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Nuclear Angular Correlation on ^{57}Fe

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Motivation

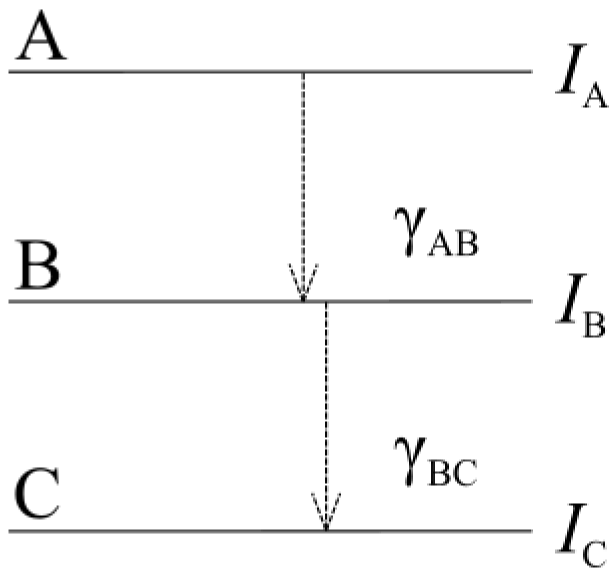
- Additional method for Emission Mössbauer Spectroscopy
- Decision between quadrupole or magnetic origin of interactions
- Measurement of hyperfine interaction in liquid materials
- Precise measurement of weak hyperfine magnetic fields

Aims

- Building of a suitable setup for angular correlation measurements
- Study of hyperfine interactions in amorphous metals
- Comparison of quadrupole splitting in liquids and frozen state

Angular Correlation

- Nuclear technique investigating the nuclear energy levels involved in nuclear transitions emitting particles or quanta
- Nuclei with three or more energy levels
- Transitions between the energy levels are carried out by emittions of gamma radiations
  - γ - γ cascade



Time-Dependent Unperturbed AC

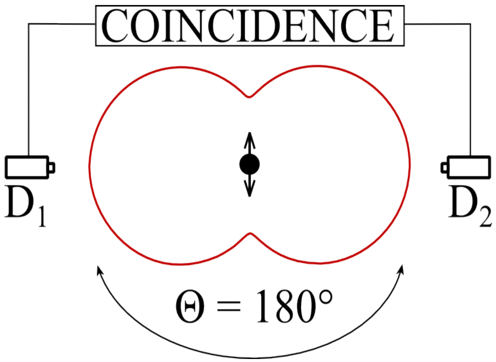
- Suppose that the intermediate state *B* has a finite lifetime τ_N
  - Explicitly exclude any interaction leading to precession while nucleus is in the intermediate level

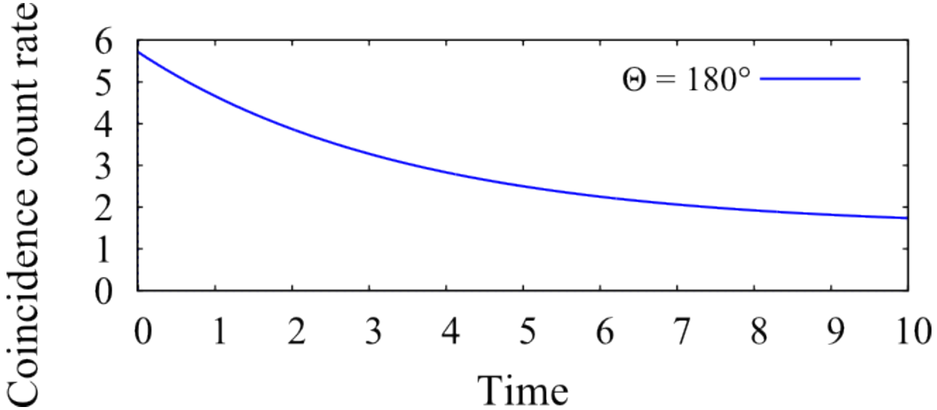
- Time dependent angular correlation function decays exponentially with lifetime τ_N of intermediate level (no time dependence in angular part!)

$$W(\theta, t) \propto \exp\left(\frac{-t}{\tau_N}\right) \sum_k A_{kk} P_k(\cos\theta)$$

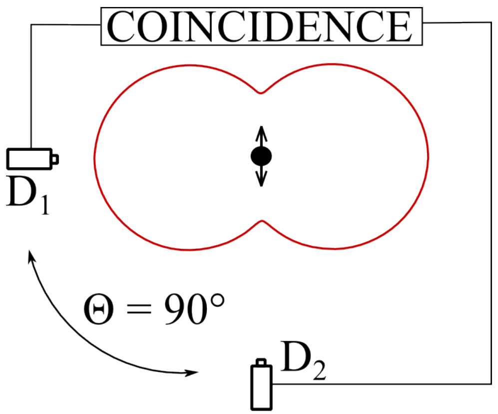
Time-Dependent Unperturbed Angular Correlation

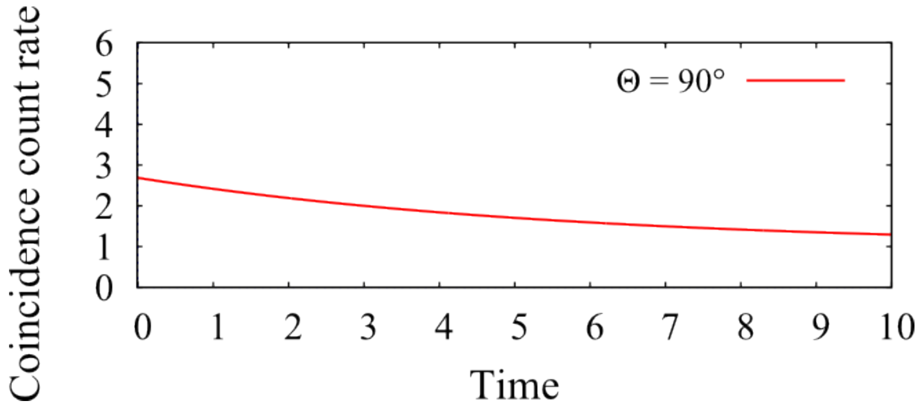
- Coincidence histograms
  - Function of the time elapsed between emission of γ_1 and γ_2



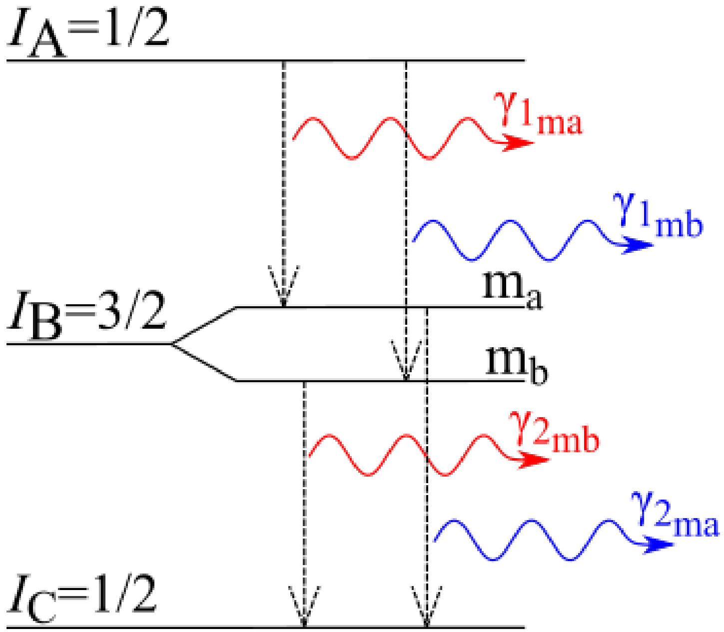


- Different coincidence countrates for detectors at 180° and 90°





Time-Dependent Perturbed Angular Correlation



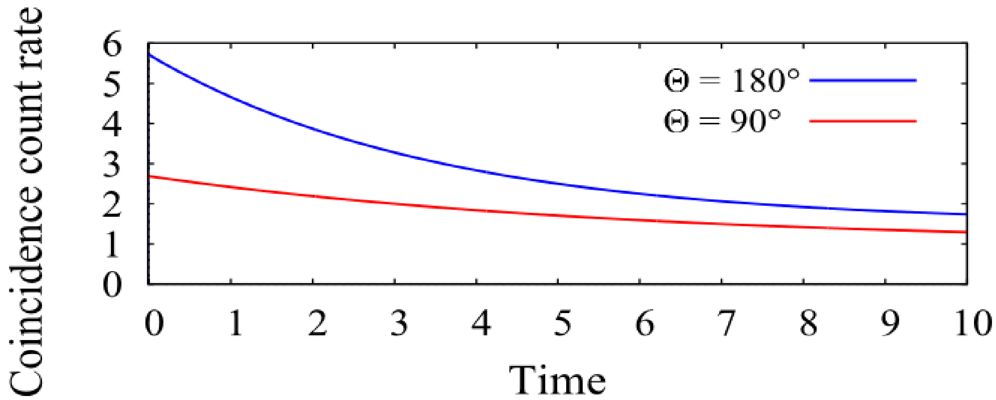
- Nucleus in the intermediate state with non-zero lifetime τ_N interacts with extranuclear perturbating field → splitting into sublevels m_a and m_b.
- Lifetime in range 10 ns < τ_N < 1000 ns causes a mixing between intermediate sublevel m_a and m_b.
  - Deexcitation: level A → sublevel $m_a(m_b)$ → sublevel $m_b(m_b)$ → level C
  - Described by the perturbation function $G_{kk}(t)$ in the angular correlation function

$$W(\theta, t) \propto \exp\left(\frac{-t}{\tau_N}\right) \sum_k A_{kk} G_{kk}(t) P_k(\cos\theta)$$

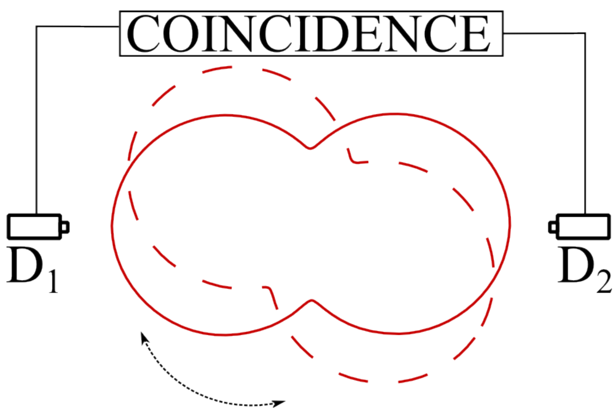
- Detection of coherent superposition of both γ-quanta leads to quantum beats in the coincidance count rate between γ1 and γ2 with the beat frequency being $\omega = \Delta/\hbar$.

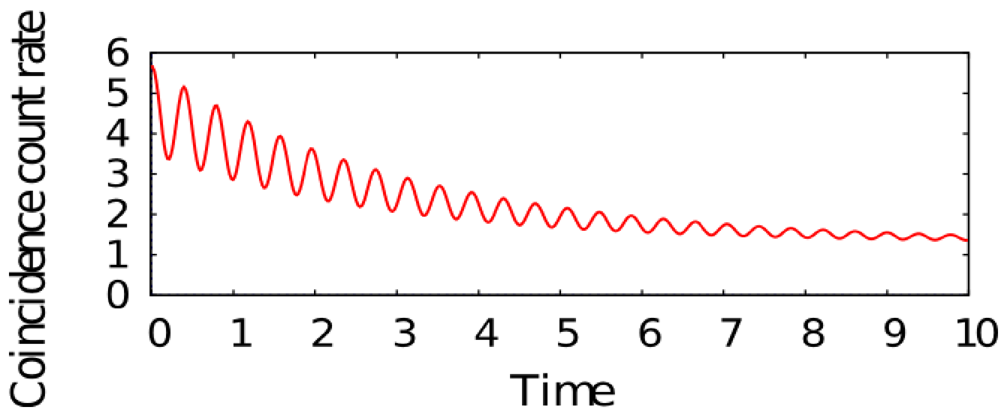
Time-Dependent Perturbed Angular Correlation

- The intermediate state is unsplit

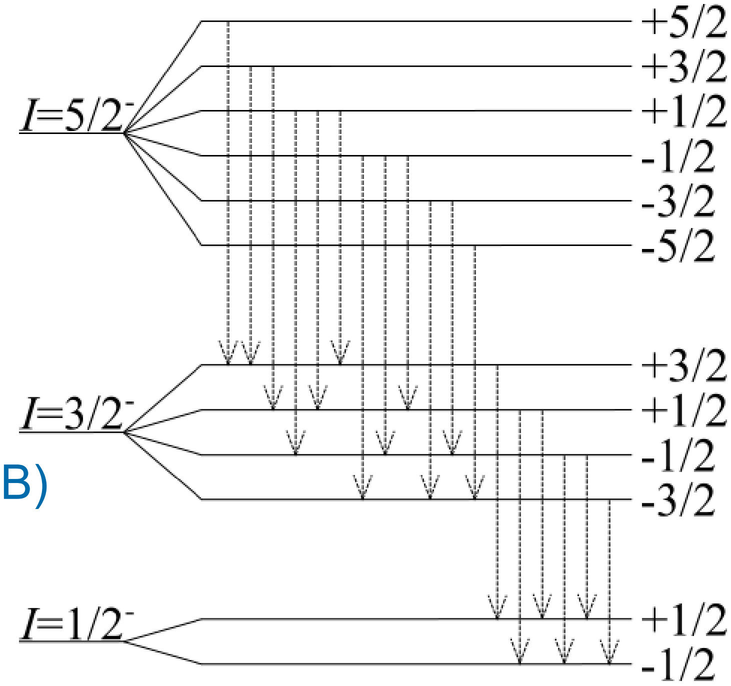


- The intermediate state is split by hyperfine interactions (*Q* and *B*)
  - Time-dependence in amplitude and angle θ between γ_1 and γ_2
  - Spin precession





Angular correlation on ^{57}Fe



- ^{57}Co (271.8 days) decays via electron capture to the exited level of ^{57}Fe with energy 136.47 keV
- The second excited state (level A)
  - I_A = 5/2, odd parity, long τ_N
- The first excited (intermediate) state (level B)
  - I_B = 3/2, odd parity, τ_N = 97.8 ns
- The ground state (level C)
  - I_C = 1/2, odd parity, stable
- Both transitions, $5/2^-$ (γ_2) $3/2^-$ and $3/2^-$ (γ_1) $1/2^-$, are a **magnetic dipole**

→ Angular correlation function: $W(\theta,t)=e^{\frac{-t}{97.8\cdot 10^{-9}}}[1+\frac{1}{20}\cdot G_{22}(t)\cdot(\frac{3}{2}\cos^2(\theta)-\frac{1}{2})]$

- This is derived from probabilities of transitions between energetic states of the nucleus.

Angular correlation on ^{57}Fe

- Hamiltonian of mixed state H_{MIX}
  - eigenvalues + eigenvectors

$$H_{MIX} = \begin{pmatrix} \frac{eQV}{4} - \frac{3}{2} B\gamma\hbar \mathrm{Cos}[\theta] & \frac{1}{2}\sqrt{3}\, B e^{i\phi}\gamma\hbar \mathrm{Sin}[\theta] & \frac{eQV\eta}{4\sqrt{3}} & 0 \\ \frac{1}{2}\sqrt{3}\, B e^{-i\phi}\gamma\hbar \mathrm{Sin}[\theta] & -\frac{1}{4} eQV - \frac{1}{2} B\gamma\hbar \mathrm{Cos}[\theta] & B e^{i\phi}\gamma\hbar \mathrm{Sin}[\theta] & \frac{eQV\eta}{4\sqrt{3}} \\ \frac{eQV\eta}{4\sqrt{3}} & B e^{-i\phi}\gamma\hbar \mathrm{Sin}[\theta] & -\frac{1}{4} eQV + \frac{1}{2} B\gamma\hbar \mathrm{Cos}[\theta] & \frac{1}{2}\sqrt{3}\, B e^{i\phi}\gamma\hbar \mathrm{Sin}[\theta] \\ 0 & \frac{eQV\eta}{4\sqrt{3}} & \frac{1}{2}\sqrt{3}\, B e^{-i\phi}\gamma\hbar \mathrm{Sin}[\theta] & \frac{eQV}{4} + \frac{3}{2} B\gamma\hbar \mathrm{Cos}[\theta] \end{pmatrix}$$

- Calculation of „single crystal“ perturbation function

$$G_{k_1k_2}^{N_1N_2}(t) = \sum_{m_a m_b} (-1)^{2I+m_a+m_b} \sqrt{(2k_1+1)(2k_2+1)} \begin{pmatrix} I & I & k_1 \\ m_{a'} & -m_a & N_1 \end{pmatrix} \begin{pmatrix} I & I & k_2 \\ m_{b'} & -m_b & N_2 \end{pmatrix}$$

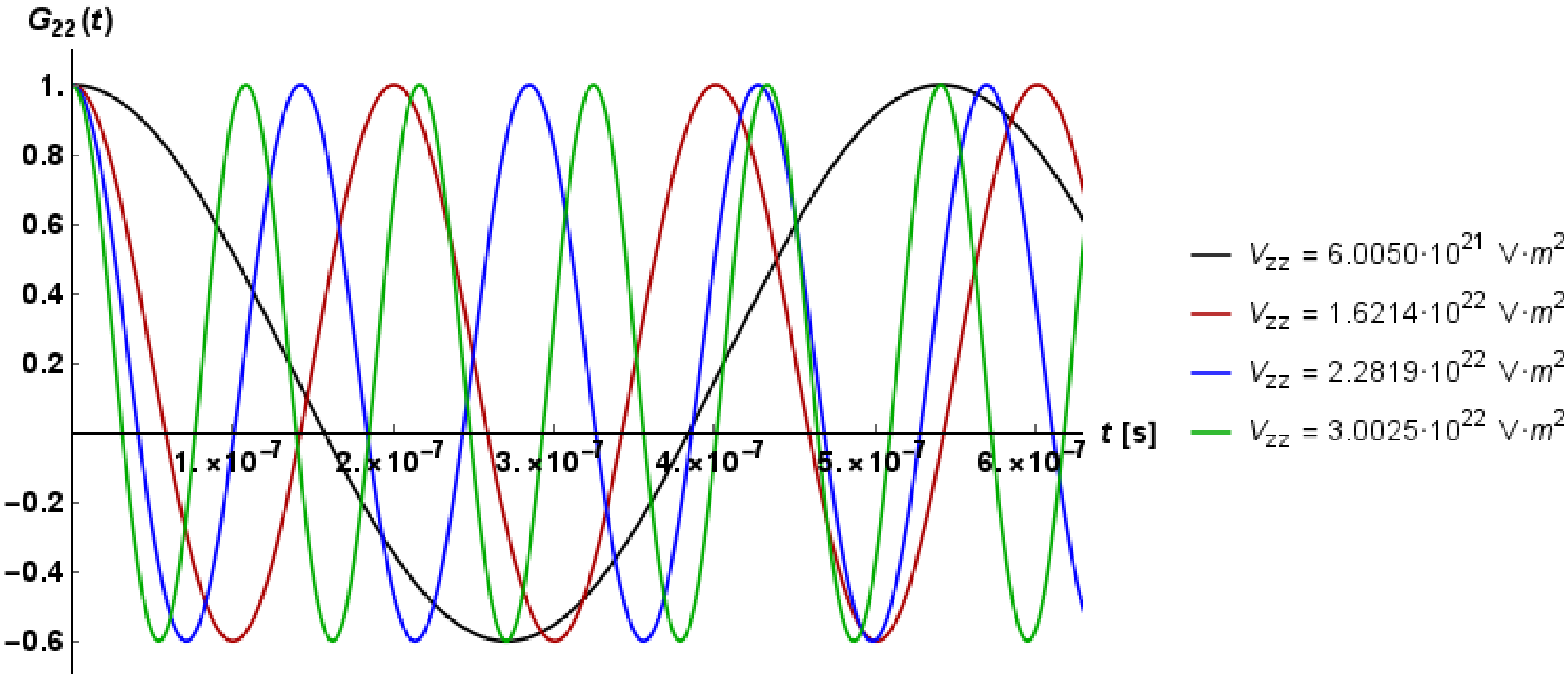
$$\cdot \sum_{mm'} \langle m_b|m\rangle^* \langle m_a|m\rangle \langle m_{b'}|m'\rangle \langle m_{a'}|m'\rangle^* \exp\left(\frac{-i}{\hbar}(E_m - E_{m'})t\right)$$

- Calculation of „powder“ perturbation function
  ($k_1 = k_2 = k$, $N_1 = N_2 = N$)

$$G_{kk}(t) = \frac{1}{2k+1} + \sum_{N=-k}^{k} G_{kk}^{NN}(t)$$

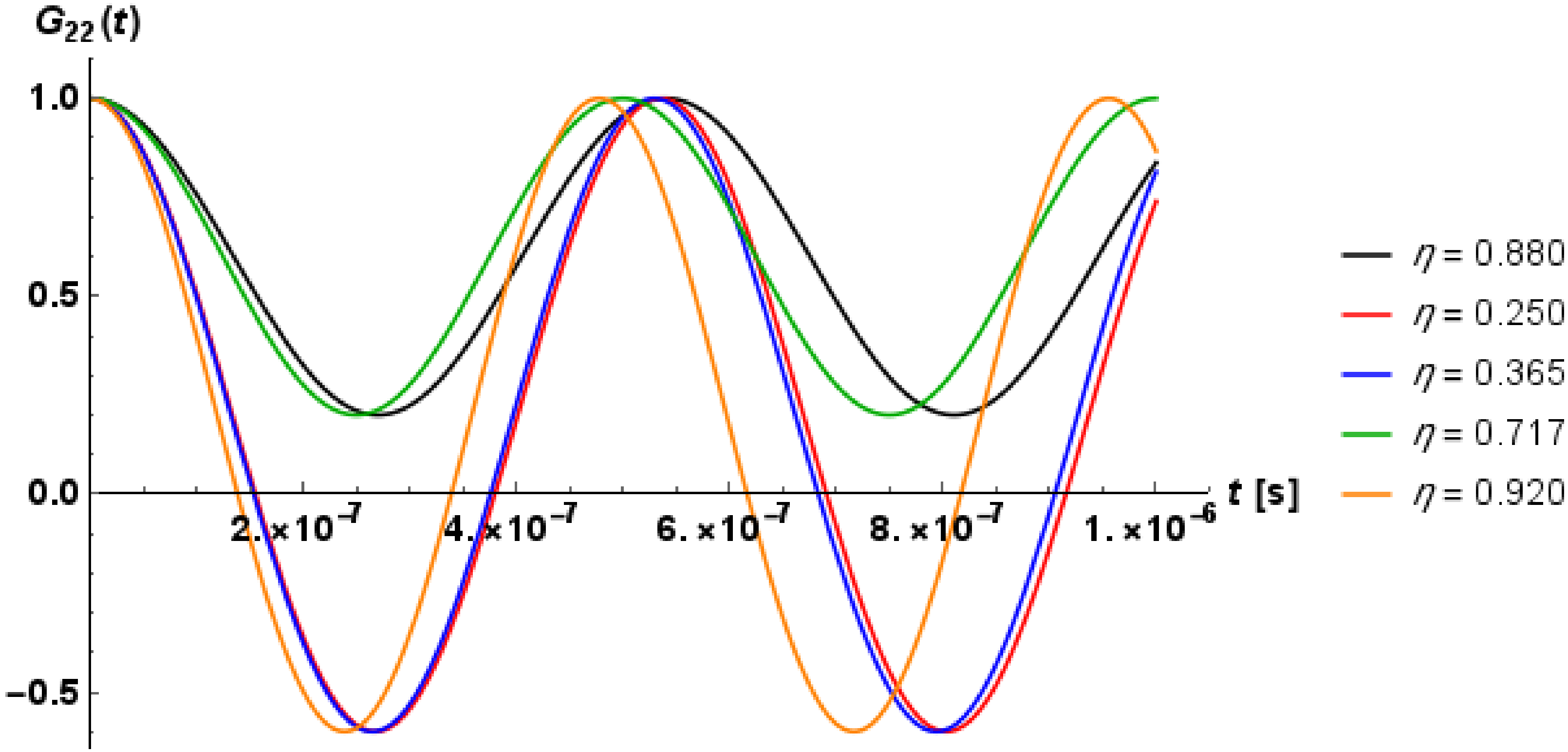
Angular correlation on ^{57}Fe

- $G_{22}(t)$ of pure quadrupole interactions with η = 0 (axial symmetry) for different V_{zz} (the largest component of the electric field gradient tensor)



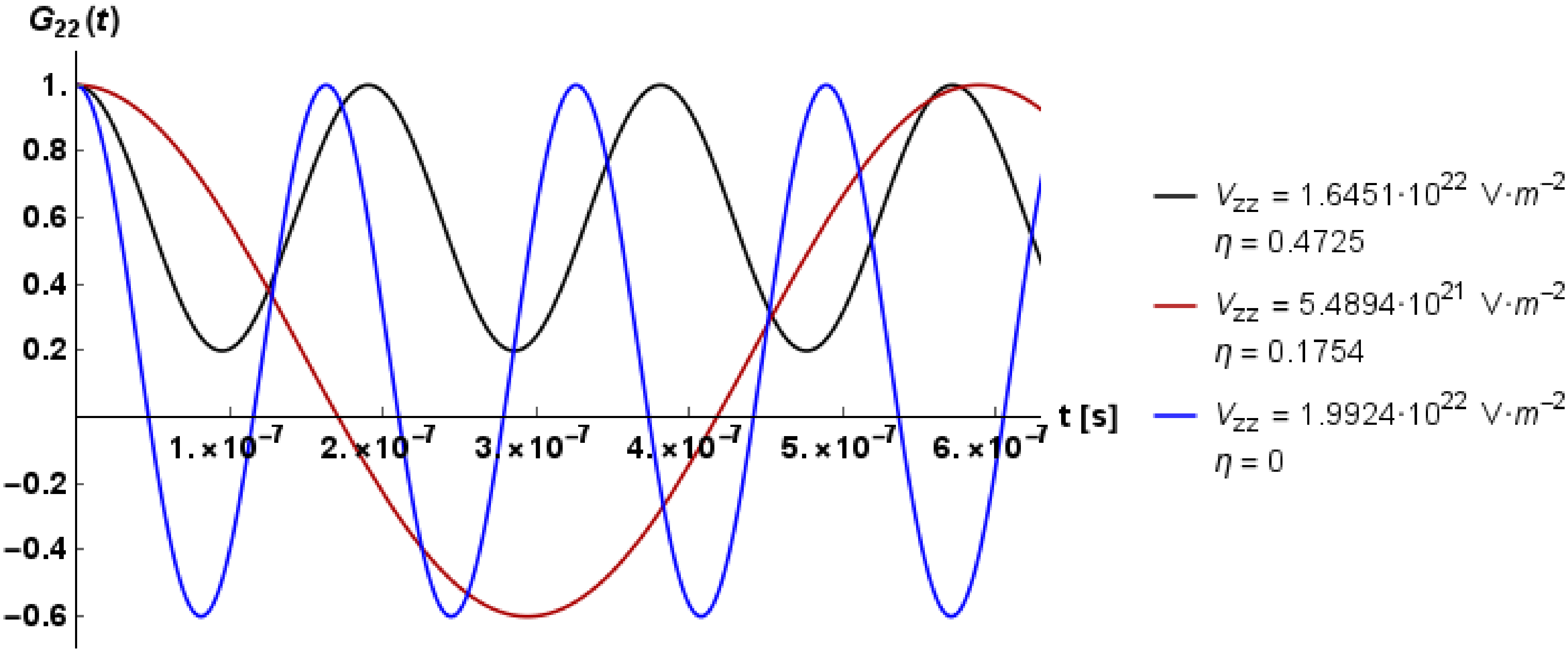
Angular correlation on ^{57}Fe

- $G_{22}(t)$ of pure quadrupole interactions with $V_{zz} = 6.005 \cdot 10^{21}\ V \cdot m^{-2}$ for different η



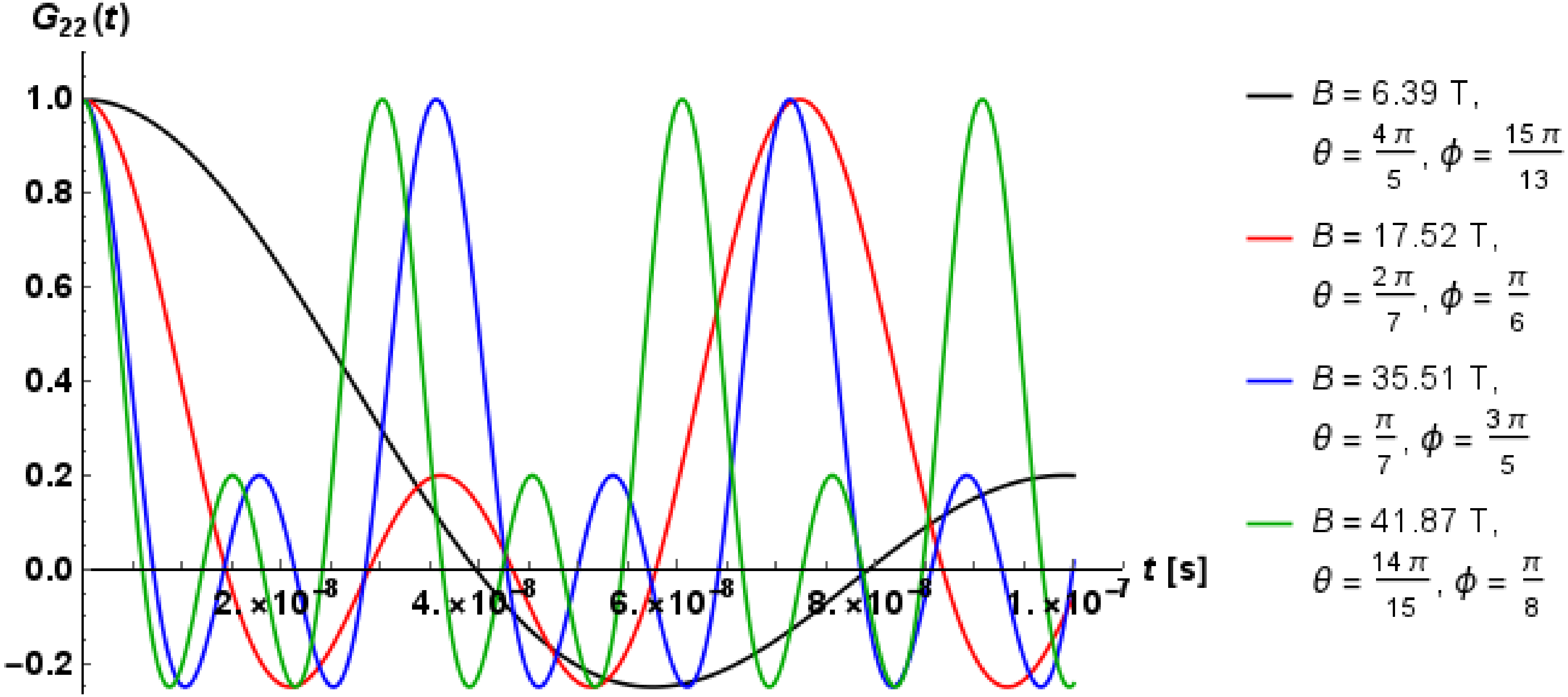
Angular correlation on ^{57}Fe

- $G_{22}(t)$ of pure quadrupole interactions with random combination of V_{zz} and η



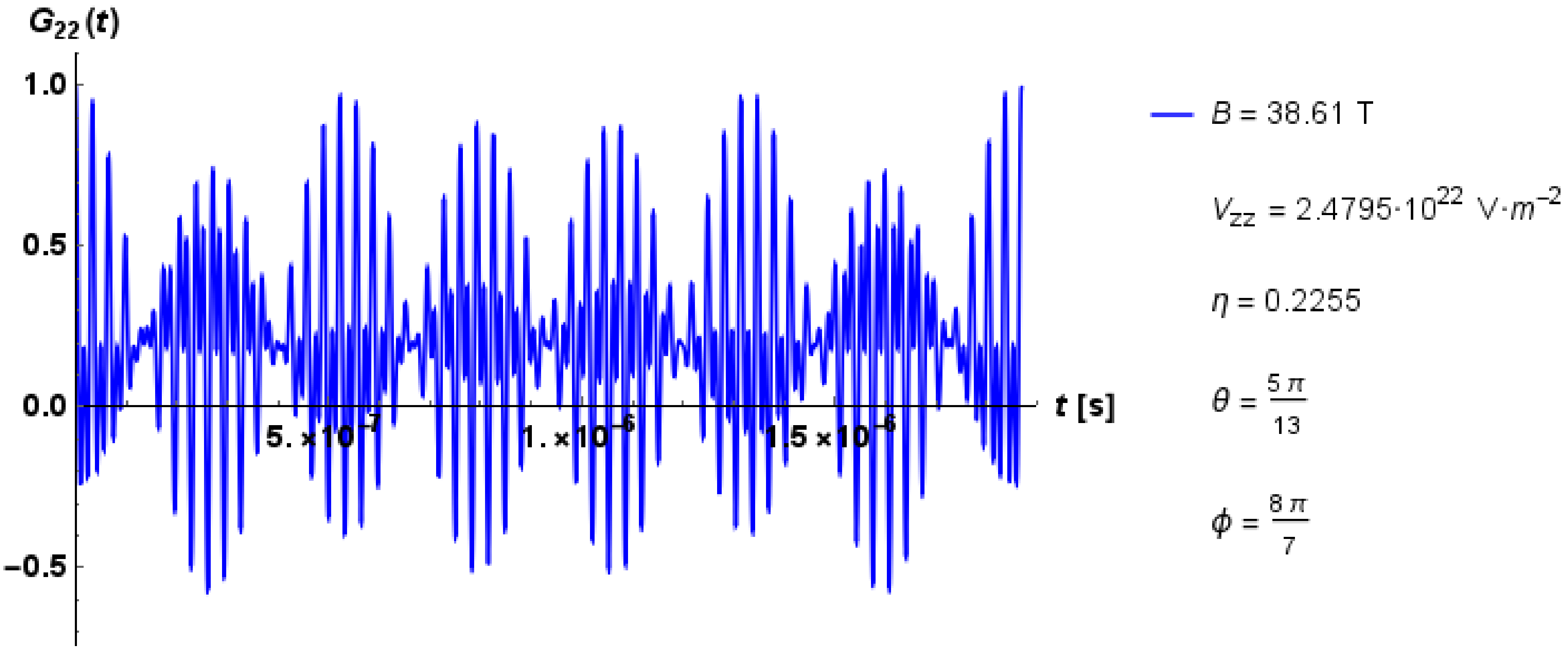
Angular correlation on ^{57}Fe

- $G_{22}(t)$ of pure magnetic interactions with random combination of *B*, *θ* and *φ*



Angular correlation on ^{57}Fe

- $G_{22}(t)$ of mixed interactions with random combination of V_{zz}, η, B, θ and φ



Plans for Future

- Developing a program for evaluation of TDPAC data
  - Numerical calculation of $W(\theta,t)$

- Comparison of experimental data of quadrupole splitting values obtained by MS measurement (frozen sample) and TDPAC (liquid sample)
  - Fitting of experimental data by using method of the smallest squares

- Study of hyperfine interactions in amorphous metals using TDPAC method

Conclusion

- Nuclear angular correlation is an additional method for Emission Mössbauer spectroscopy for determination of quadrupole or magnetic origin of interactions
- Basic principles of angular correlation
- Time-Dependent Unperturbation Angular correlation
- Time-Dependent Perturbation Angular correlation
- Calculations of perturbation function $G_{22}(t)$ for the specific cases of ^{57}Fe
- Developing a program evaluating experimental data from TDPAC experiments

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Thank you for your attention!

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