Coherent Enhancement of Linewidth and its Utilization in Optical Determination of ^{229m}Th isomer transition

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

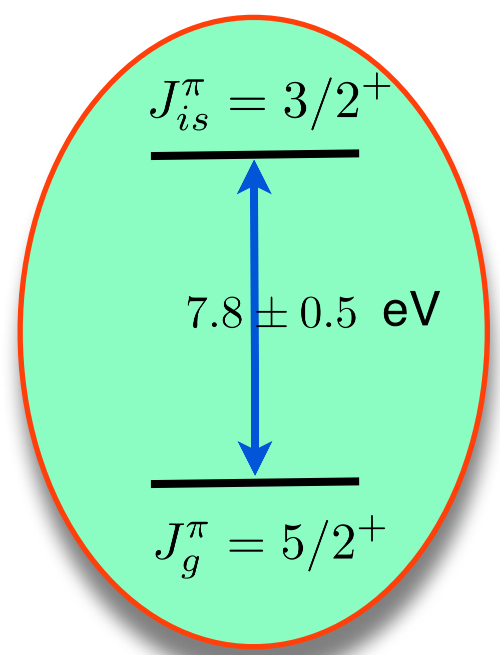
Quest for a Nuclear Frequency standard

Why ??

Better accuracy and stability

Minimum perturbation - thus easier interrogation

Candidate :



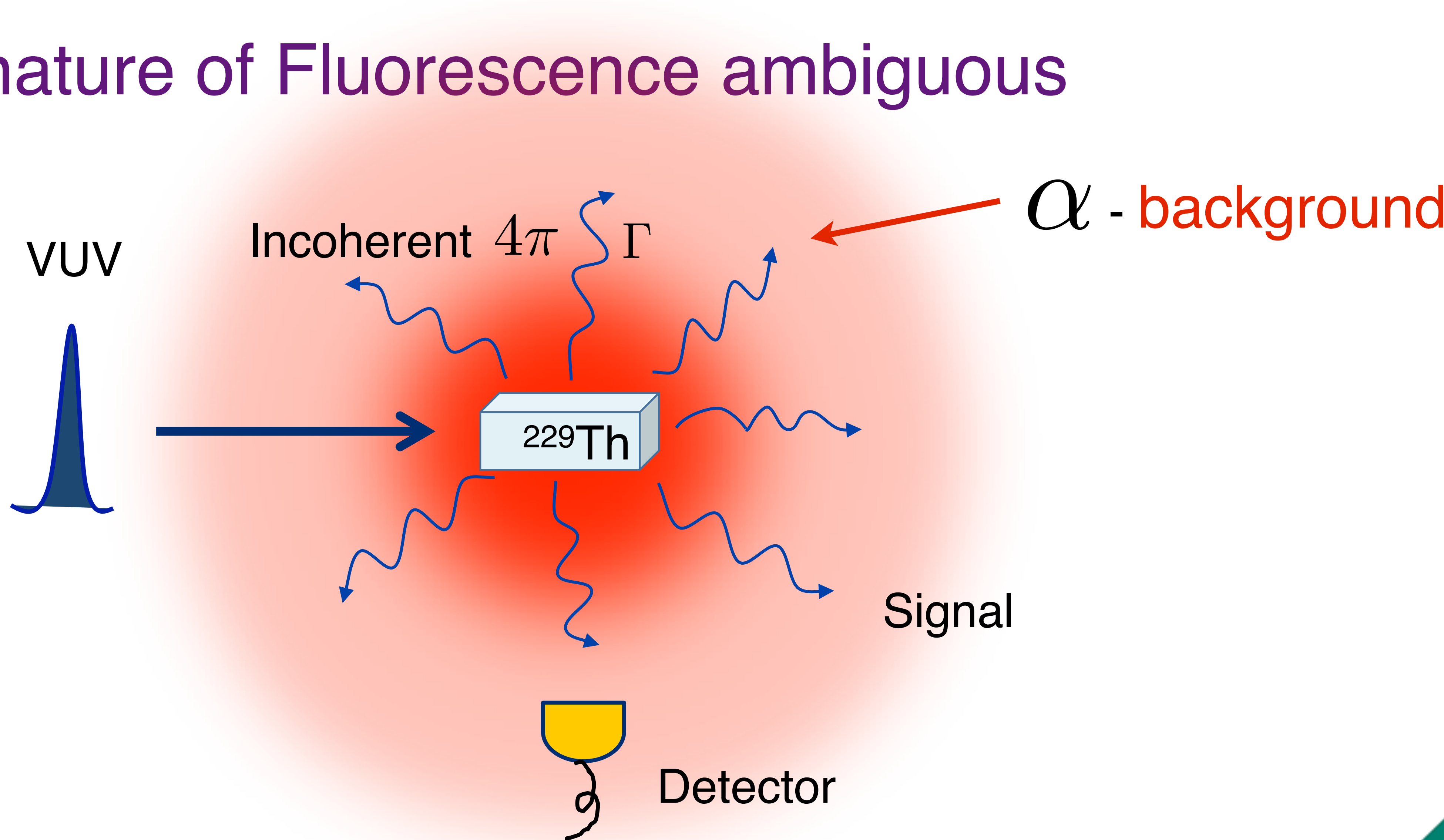
B.R. Beck et. al. LLNL-PROC-415170 (2009)
W.G. Rellergert et. al. PRL 104, 200802 (2010)
C. J. Cambell, A. G. Radnaev and A. Kuzmich, PRL 106, 223001 (2011).

Principle obstacles !!

Uncertainty of isomeric energy

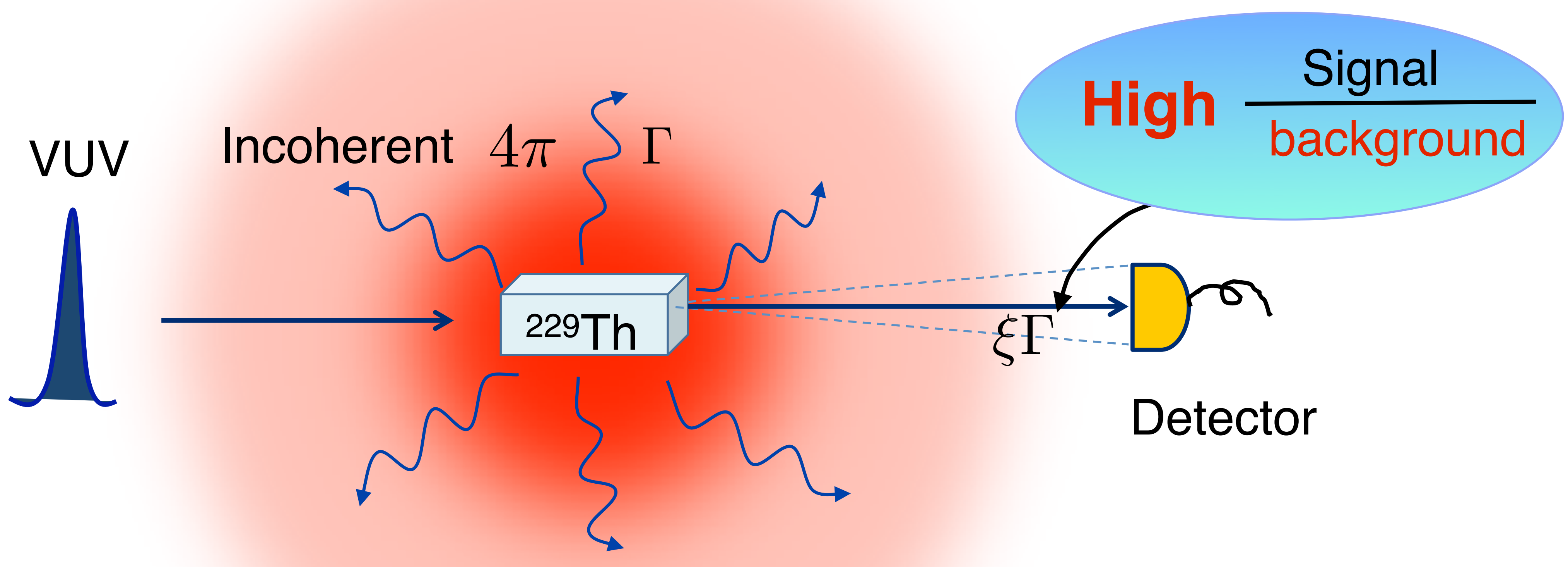
Weak signal compared to background

Signature of Fluorescence ambiguous



Possible Solution

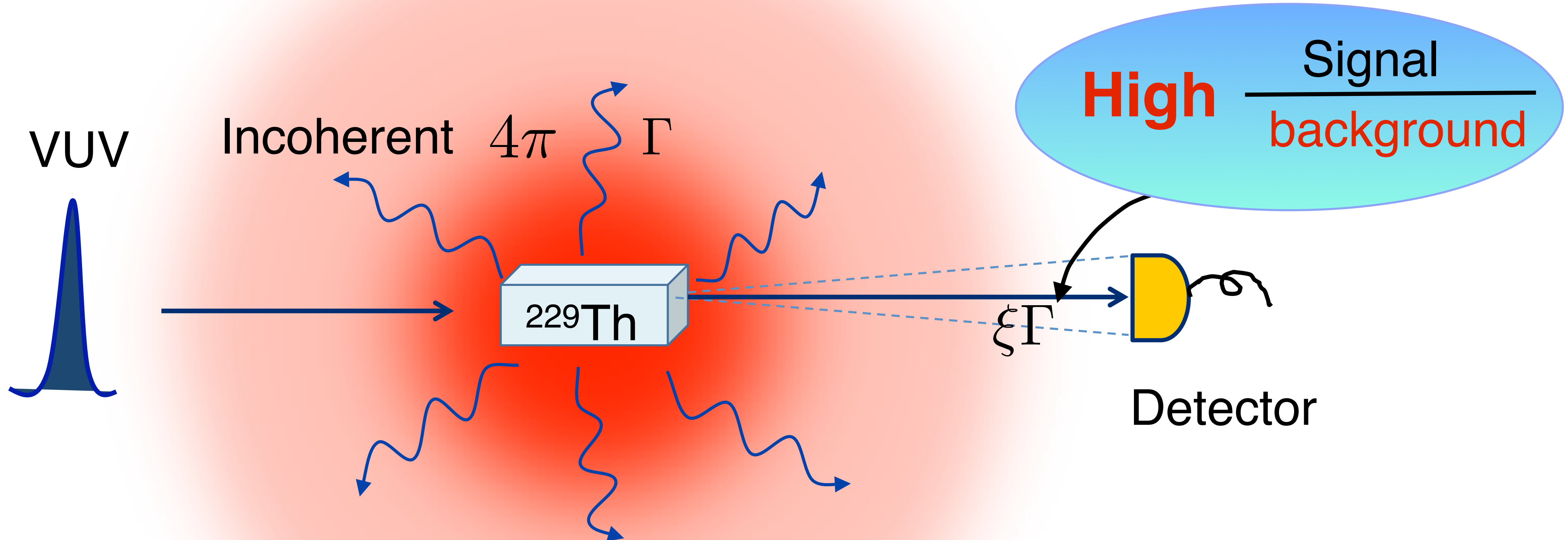
Measuring the signal in the forward direction



Coherent scattering in the forward direction leads enhancement of linewidth

Possible Solution

Measuring the signal in the forward direction

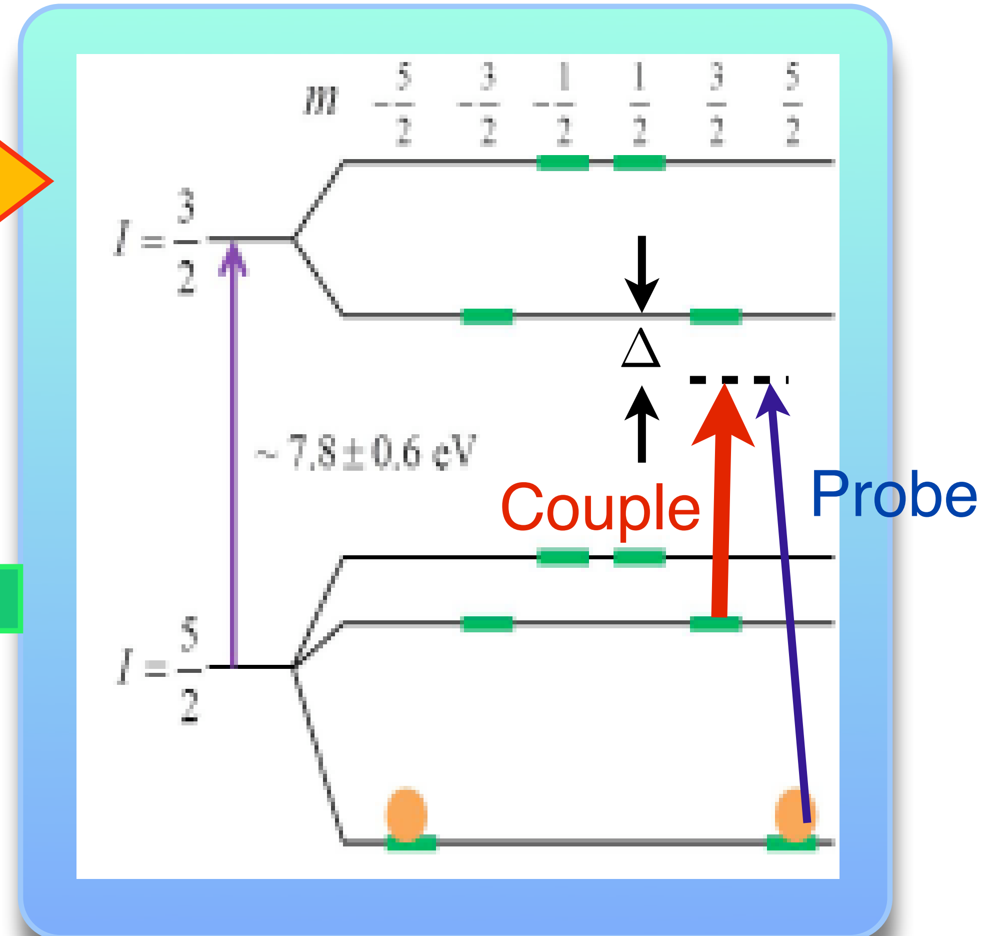


Coherent scattering in the forward direction leads enhancement of linewidth

But what about measuring the transition energy ?

Measuring the Transition energy

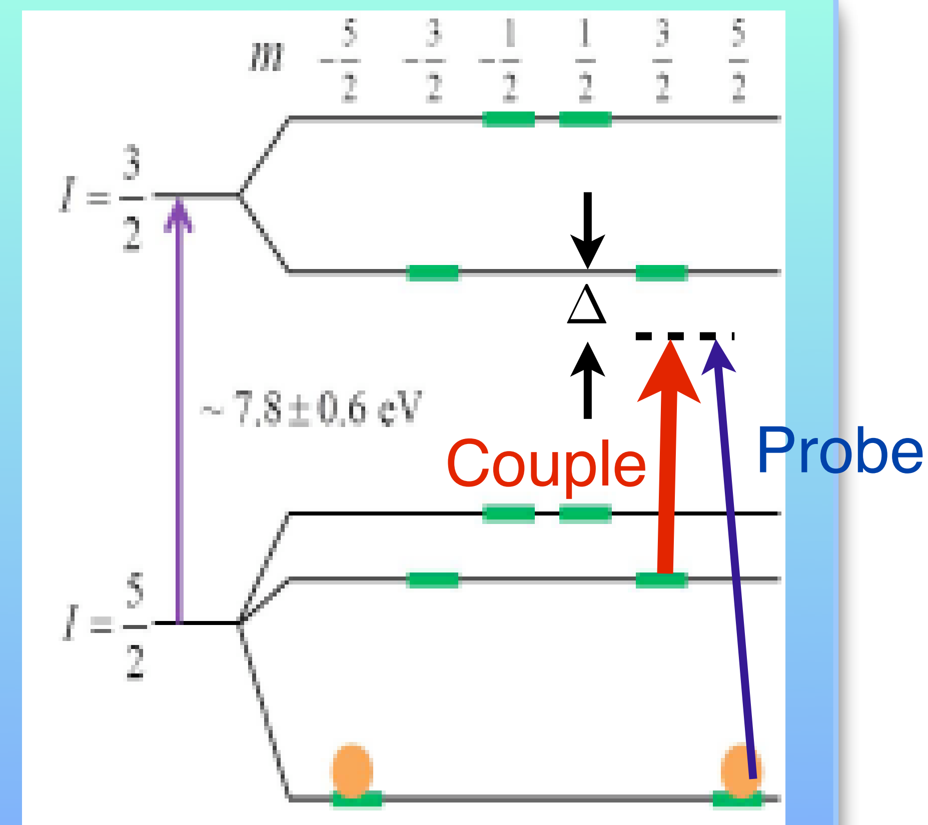
Coherent fast decay in forward direction



coherent FS time spectra of Probe

Measuring the Transition energy

Coherent fast decay in forward direction



coherent FS time spectra of Probe

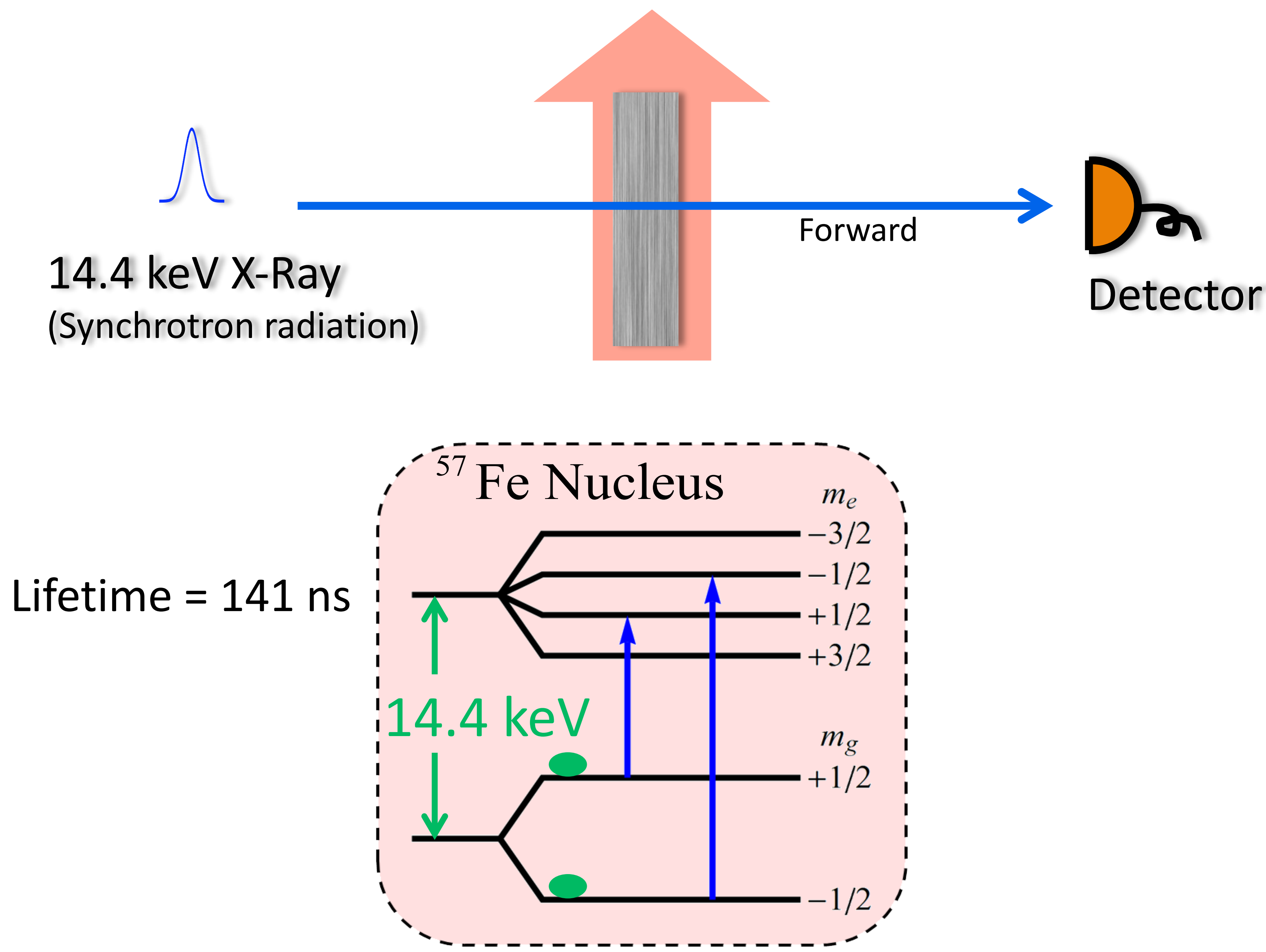
Measurement of transition energy with high accuracy

Coherent Forward Scattering - ^{57}Fe the perfect testbed

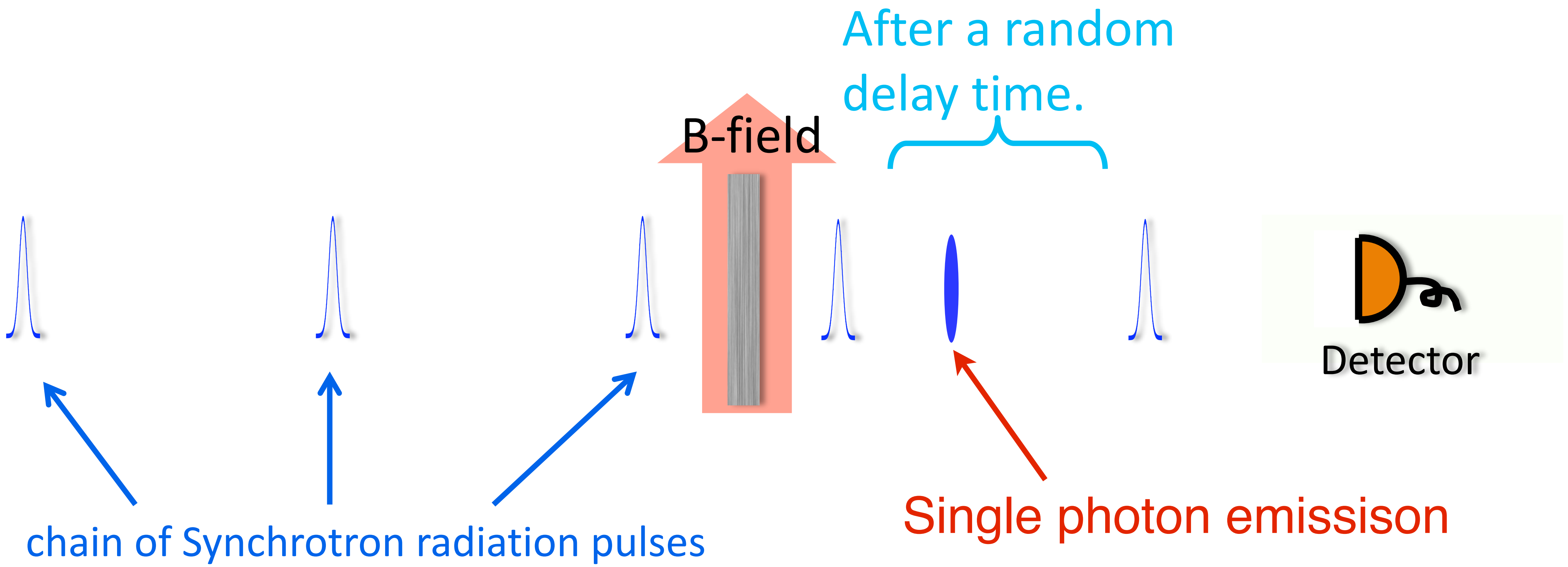
Coherent Forward Scattering and enhancement of line-width in ^{229}Th

Measurement of Isomeric transition energy using coherent enhancement of line-width

Coherent forward scattering in Nuclei

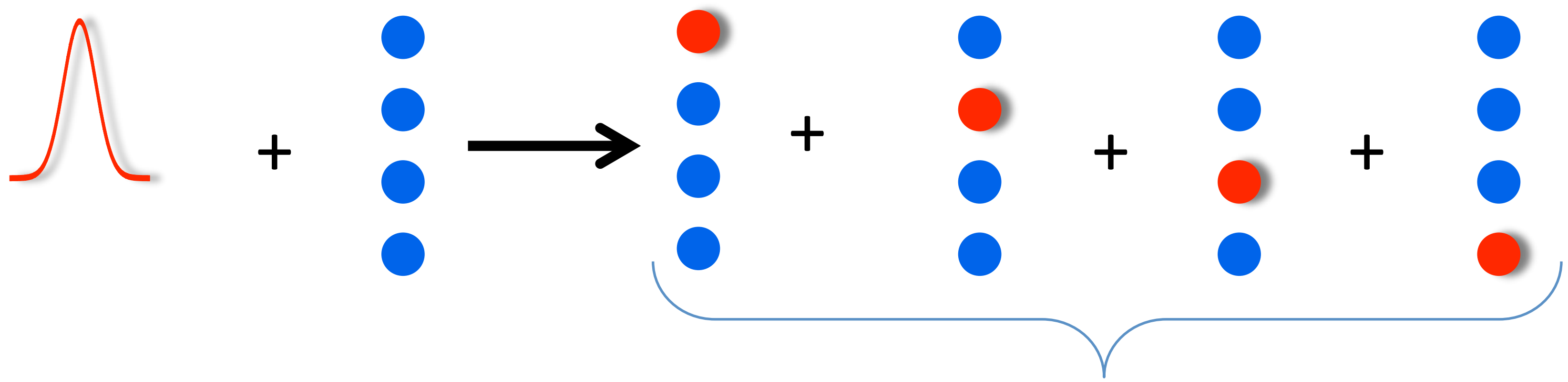


NFS of Synchroton radiation



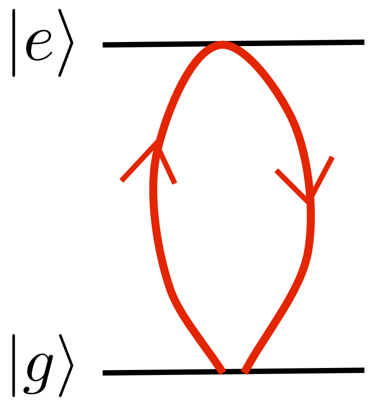
R. Röhlsberger, Book, Springer-Verlag (2004)

Nuclear Exciton



Exciton State

$$\frac{1}{\sqrt{N}}\sum_i e^{i\vec{k}\cdot\vec{r}_i}|g\rangle|e_i\rangle$$



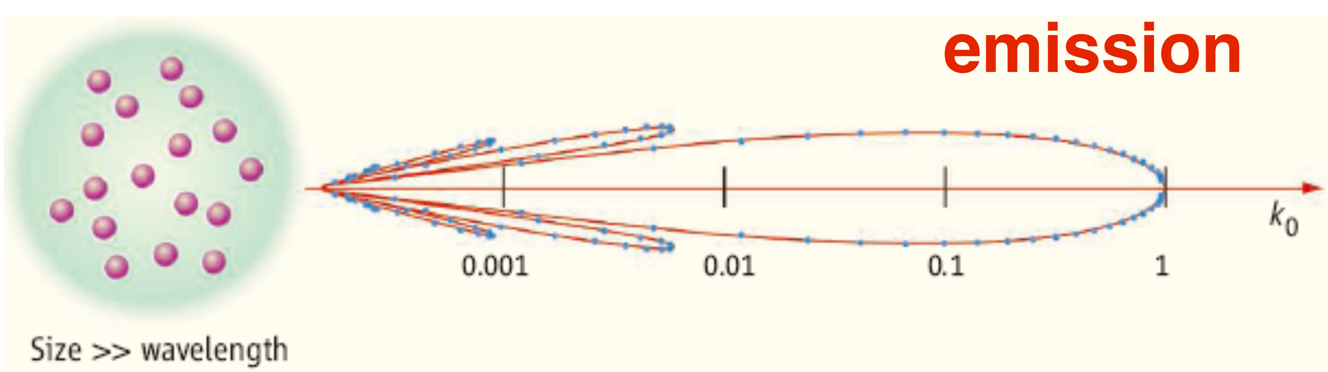
Coherent scattering

recoil-less

No spin flip

Explains Forward Emission

Gives coherent line-broadening in emission



Timed-Dicke state
Quantum Optics

J. P. Hannon and G. T. Trammell, Hyp. Int 123/124 , 127 (1999)
M. O. Scully and A. A. Svidzinsky, Science 325, 1510 (2009)
R. Röhlsberger, Book, Springer-Verlag (2004)

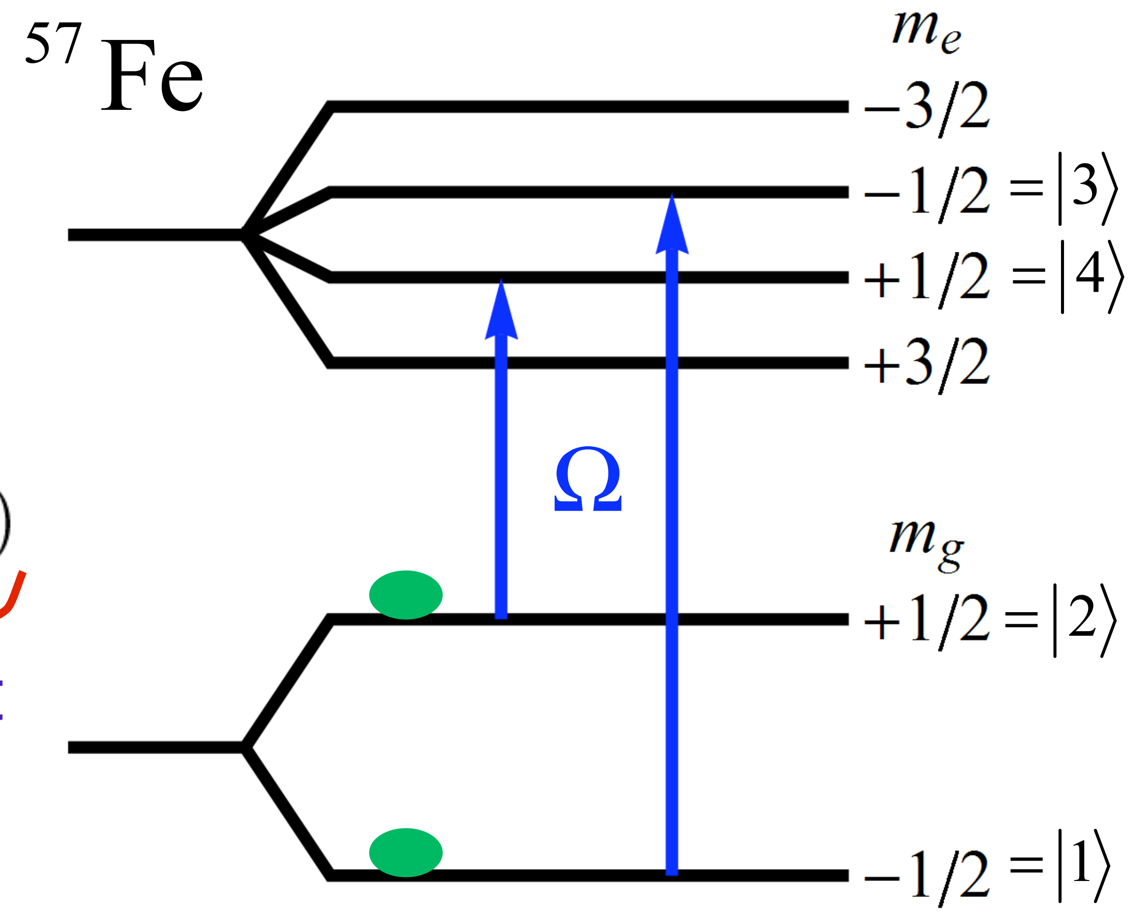
Semi-classical approach

Maxwell - Bloch

$$\partial_t \widehat{\rho} = \frac{1}{i\hbar}\left[\widehat{H}, \widehat{\rho}\right] + \widehat{\rho}_s \ ,$$

$$\frac{1}{c}\partial_t \Omega + \partial_y \Omega = \underbrace{i\eta\left(\rho_{31} + \rho_{42}\right)}_{\text{Transition current}}$$

Transition current



M. D. Crisp, PRA. 1, 1604 (1970)

Yu. Shvyd'ko, et. al, PRB. 59, 9132 (1999)

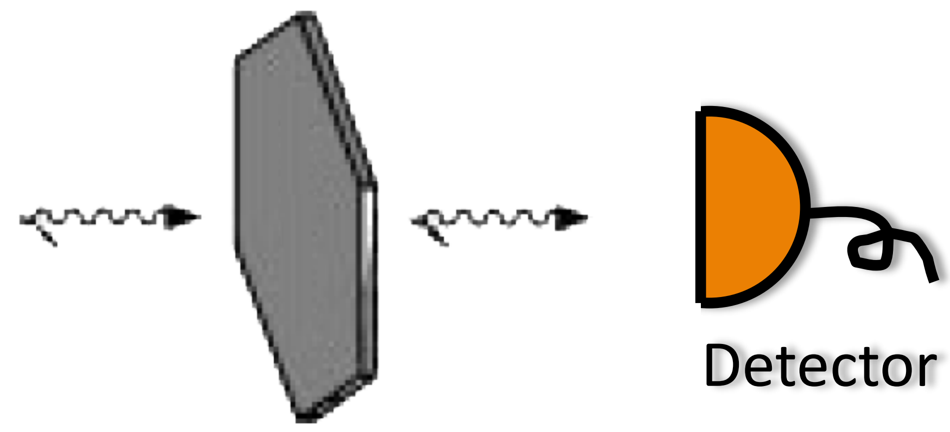
U. van Brück, Hyperfine Interact. 123, 483 (1999)

R. Röhlsberger, Book, Springer-Verlag (2004)

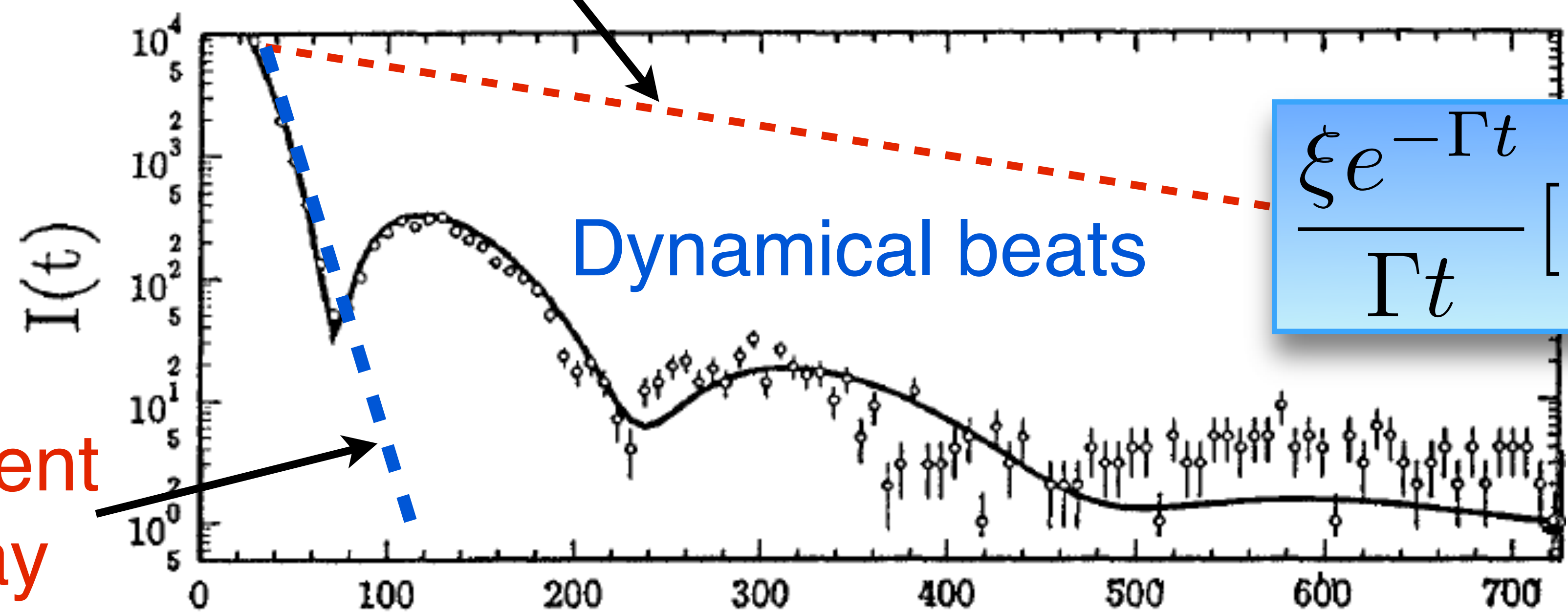
W.-T. Liao, A. Pálffy, C. H. Keitel, arXiv:1205.5503v1 (2012)

Time domain spectrum of NFS

In absence of magnetic field



$e^{-\Gamma t}$ Spontaneous emission



$$\frac{\xi e^{-\Gamma t}}{\Gamma t}[J_1(2\sqrt{\xi \Gamma t})]^2$$

Γ_c

$$t < 1/(\xi\Gamma) \quad \Gamma_c = \xi\Gamma$$

J_1: Bessel function of 1st kind

Γ: Spontaneous Decay Rate

ξ: Resonant Thickness

J. P. Hannon and G. T. Trammell, Hyp. Int 123/124 , 127 (1999)
U. van Brück, Hyperfine Interact. 123, 483 (1999)

In presence of magnetic field

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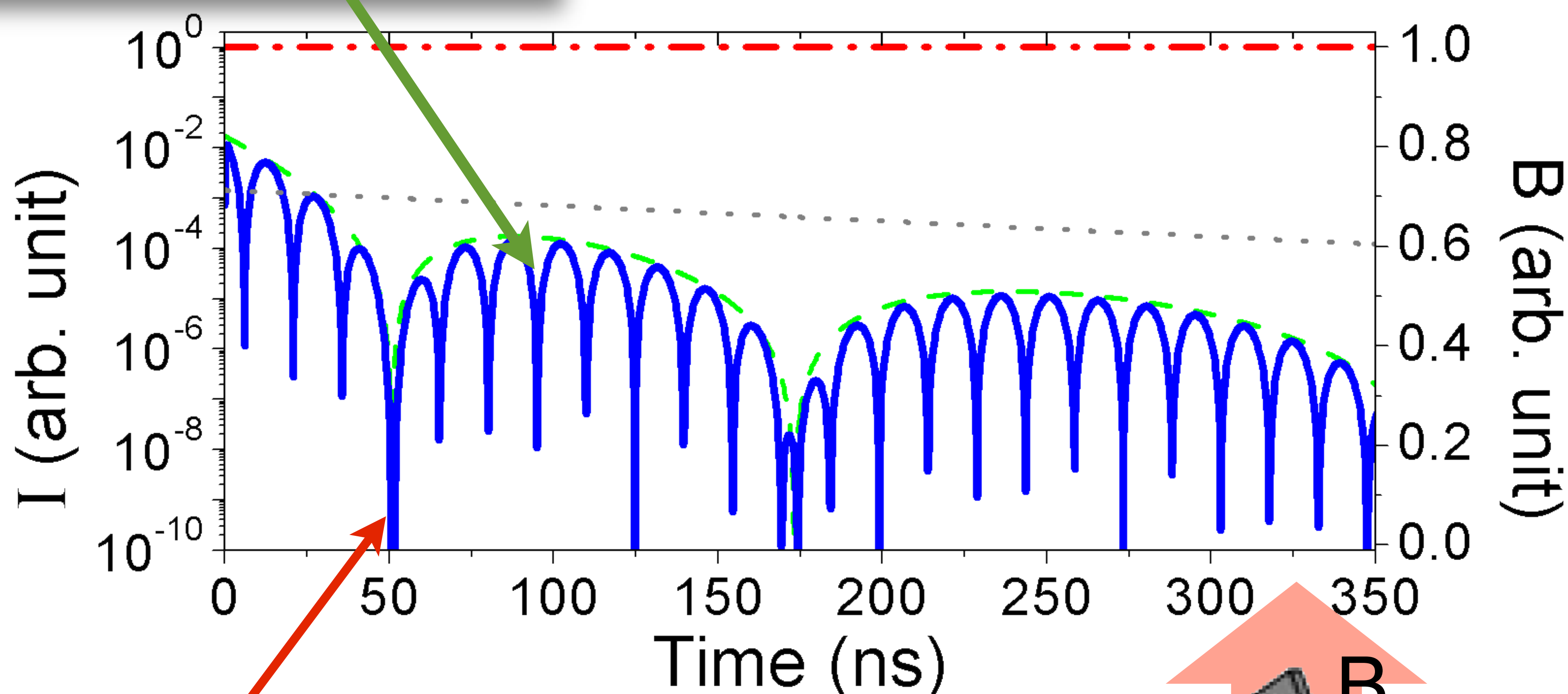
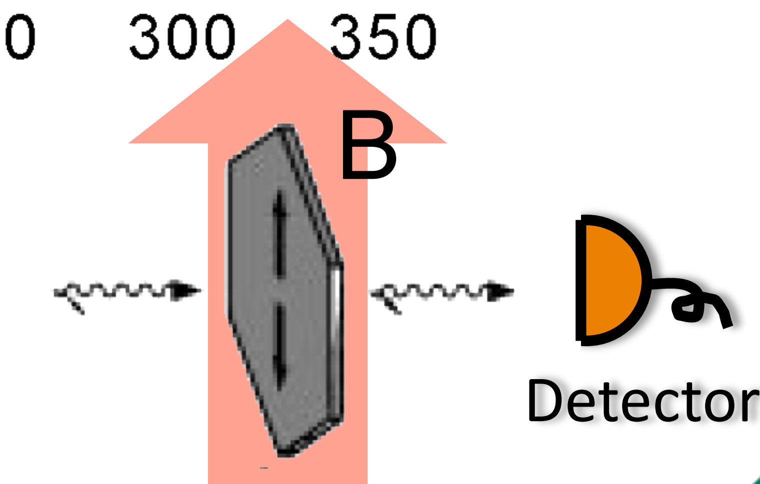


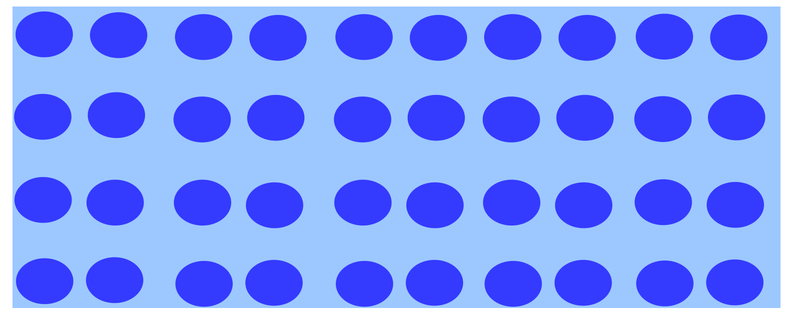
Quantum Beats



M. D. Crisp, PRA. 1, 1604 (1970)

Yu. Shvyd’ko, et. al, PRB. 59, 9132 (1999)

^{229}Th doped VUV crystals



^{229}Th:$LiCaAlF_6$ ^{229}Th:CaF_2

Transparent around the probable isomeric wavelength ~ 160 nm

High doping density of Thorium ~ 10^{18}-10^{19} /cm^3 achievable

Electronic band gap of 10 eV , no internal conversion

^{229}Th in the crystal lattice confined to Lamb-Dicke regime, Lamb-Mossbauer factor ~ 1

W.G. Rellergert et. a. PRL 104, 200802 (2010)
G. A. Kazakov et. al. NJP 14, 083019 (2012)

Shifts and Broadening

Spontaneous line-width of isomeric transition ~ 0.1 mHz

Temperature dependent shifts due to electric monopole interaction ~ 10 kHz/K

Temperature dependent shifts due to 2nd order doppler effect ~ 70 Hz (77 k)

Temperature dependent inhomogeneous broadening due to 2nd order Doppler effect ~ 70 Hz (77k)

Inhomogeneous broadening due to magnetic dipole interaction ~ Few hundred Hz

Homogeneous broadening ??

W.G. Rellergert et. a. PRL 104, 200802 (2010)
C. J. Cambell, A. G. Radnaev and A. Kuzmich, PRL 106, 223001 (2011)
G. A. Kazakov et. al. NJP 14, 083019 (2012)

Coherent Line-broadening in ^{229}Th

Why ??

High density of Thorium ~ 10^{18}-10^{19} /cm^3

^{229}Th in the crystal lattice confined to Lamb-Dicke regime

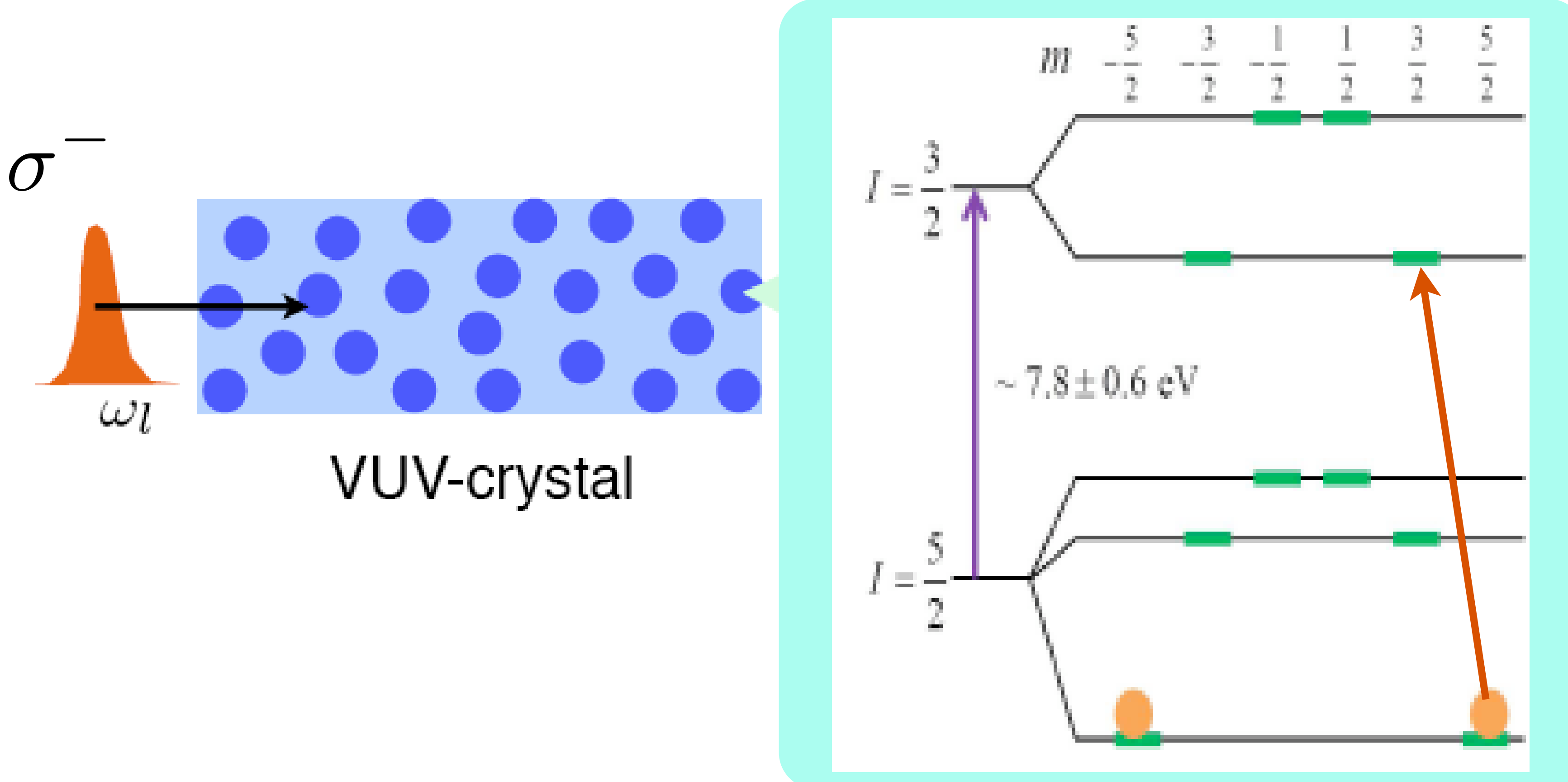
Mossbauer like transition - no recoil

Narrow line-width, weak coupling - favourable condition for formation of exciton

Coherent forward scattering same as Fe can be used

How much is the coherent broadening ?

W.G. Rellergert et. a. PRL 104, 200802 (2010)
C. J. Cambell, A. G. Radnaev and A. Kuzmich, PRL 106, 223001 (2011)
G. A. Kazakov et. al. NJP 14, 083019 (2012)



$$E_m^{is(g)} \simeq Q_{is(g)}(1-\gamma_\infty)\phi_{zz}\frac{[3m^2 - I_{is(g)}(I_{is(g)}+1)]}{4I_{is(g)}(2I_{is(g)}-1)]}$$

$Q_{is(g)} = 1.8$ eb (3.15 eb) $\qquad \gamma_\infty = -(100-200)$

$$(1-\gamma_\infty)\phi_{zz} \sim -10^{18}\ \mathrm{V/cm^2}$$

E. V. Tkalya, PRL 106, 162501 (2011)
G. A. Kazakov et. al. NJP 14, 083019 (2012)

Coherent Line-broadening in ^{229}Th

$$I(\tau) = \mathcal{E}_0^2 \xi e^{-\tau} [J_1(\sqrt{4\xi\tau})]^2/\tau \qquad \tau = \Gamma t$$

Effective resonance thickness $\xi = \frac{1}{4}\sigma N L$

Nuclear resonance cross-section $\sigma = 2\pi \frac{2I_e + 1}{2I_g + 1} \left(\frac{\hbar c}{E_n}\right) \frac{1}{1+\alpha} f_{LM}$

Immediately after excitation $I(\tau) = \mathcal{E}_0^2 \xi^2 e^{-(\xi+1)\tau}$

$$t < 1/(\xi\Gamma)$$

Coherent enhancement of decay rate by a factor ξ

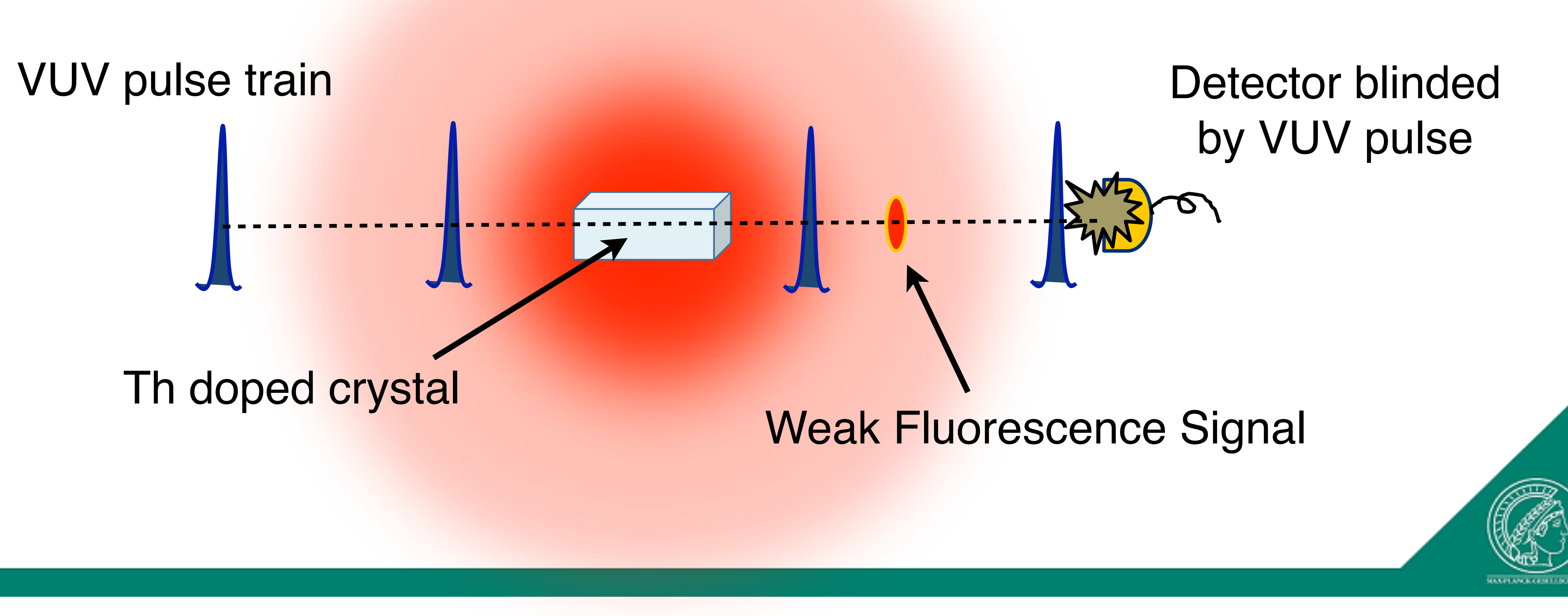
$N = 10^{18} - 10^{19}/\text{cm}^3$ $L = 10\ \text{mm}$ $\sigma \simeq 10^{-12}\ \text{cm}^2$

Coherent enhancement of Decay $\xi \simeq 10^6 - 10^7$

Homogeneous line broadening $\xi\Gamma \simeq 0.1 - 1kHz$

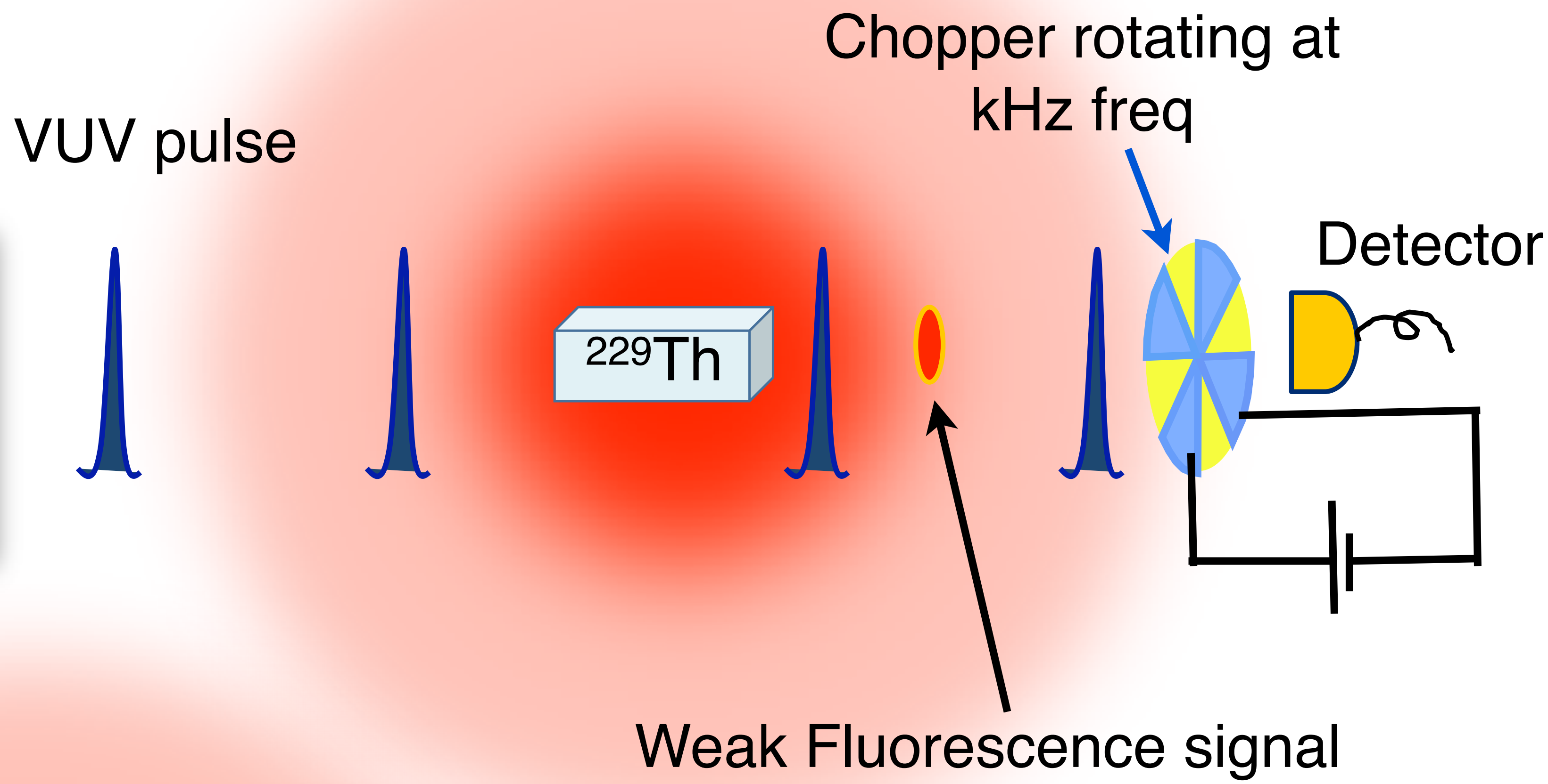
ms time scale for signal collection, high repetition rate of events, lot more data collection

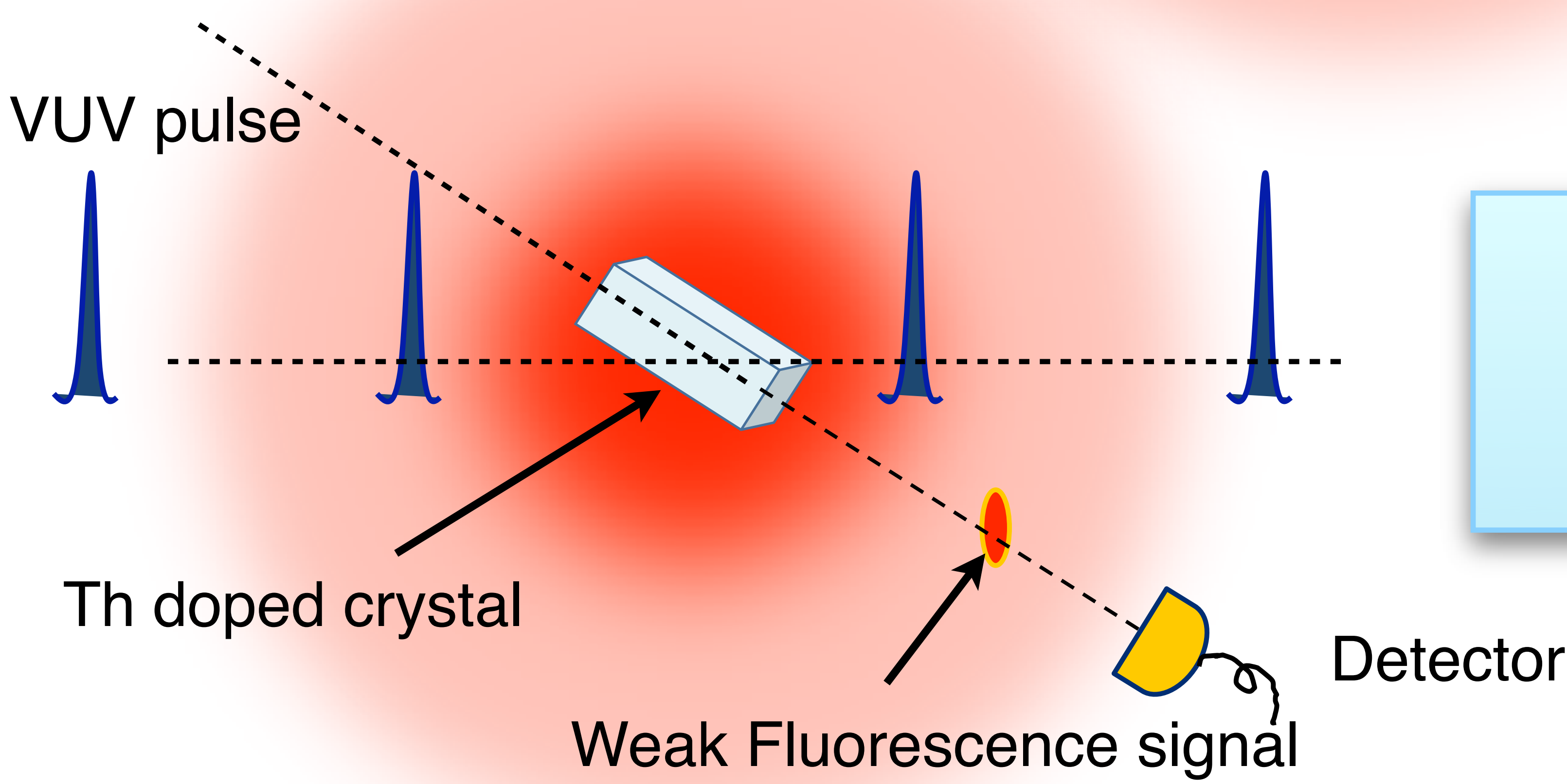
Possible issues in measurement



Solutions:

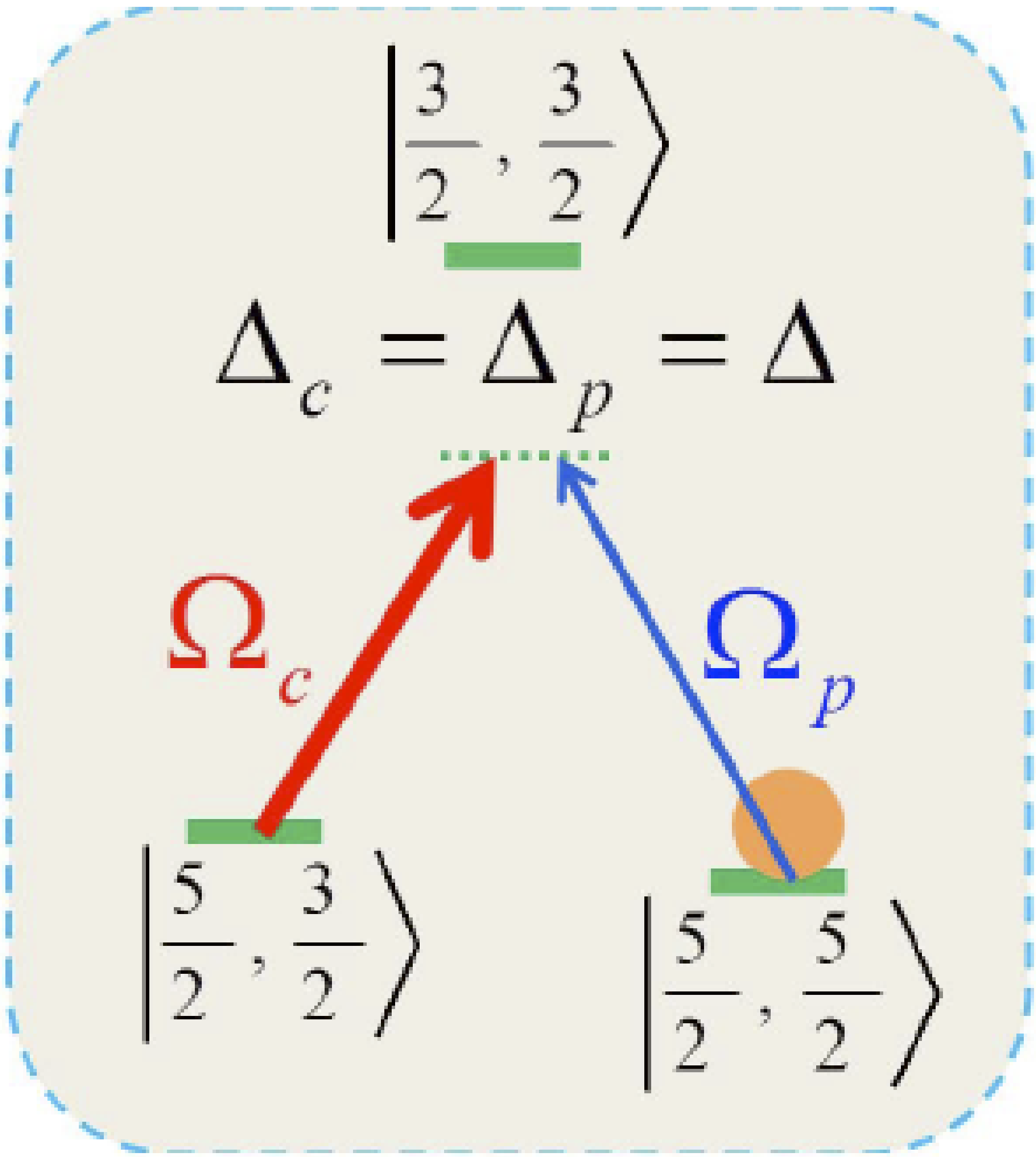
Using a chopper to block the VUV excitation pulse





Rotation of Crystal in ms time scale

Utilization of line-broadening towards determination of the isomeric transition energy



- Two field spectroscopy
- Strong couple, weak probe
- Autler-Townes Splitting
- Splitting induced Quantum beats

Maxwell - Bloch Equations

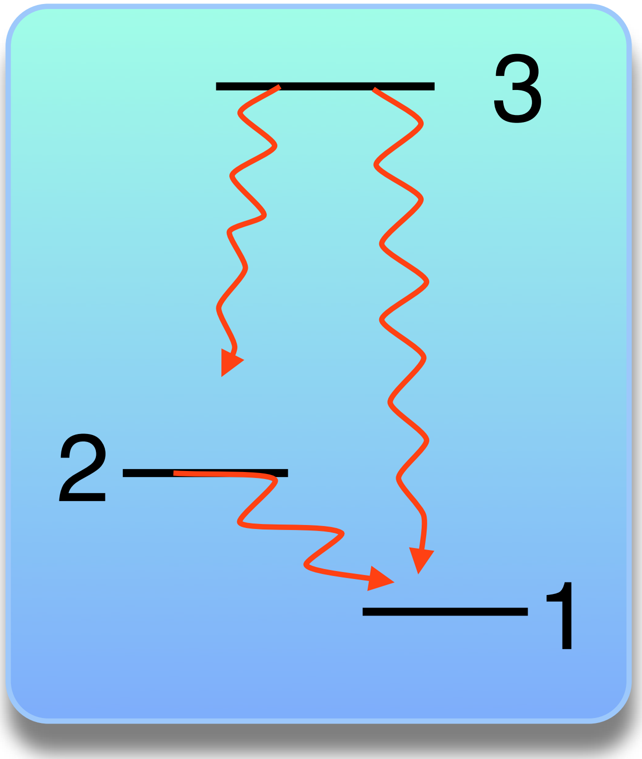
$$\frac{1}{c}\partial_t\Omega_p + \partial_y\Omega_p = i\eta a_{31}\rho_{31}$$

$$\eta = \frac{\Gamma\xi}{2L}$$

Poster by Wen-Te Liao, EMMI Worshop

Clebsch - Gordon co-efficients of allowed transition

$$(a_{31}, a_{32}) = (\sqrt{2/3}, -2/\sqrt{15})$$



Relaxation and decoherence rates

$$(\gamma_{31}, \gamma_{32}, \gamma_{21}) = 2\pi \times (251, 108, 30) Hz$$

Rabi Frequency

$$\Omega_{p(c)} = \frac{4\sqrt{\pi}}{\hbar} \left[\frac{I^{eff}_{p(c)} (L+1) B(\mu L)}{c\epsilon_0 L} \right]^{1/2} \frac{k^{L-1}_{31(2)}}{(2L+1)!!} Exp[\frac{-n\tau}{\sqrt{2}T}]$$

n = 1 for probe, = 0 for control $\quad T = 10\mu s$

Wen-Te Liao, S. Das, A. Palffy and C. H. Keitel, arxiv: 1210.3611 (2012)

G. A. Kazakov et. al. NJP 14, 083019 (2012), Poster by Wen-Te Liao, EMMI Worshop

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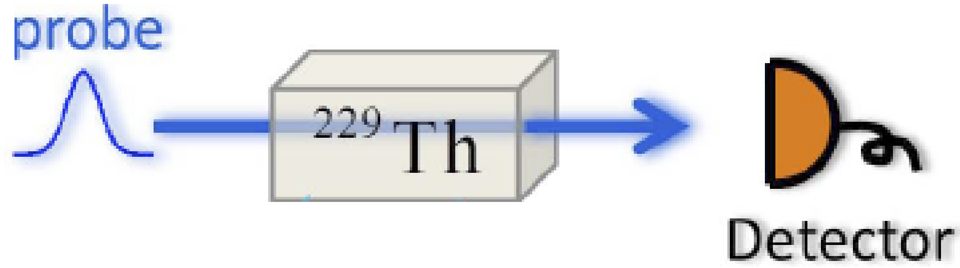
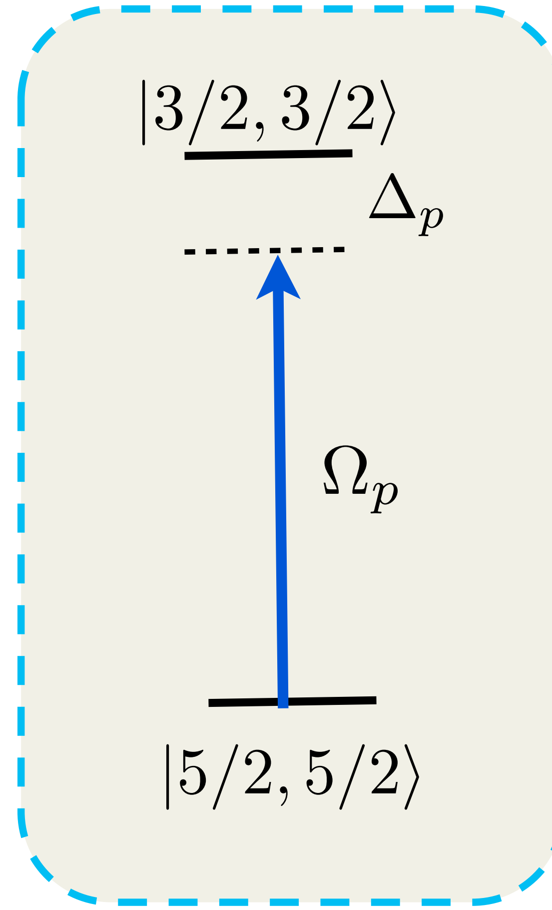
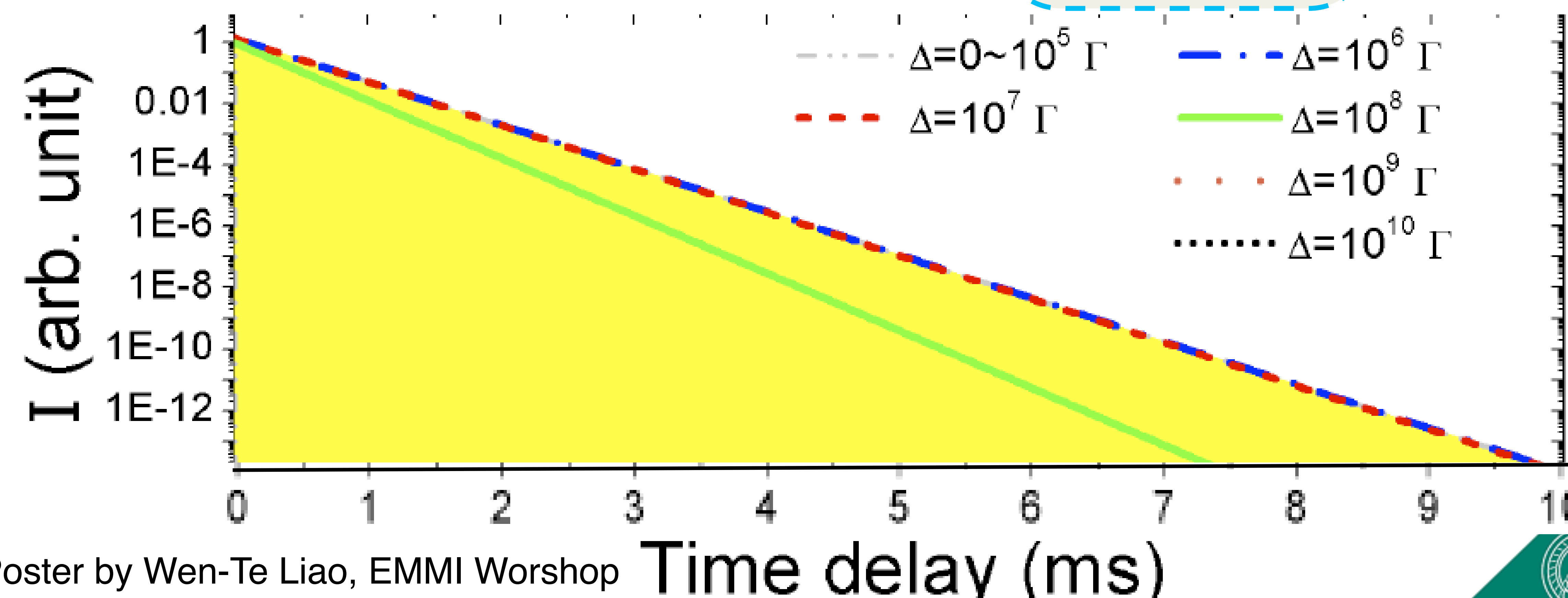


$$E = \hbar(\omega_p + \Delta_p)$$





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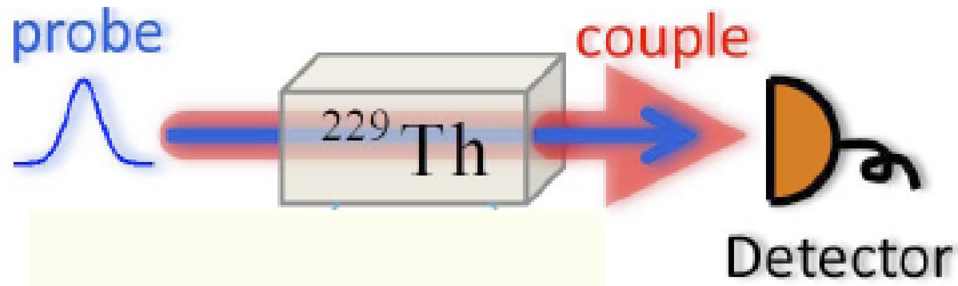

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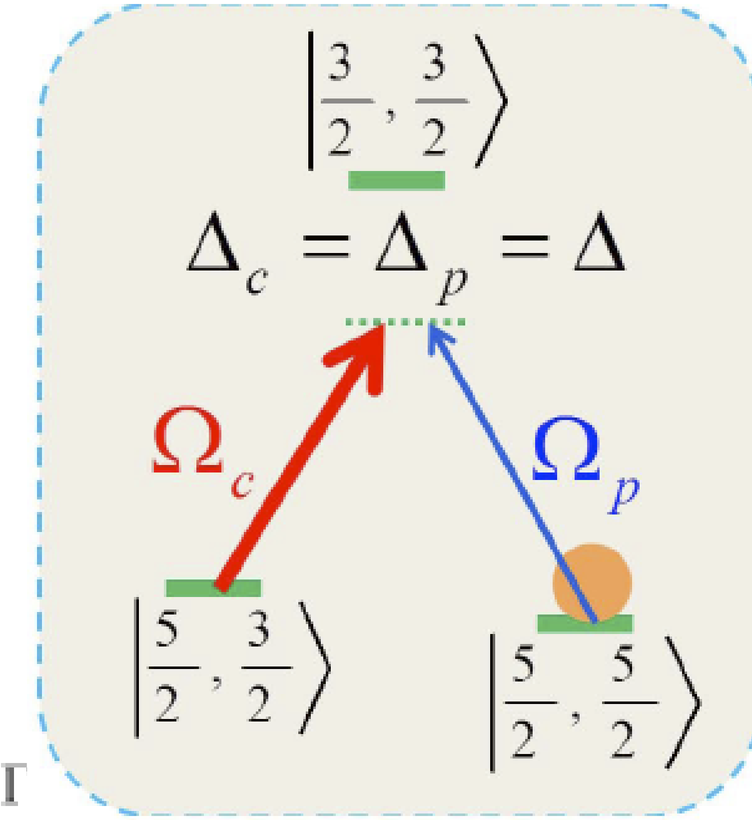

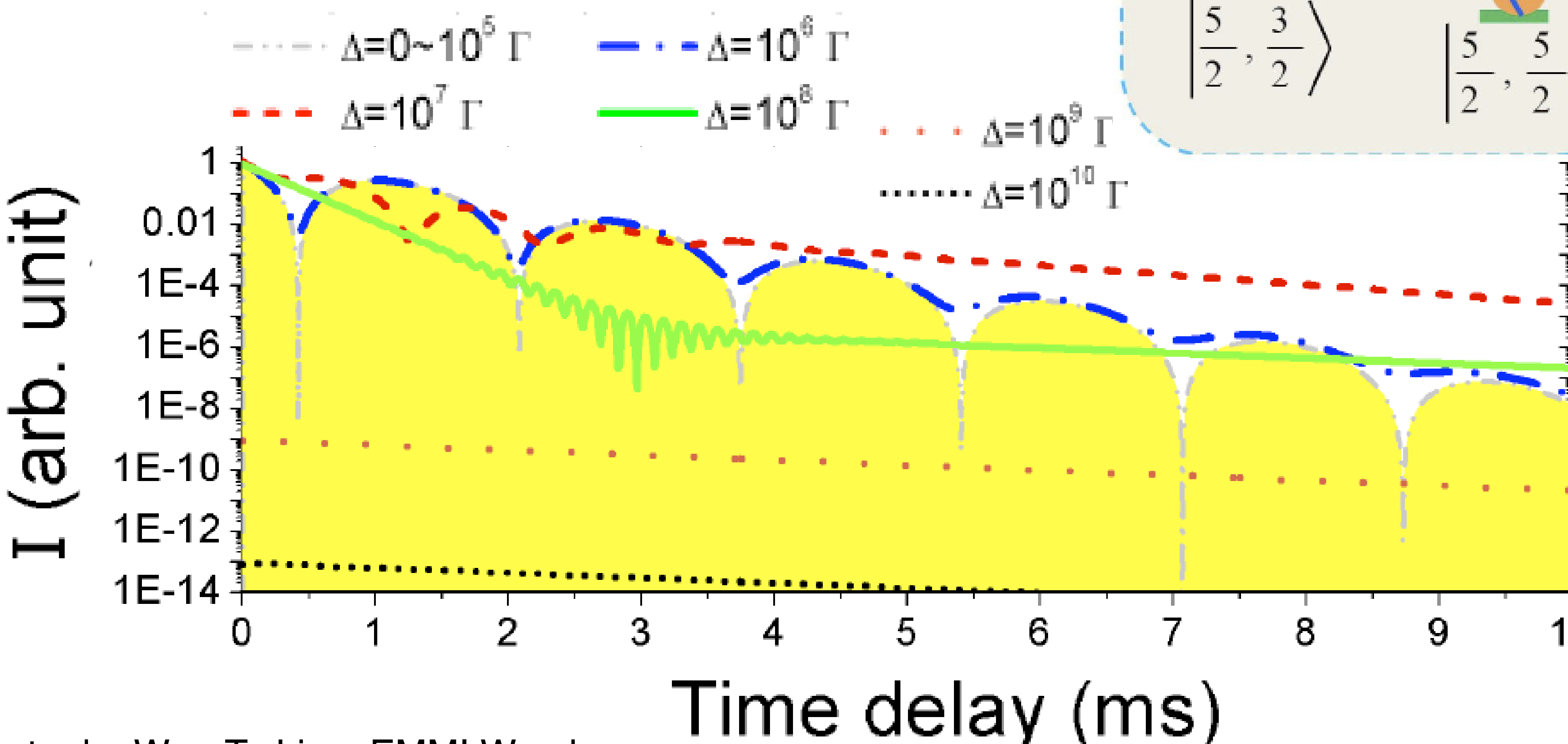

Poster by Wen-Te Liao, EMMI Worshop

Wen-Te Liao, S. Das, A. Palffy and C. H. Keitel, arxiv: 1210.3611 (2012)

Conclusions

Coherent scattering from Th-ensemble in forward direction leads to faster decay - in ms time scale

Forward direction suitable for signal measurement, high signal to background ratio, more signal collection in a time interval

NFS time spectra of the probe in a couple-probe scheme gives quantum beat - a clear signature of isomeric transition

Energy of the isomeric transition can be evaluated to an accuracy of 10Hz by fitting the detuning dependent measured NFS time spectra with theory

Thanks for your interest