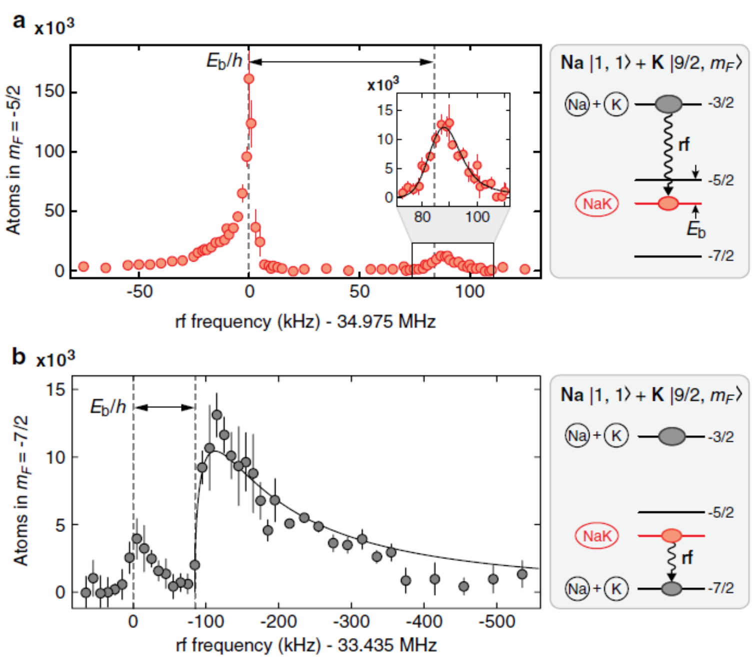


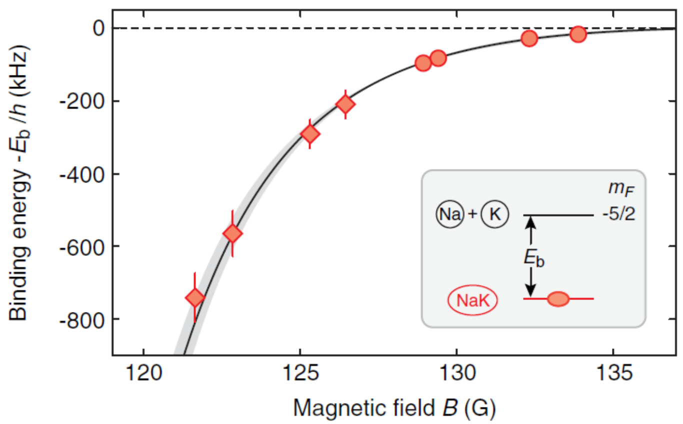




Binding energy measurements

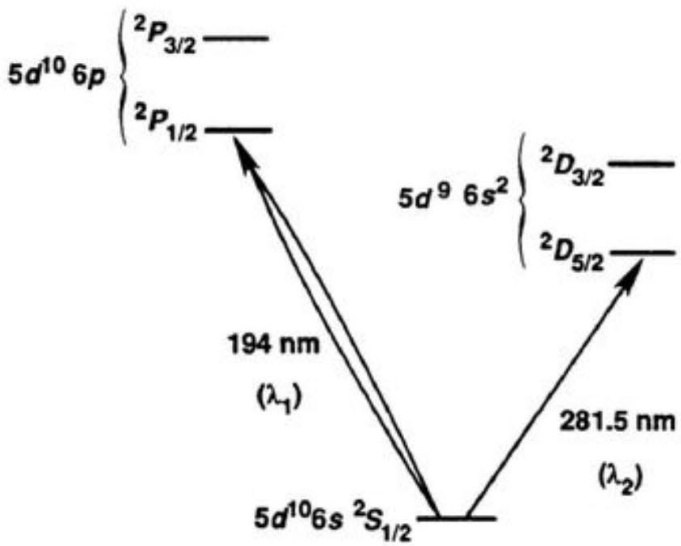


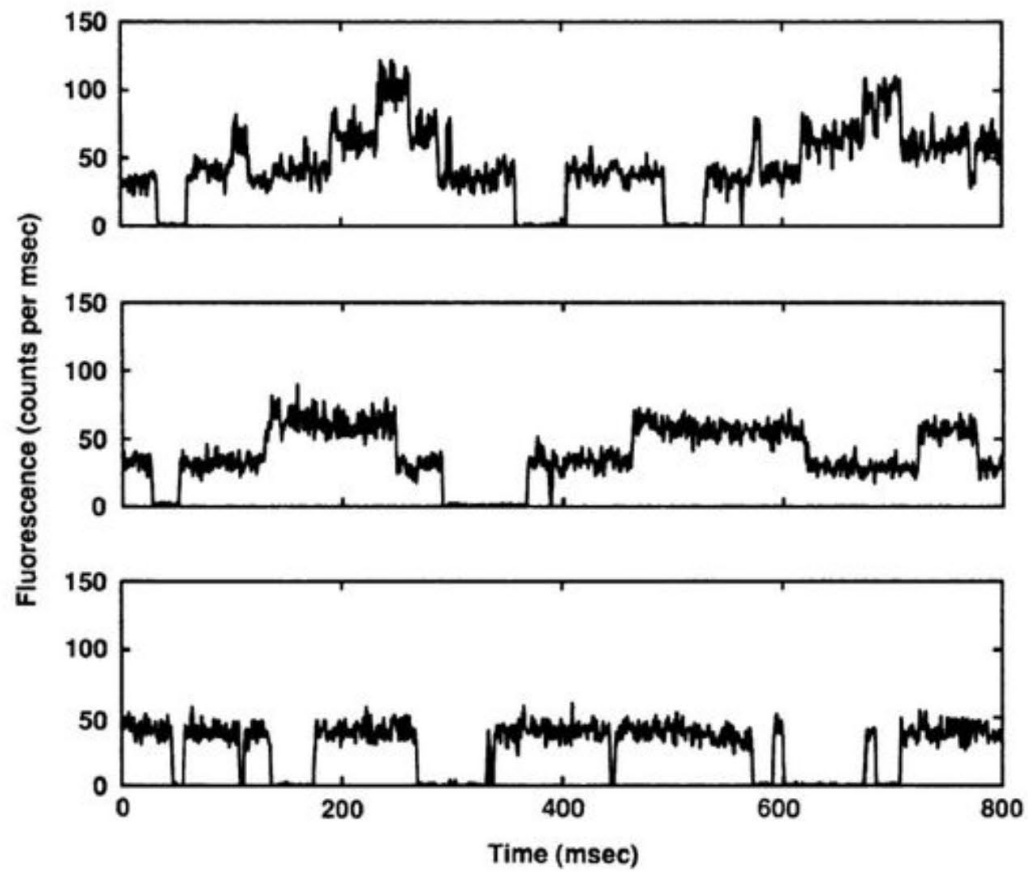




$$E_b \approx \frac{\hbar^2}{2\mu(a-\bar{a})^2}$$

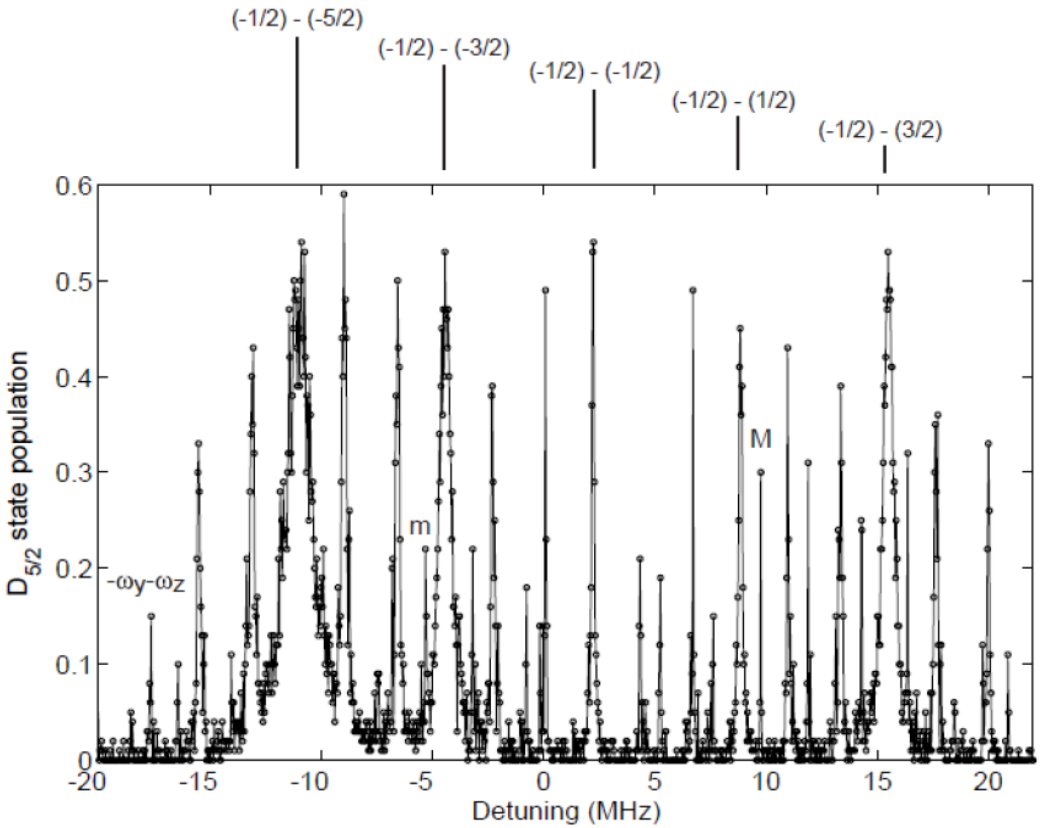
Quantum jump spectroscopy

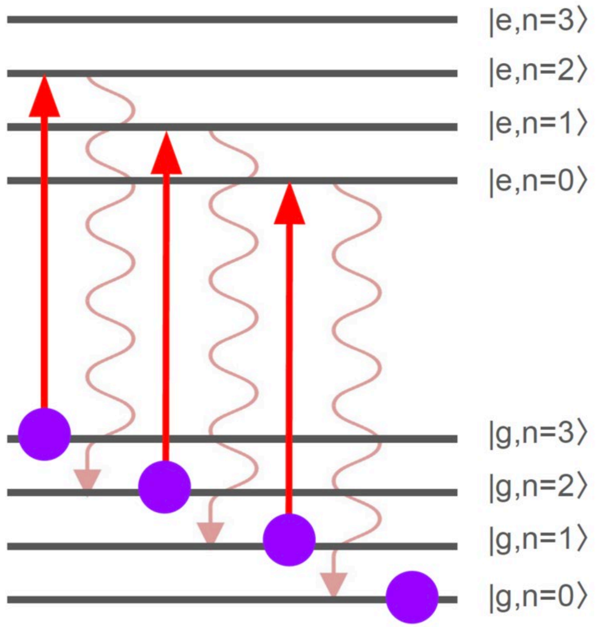




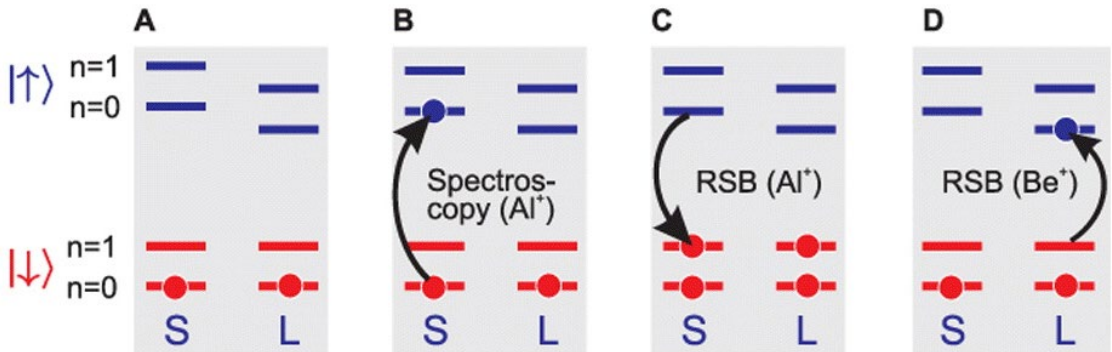
W.M. Itano, J.C. Bergquist, and D.J. Wineland, Science 37, 612 (1987)

Quantum logic spectroscopy





Quantum logic spectroscopy



$$\Psi_0 = |\downarrow\rangle_S|\downarrow\rangle_L|0\rangle_m$$

excite

$$\Psi_0 \rightarrow \Psi_1 = (\alpha|\downarrow\rangle_S + \beta|\uparrow\rangle_S)|\downarrow\rangle_L|0\rangle_m$$

$$= (\alpha|\downarrow\rangle_S|0\rangle_m + \beta|\uparrow\rangle_S|0\rangle_m)|\downarrow\rangle_L$$

red sideband π pulse

$$\Psi_1 \rightarrow \Psi_2 = (\alpha|\downarrow\rangle_S|0\rangle_m + \beta|\downarrow\rangle_S|1\rangle_m)|\downarrow\rangle_L$$

$$= |\downarrow\rangle_S|\downarrow\rangle_L(\alpha|0\rangle_m + \beta|1\rangle_m)$$

red sideband π pulse

$$\Psi_2 \rightarrow \Psi_{final} = |\downarrow\rangle_S(\alpha|\downarrow\rangle_L + \beta|\uparrow\rangle_L)|0\rangle_m$$