Nuclear Resonant Scattering (NRS) and its Applications using pulsed SR

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Dr. Zhang Xiaowei

Why Nuclear Scattering using Synchrotron Radiation?

- 1) Obtain an ultra-monochromatic x-ray beam: a frontier of energy resolution
- 2) Develop some new experimental techniques: inelastic, quasi-elastic x-ray scattering
- 3) Develop new possibility of traditional Mössbauer spectroscopy
- 4) Develop applications of ultra-monochromatic x-ray beam: x-ray wavelength standard

γ-ray vs. synchrotron radiation

	γ-ray	**SR**
Energy bandwidth	10^{-8}eV	10^{-3}~10^{-2}eV
Relative brilliance	1	>10^{5}
Polarization	poor or difficult	ideally
Pulsed radiation	difficult	ideally
Energy tunability	ΔE~100μeV	ideally

Overcome a huge S/N

technique	Signal (Nuclear scattering)	Noise (Electric scattering)
Time gated detection	Time-delayed response	Prompt response
Polarization dependence	M1, E2	E1
Specialized optical device	allowedly	forbidden

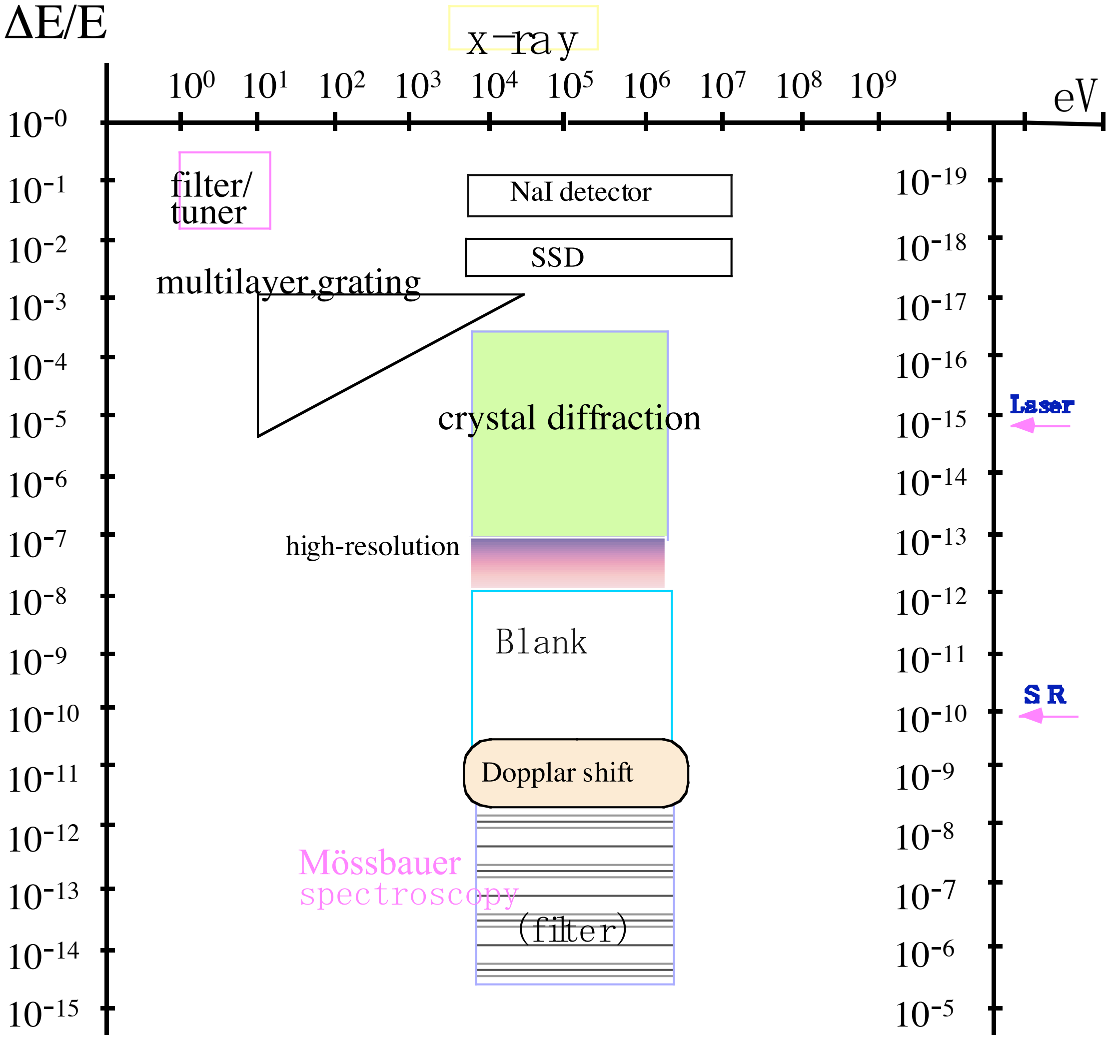
Ultra-monochromatic x-ray beam can only be obtained from a nuclear system in solid, can not be obtained from any electric systems.

Resolution power of diffraction lattice is limited by error of $\Delta d/d$.

Nature of nuclei frequency resonance in x-ray range (Mössbauer resonance) is a key technique of Ultra-monochromatic x-ray beam.

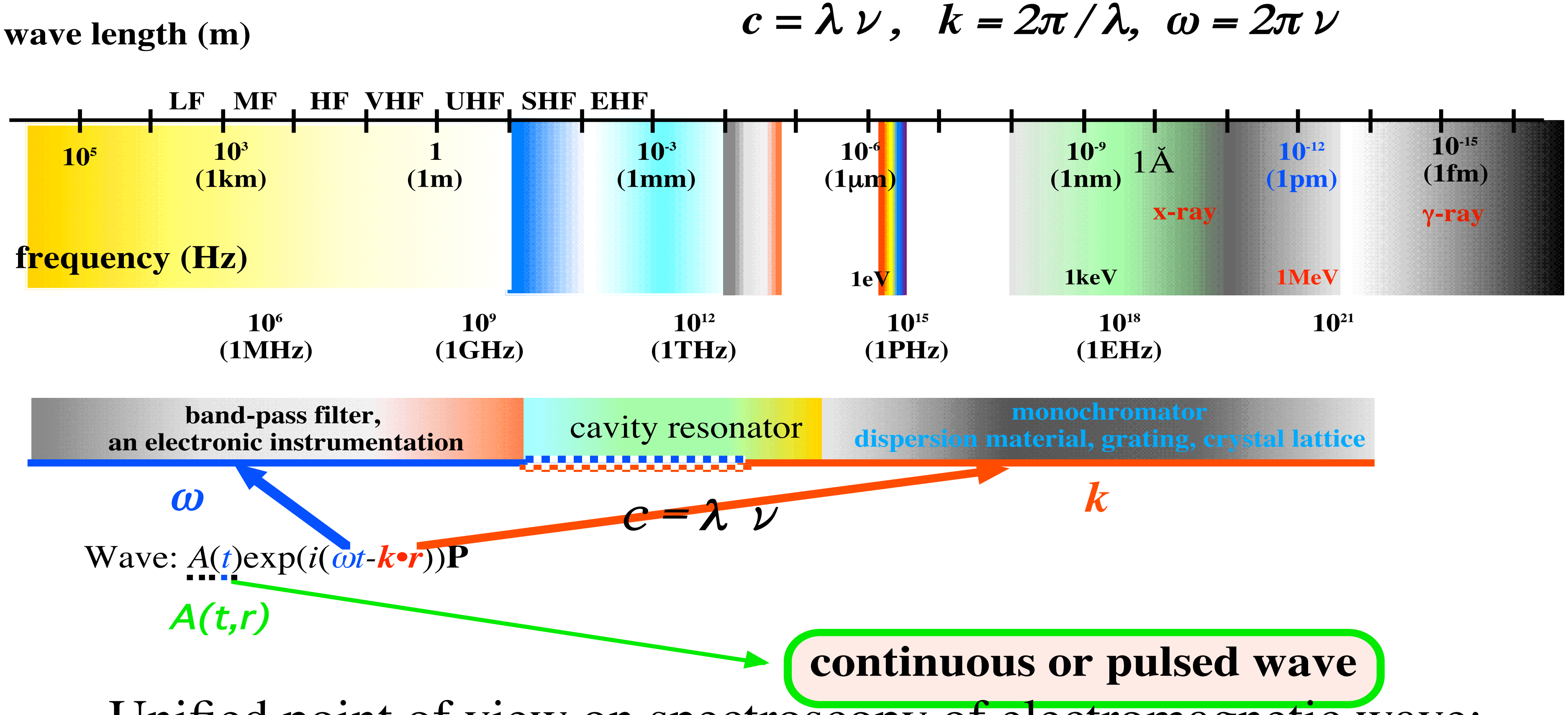
To separate nuclear resonant signal from electric scattering, the difference in behavior of pulse response is utilized.

Scale of energy resolution



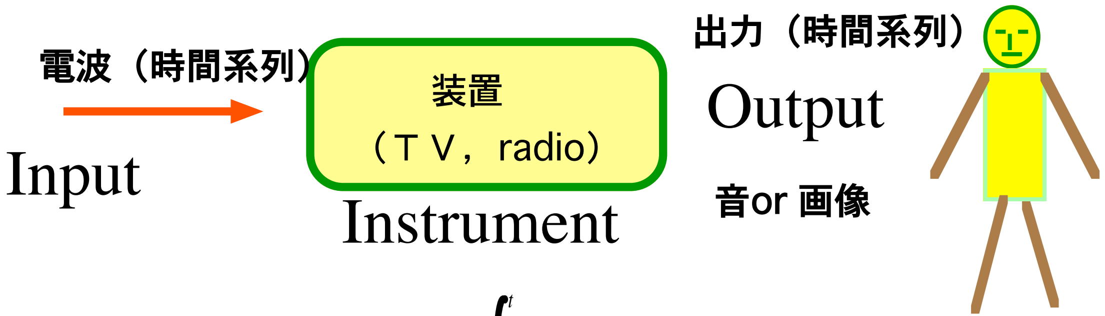
principle and operation in Electromagnetic Waves Spectroscopy

$$c = \lambda \nu, \quad k = 2\pi / \lambda, \quad \omega = 2\pi \nu$$



Unified point of view on spectroscopy of electromagnetic wave:
Spectrometer operates on ω in long wavelength range,
operates on $k(= \omega / c)$ in high frequency range.

Frequency tuning in radio-wave band



数学表現
Mathematical description

$$y(t) = \int_{-\infty}^{t} g(t-\tau)x(\tau)d\tau$$

時空間
t-space

$$= \int_{-\infty}^{\infty} g(t-\tau)x(\tau)d\tau,\ when\ t-\tau<0,\ g(x)=0$$

周波数空間
ω-space

$$\underline{Y(\omega)} = \underline{G(\omega)}\,\underline{X(\omega)}$$

出力　装置関数　入力

電波 → 入力

音 → 出力

tuner of a radio
band-pass filter
+amp

共振回路

$$\boxed{\begin{array}{c} e^{-\alpha t/\Gamma},\ \alpha \ge 0 \\ \updownarrow \\ \dfrac{1}{\omega^2-\omega_0^2+\Gamma^2} \end{array}}$$

Spectrometer for light or x-ray

光源

（空間分布，波数分布）

Light source

Monochromator

分光器

（空間分布，波数分布）

diffractions

数学表現

Mathematical description

空間

Real space

$$h(x) = \int_{-\infty}^{x} g(x-\xi)\ f(\xi)d\xi$$

$$= \int_{-\infty}^{\infty} g(x-\xi)\ f(\xi)d\xi, when\ x-\xi<0, g(x)=0$$

波数空間

k-space

$$\underbrace{H(k)}_{\text{出力}} = \underbrace{G(k)}_{\text{装置関数}}\underbrace{F(k)}_{\text{入力}}$$

出射単色光

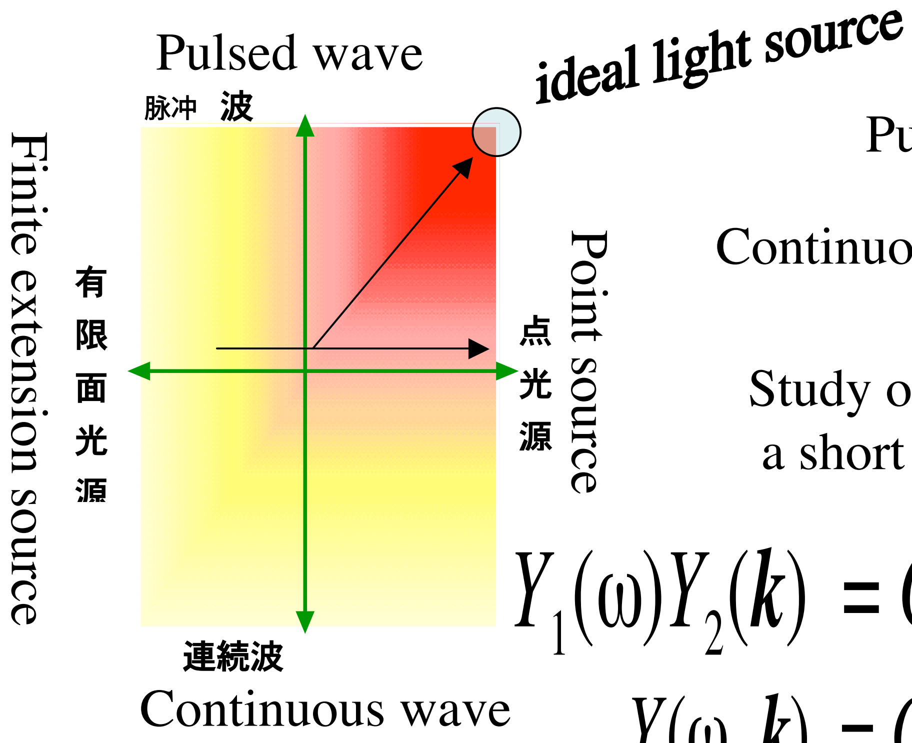
分光器＋slit

（空間周波数filer）

入射光

$$\Delta k = G$$

3-dimensional view of light source



Pulsed wave ⇔ Point source

Continuous wave ⇔ Finite extension source

Study of resonant system essentially needs
a short pulsed wave ⇔ δ function response

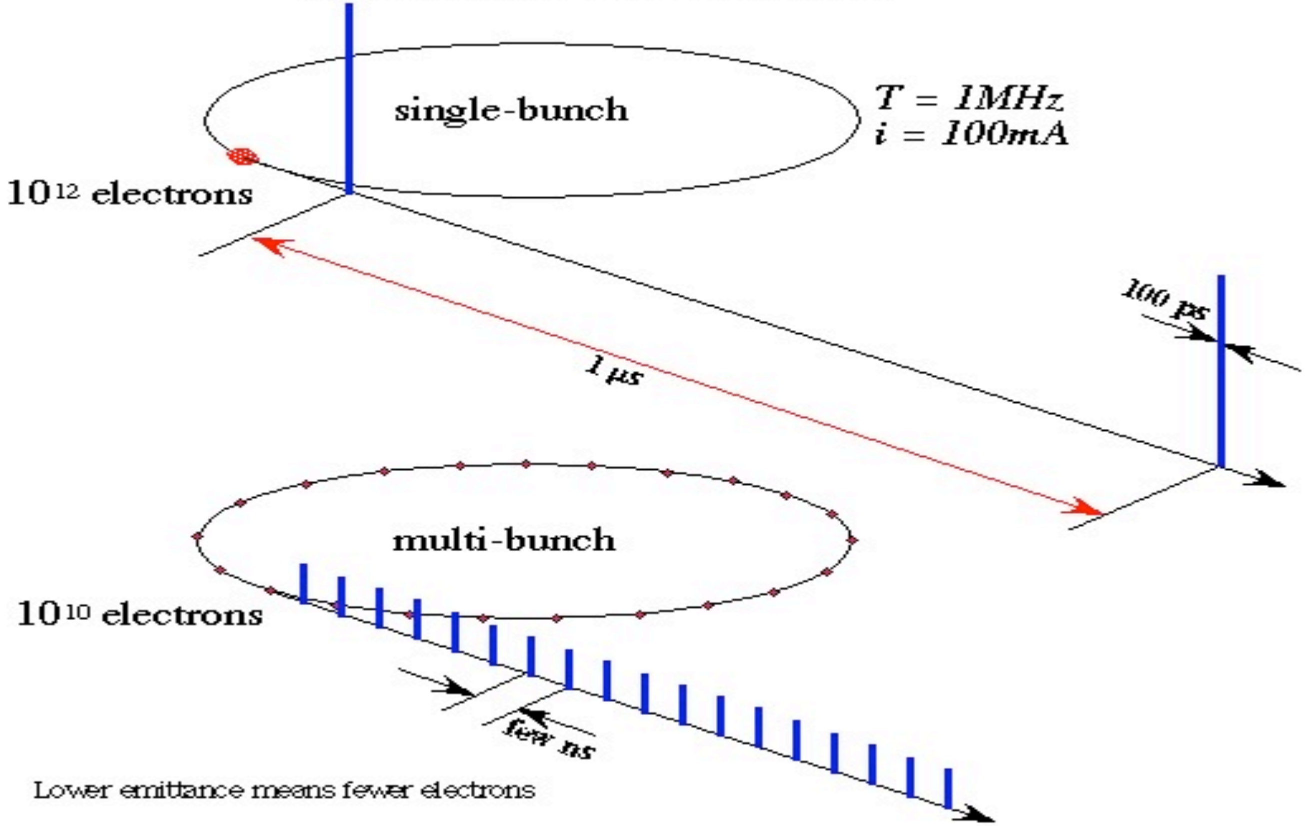
$$Y_1(\omega)Y_2(k) = G_1(\omega)G_2(k)X_1(\omega)X_2(k)$$

$$Y(\omega, k) = G_1(\omega)G_2(k)X(\omega, k)$$

$$Y(\omega, k) = G(\omega, k)X(\omega, k)$$

Few bunches ⇒ High-brilliance in time domain

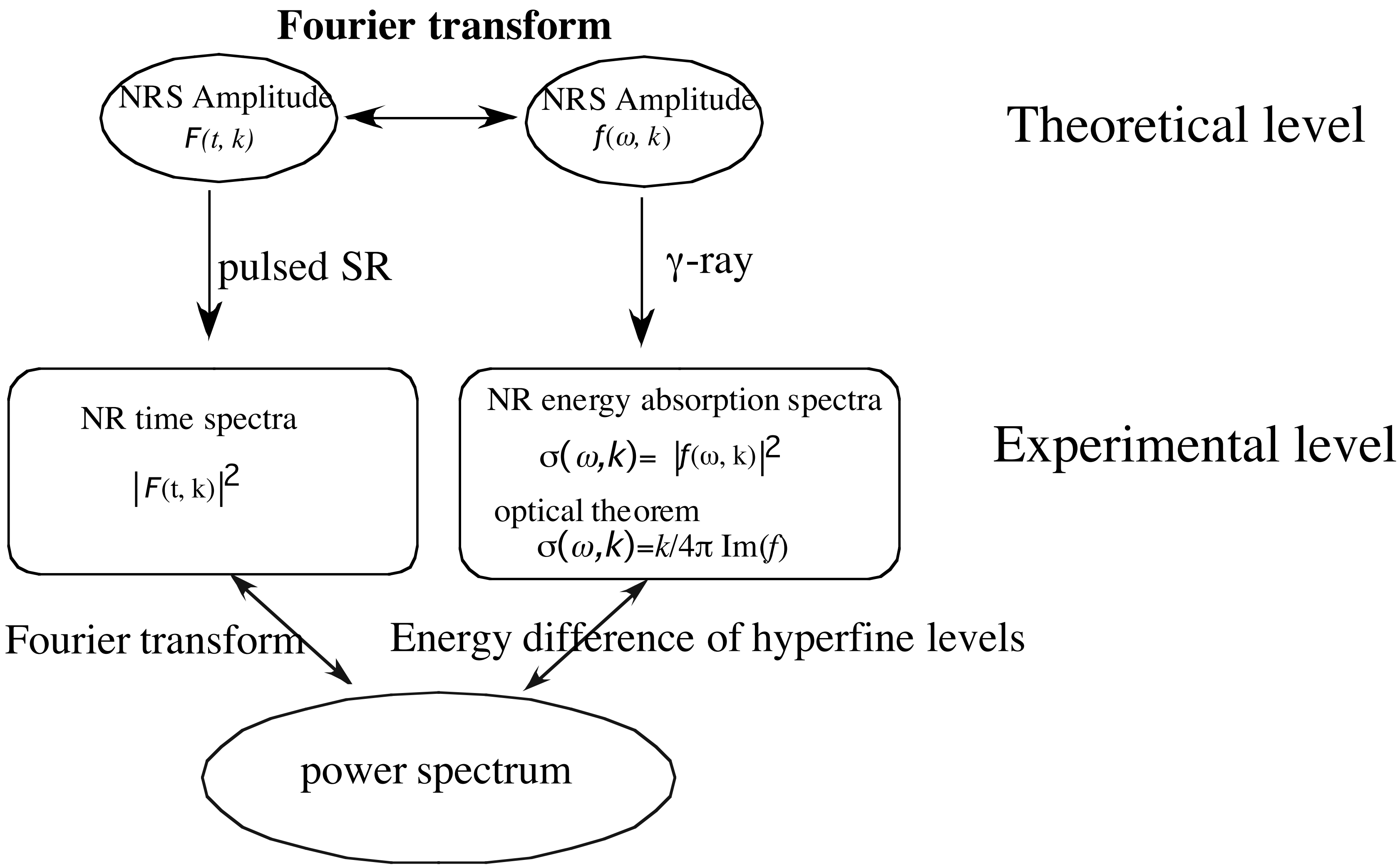
Synchrotron Radiation



Lower emittance means fewer electrons

Brilliance (photons/sec/mrad^2/mm^2/0.1%ΔE/E)	>10^{15} at 10keV (insertion device)
Polarization	linear or circular
Time structure	pulse width~100ps, revolution~1µs

Correlations between NRS in energy domain and time domain



Fourier transform

NRS Amplitude $F(t, k)$

NRS Amplitude $f(\omega, k)$

Theoretical level

pulsed SR

γ-ray

NR time spectra

$|F(\mathrm{t}, \mathrm{k})|^2$

NR energy absorption spectra

$\sigma(\omega,k) = |f(\omega, \mathrm{k})|^2$

optical theorem

$\sigma(\omega,k) = k/4\pi\ \mathrm{Im}(f)$

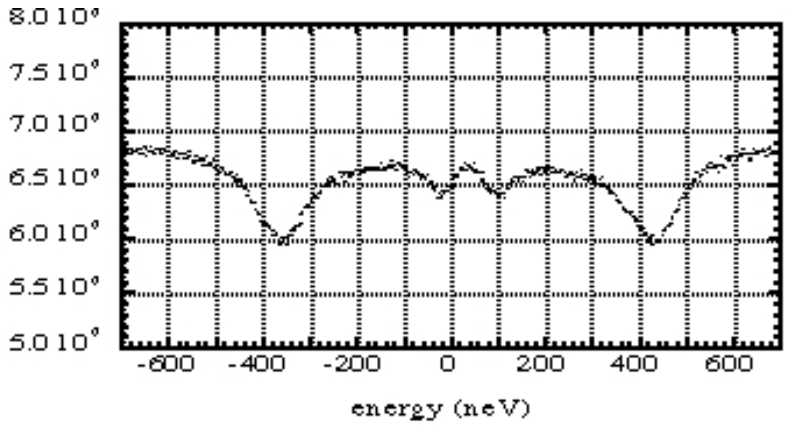
Experimental level

Fourier transform

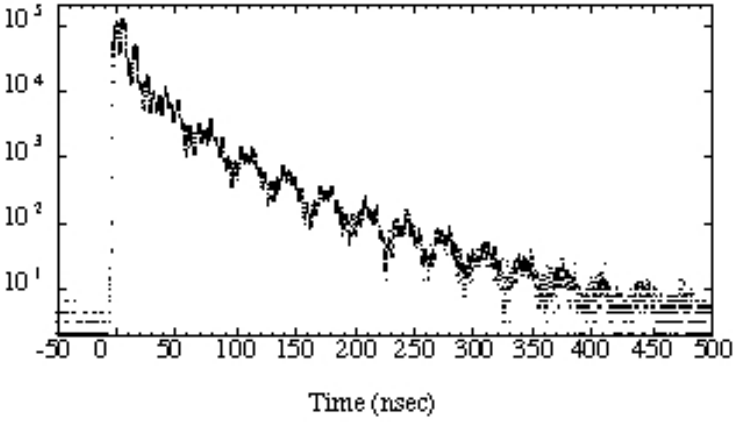
Energy difference of hyperfine levels

power spectrum

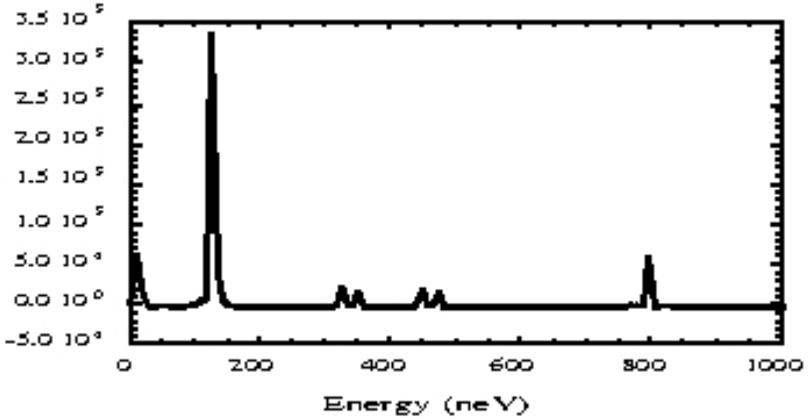
Comparing nuclear resonance in 3 worlds



Nuclear resonant absorption spectra in energy domain (Mössbauer spectra)

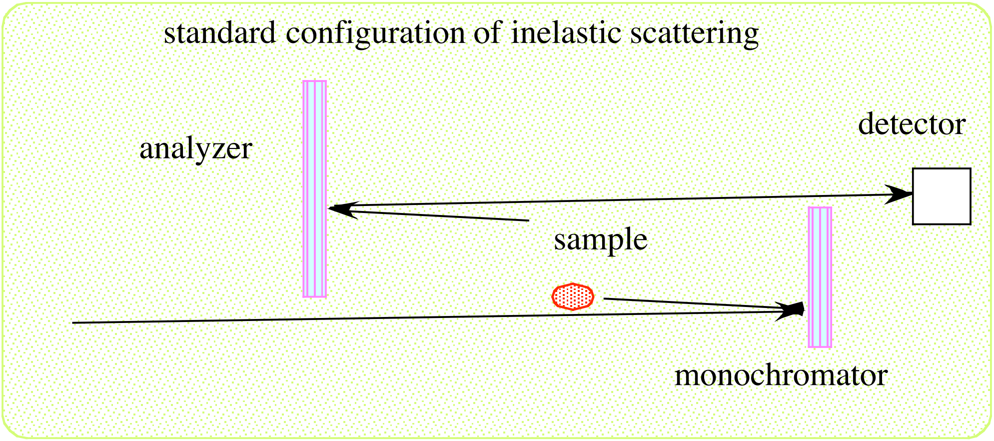


Nuclear resonant response for short x-ray pulse (Quantum beats)



Fourier transformation of quantum beats (Power spectra, energy difference between energy levels)

Develop a new experimental technique



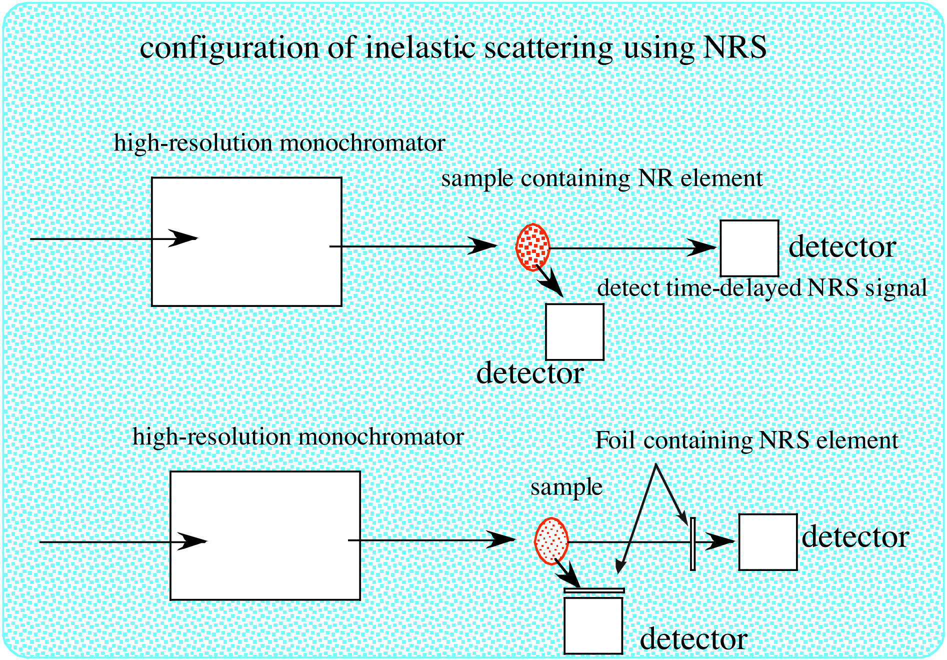
standard configuration of inelastic scattering

analyzer

detector

sample

monochromator



configuration of inelastic scattering using NRS

high-resolution monochromator

sample containing NR element

detector

detect time-delayed NRS signal

detector

high-resolution monochromator

Foil containing NRS element

sample

detector

detector

First result of inelastic NRS

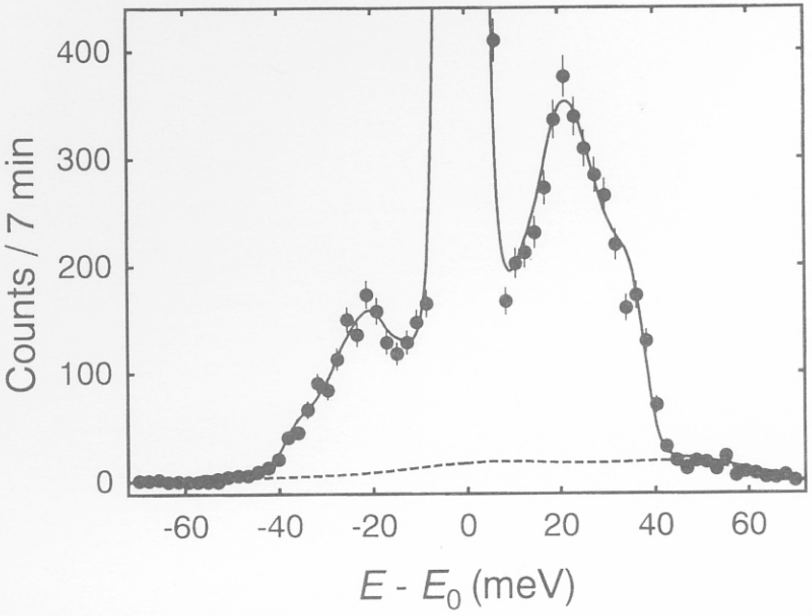
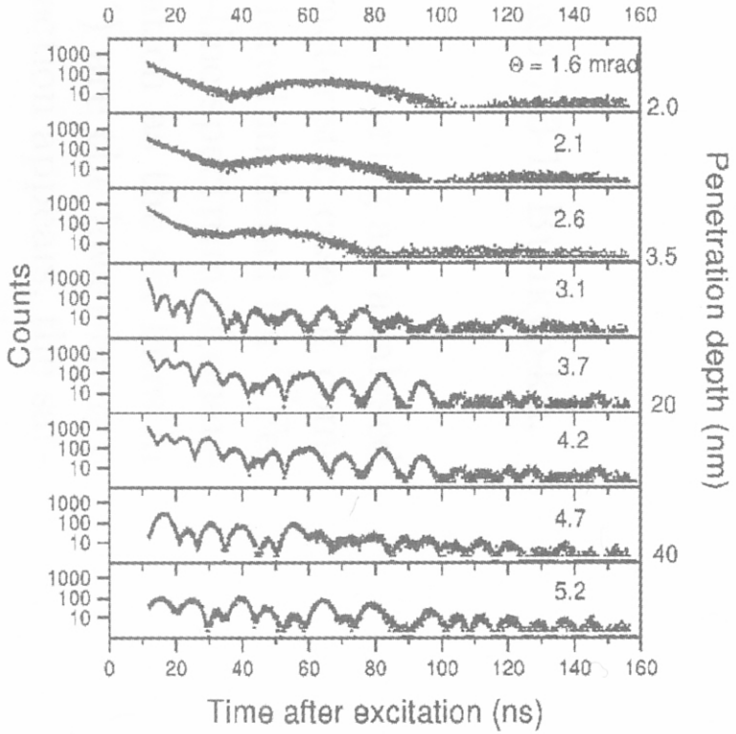


FIG. 4. Energy spectrum of nuclear resonant scattering from a polycrystalline α-^{57}Fe foil. The distance of the iron foil from the detecting plane of the APD detector was 2 mm. This is the same as in Fig. 2(b), except that the intensity scale is magnified and the sum of calculated multiphonon terms $(2 \leq n \leq 12)$ convoluted with the resolution function is shown as a dashed line. The accumulation time was converted to the value when the current of the AR was 26 mA. See also the caption of Fig. 2.

Develop new applications of traditional experimental technique

Nagy D., et al , Synchrotron Mössbauer Reflectometry in Materials Science, In: Mössbauer spectroscopy in Materials Science, Eds. Miglieni, M. and Petrids, D. (Kluwer Academic Publishers, Dordrecht, 1999) p323-336.

Control x-ray penetration depth



20 nm ^{57}Fe film on glass, heated at 285°C for 4 hrs. Magnetic fields of 0.37 T

Time domain spectra were drastically changed by adjusting applying the incident angle.

conclusion

- 1) not a simple short bunch, but **high-brilliant** short pulse
- 2) NRS technique brings us a new energy resolution frontier in x-ray region
- 3) NRS technique combines with pulsed SR let us be able to do something new where the traditional Mössbauer spectroscopy can not do