APCTP
Asia Pacific Center for Theoretical Physics

Heavy Ion Meeting
http://him.phys.pusan.ac.kr/~him

Probing Nuclear Spin Structure with Radioactive Ion Beams and Polarized Target

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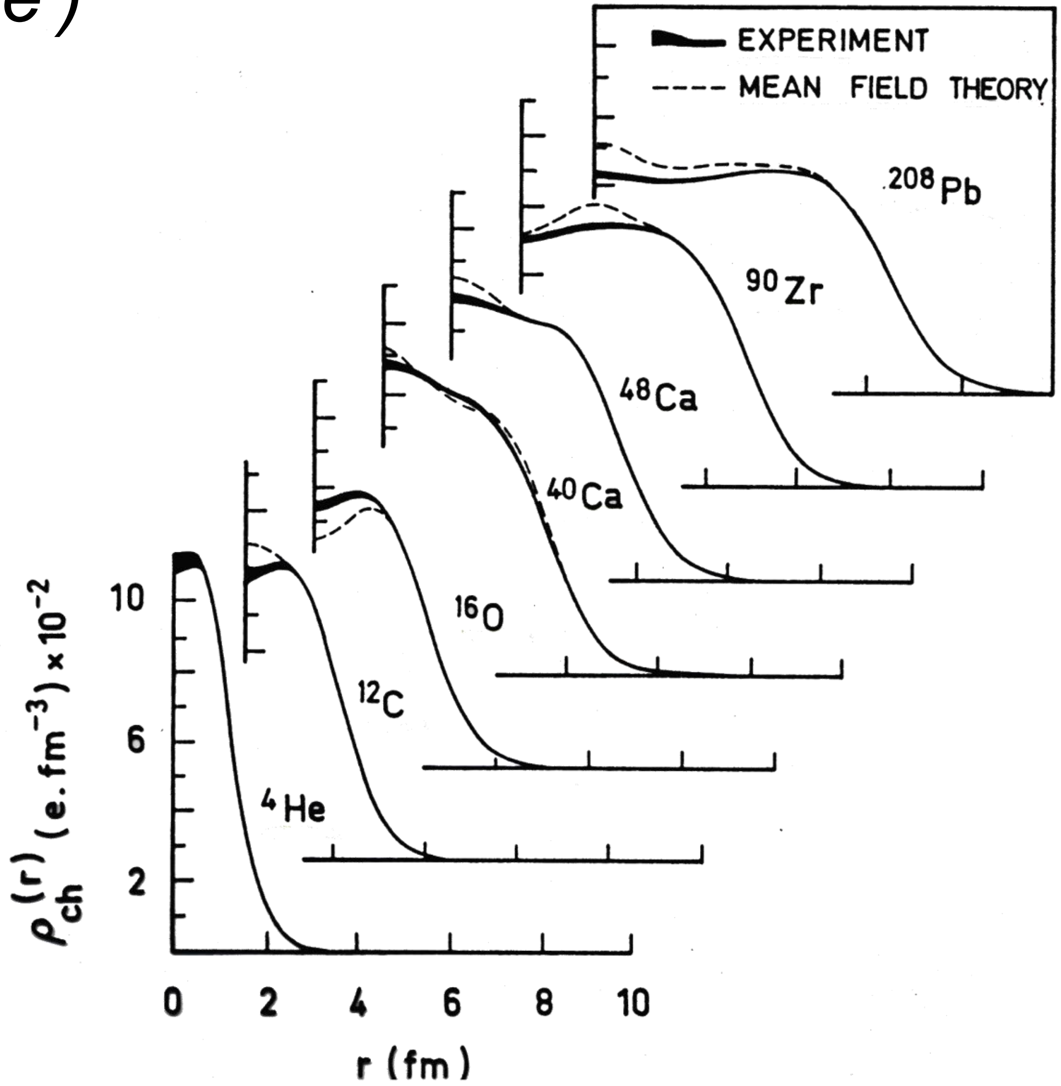
Overview

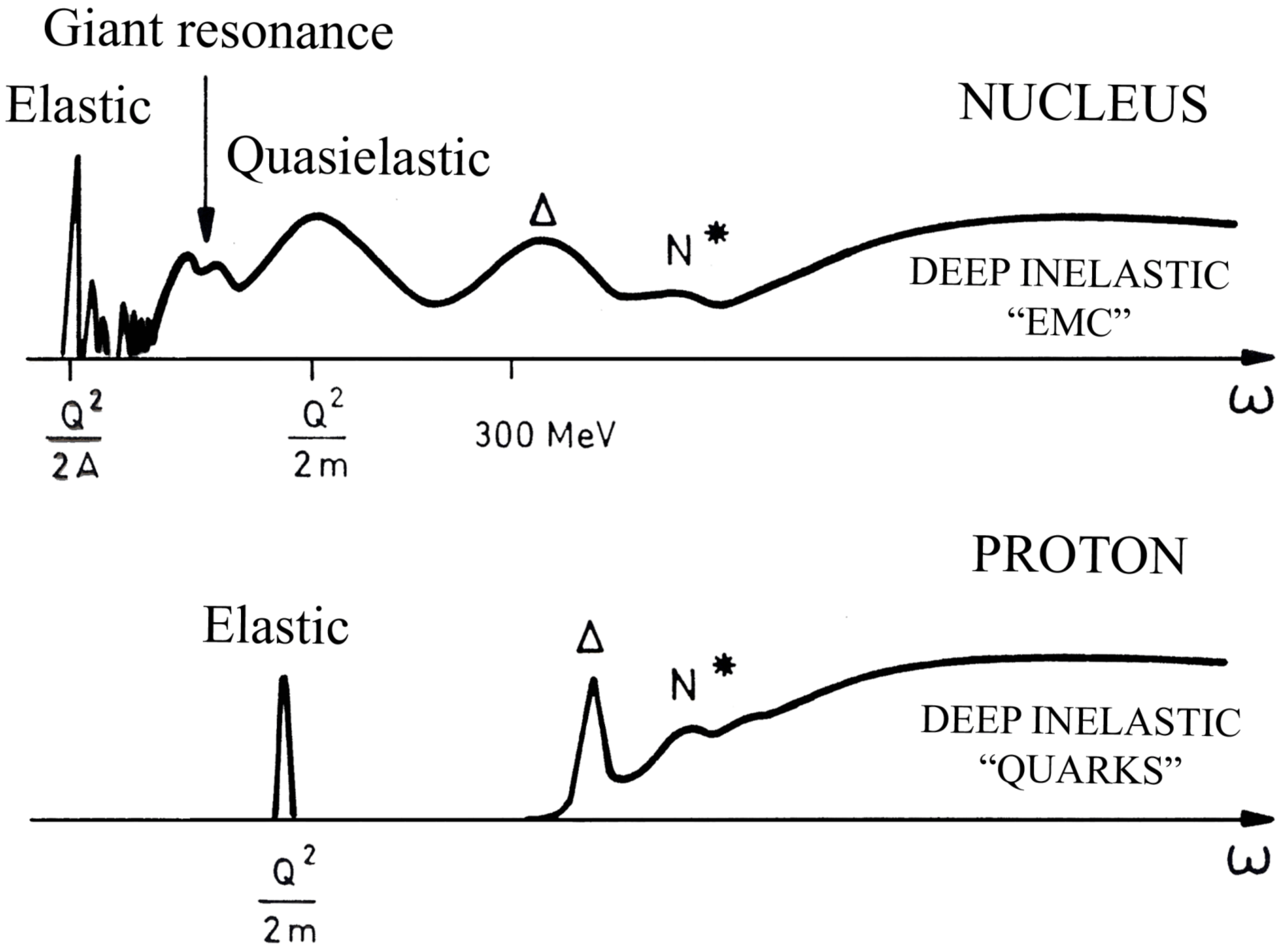
- **Electron Scattering-Kinematics, Spin Structure Function** $p(\vec{e},e'\pi^{+})n$
- **GPDs & DVCS**
- **Polarized Targets with RIB:**
  - $\vec{p}-\ {}^{6}He,\ {}^{8}He$
  - ${}^{3}\vec{He}$

Ground State Charge Density; Saclay

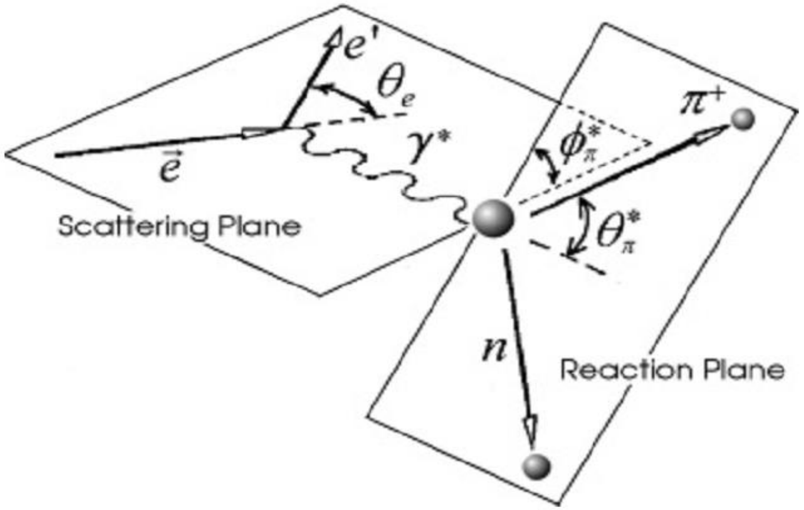
(e,e')



Energy Transfer Dependence of Cross-Section: *(e,e')*



Cross sections and Beam Asymmetries



$$p(\vec{e}, e\pi^+)n$$

Q^2 = 1.7 – 4.5 GeV^2
W = 1.15 – 1.7 GeV

PRC 77, 0152081 (2008)
K. Park, W. Kim et al.

- Over 31,000 Cross-Sections Measured
- Over 4,000 Asymmetries Measured

$$\frac{\partial^5\sigma}{\partial E_f \partial\Omega_e \partial\Omega^*_\pi} = \Gamma_\upsilon \times \frac{d^2\sigma}{d\Omega^*_\pi},$$

where

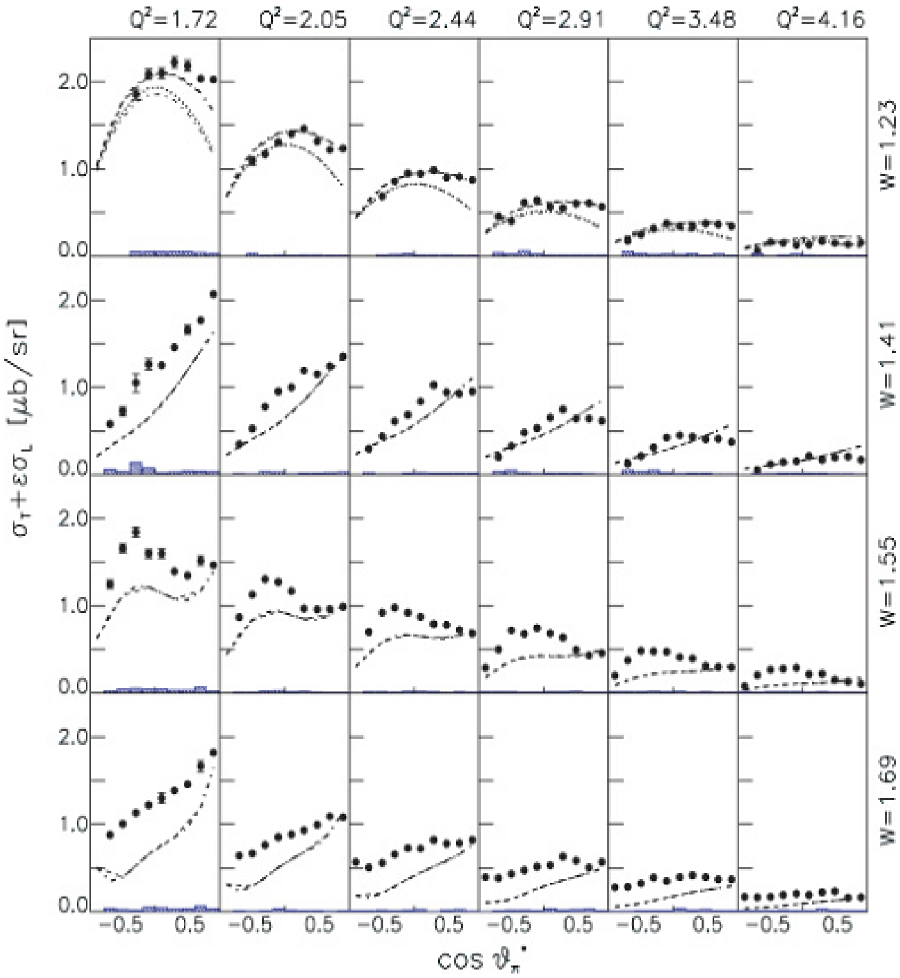
$$\Gamma_\upsilon = \frac{\alpha}{2\pi^2 Q^2}\frac{(W^2 - M_p^2)E_f}{2M_p E_e}\frac{1}{1-\epsilon}$$

$$\epsilon = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

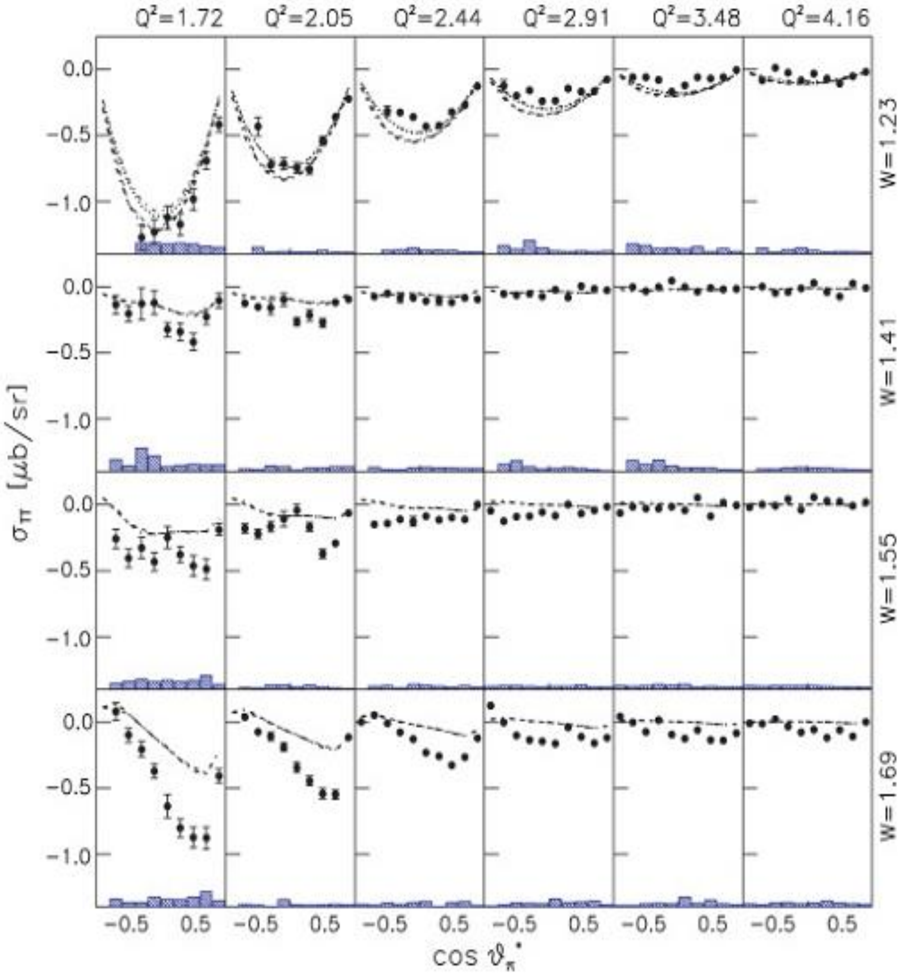
$$\frac{d^2\sigma}{d\Omega^*_\pi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi^*_\pi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi^*_\pi$$
$$+ h\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi^*_\pi.$$

Structure Functions

$\sigma_T + \epsilon\sigma_L$

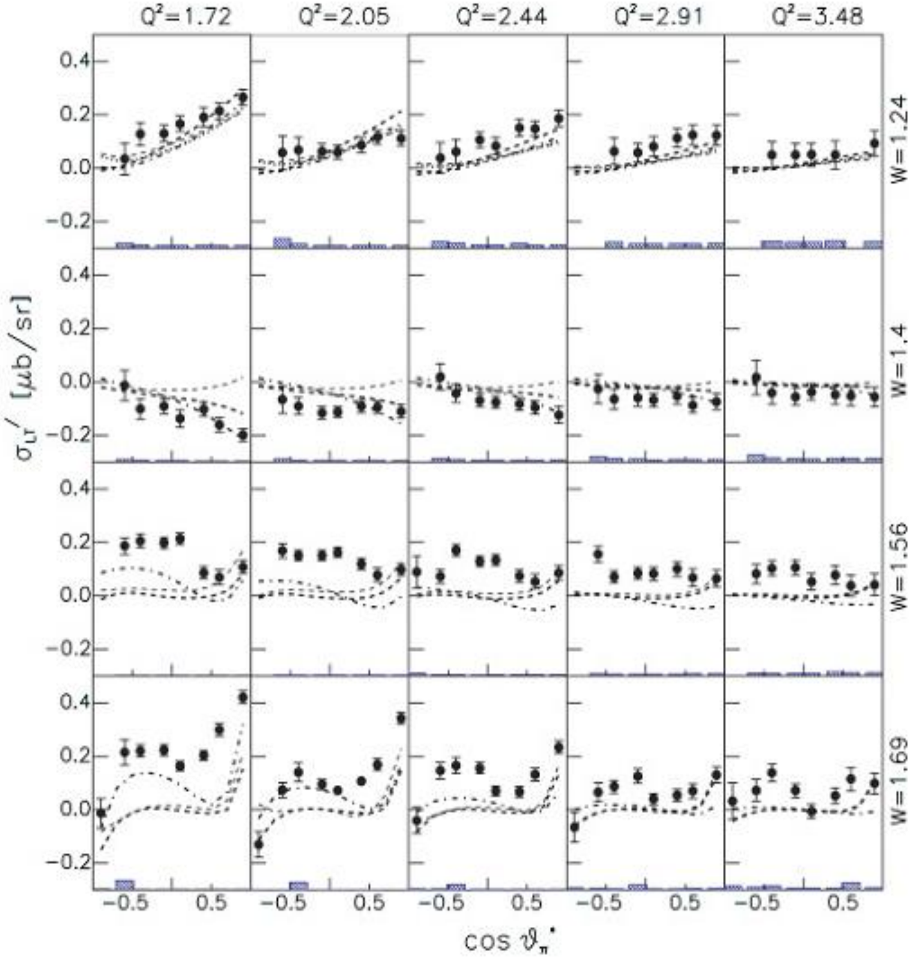


σ_{TT}

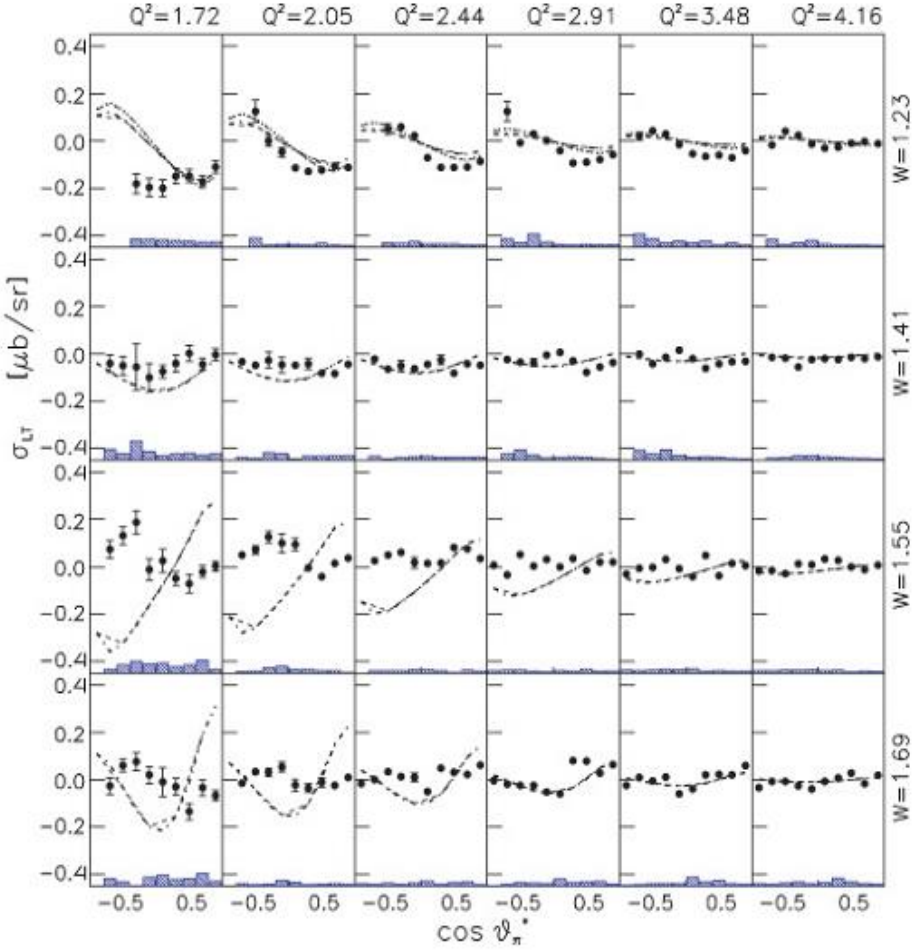


Structure Functions

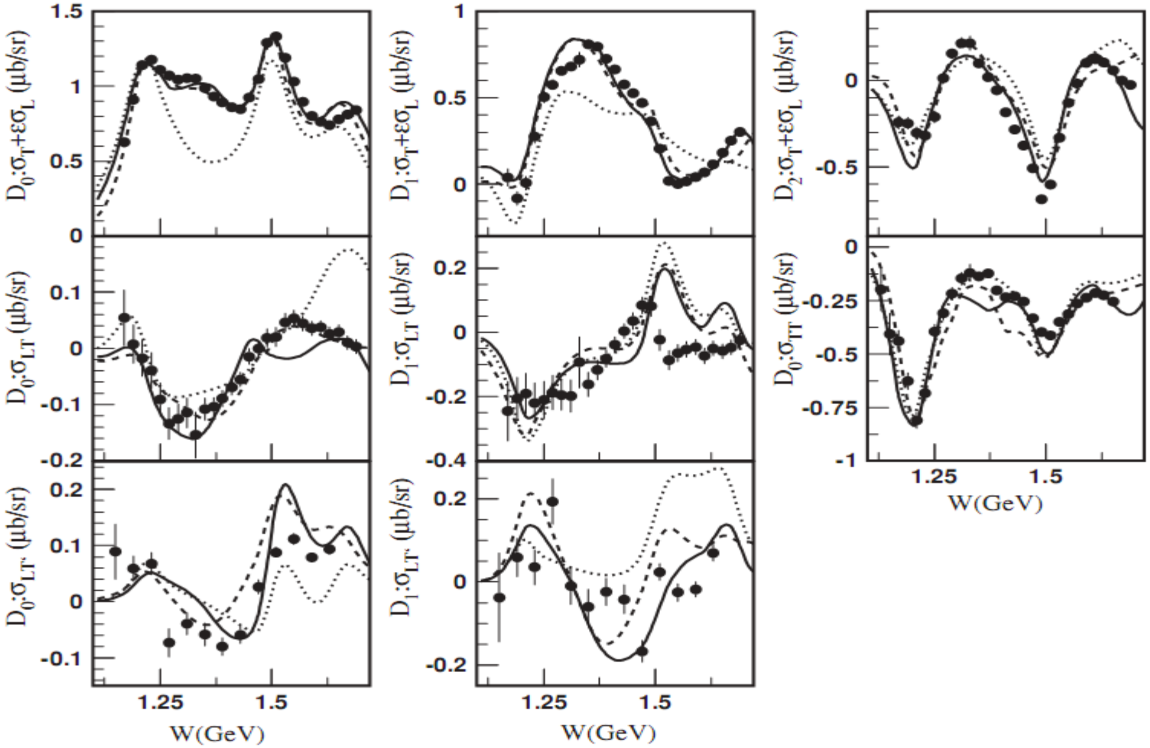
$\sigma_{LT'}$



σ_{LT}



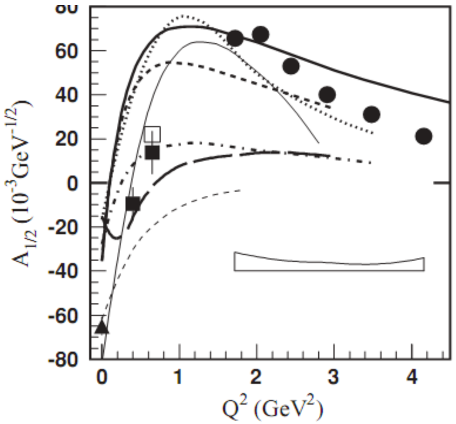
Electroexcitation of the Roper resonance for $1.7<Q^2<4.5$ GeV^2



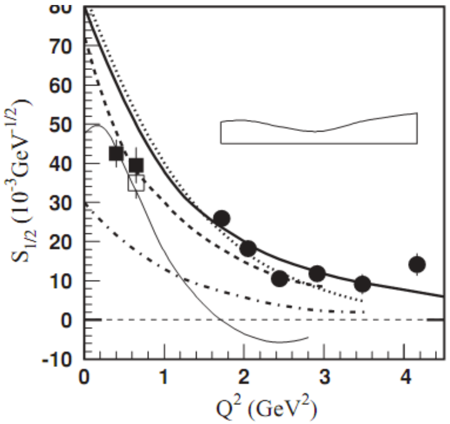
G. Aznauiy, K. Park, W.Kim
PRC 78 (2008),
PRC 80 (2009).

Dispersion Relation

Unitary Isobar Model.



Transverse



Longitudinal

Helicity Amplitude for:

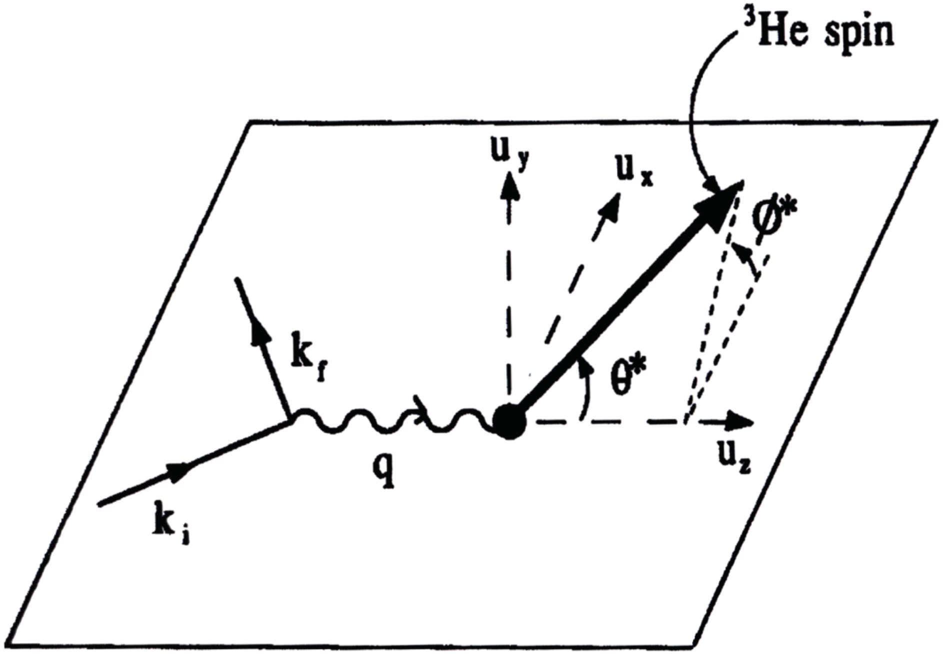
$$\gamma^* p \rightarrow N(1440)P_{11}$$

Transition:

A first Radial Excitation of the 3q Ground State

Additional Nuclear Structure Information

$$\vec{p}(\vec{e},e'p)\pi^0$$

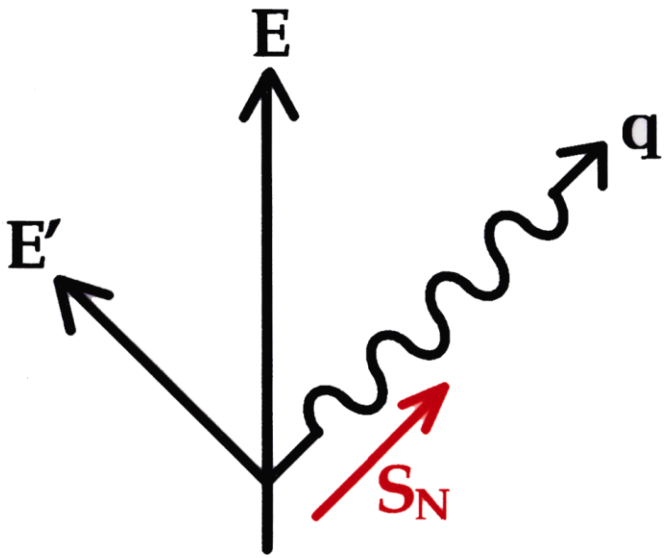


$$\frac{d^2\sigma}{d\Omega d\omega} = \sum \pm \Delta h(\theta^*, \phi^*)$$

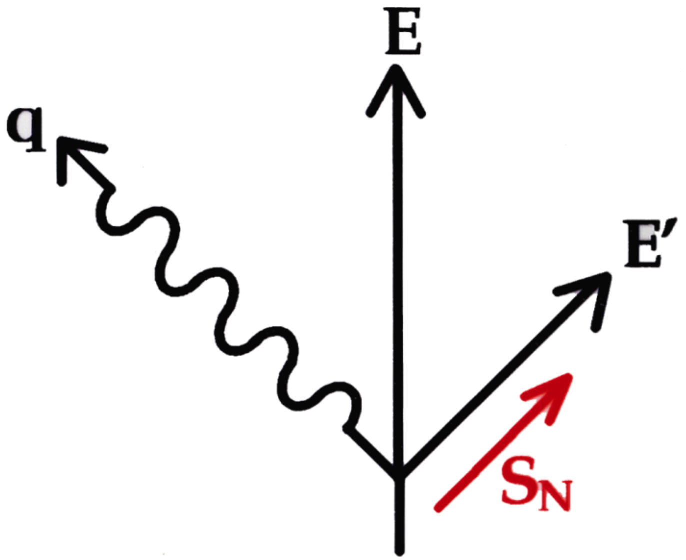
$$A = \frac{\cos\theta^* v_{T'} R_{T'} + 2\sin\theta^* \cos\phi^* v_{TL'} R_{TL'}}{v_L R_L + v_T R_T}$$

Super-Rosenbluth Separation

Simultaneous Measurements of T’ and TL’ asymmetries



Measure T′



TL′

Symmetric Detector

Generalized Parton Distributions

- **Formalism for the QCD description of deeply exclusive leptoproduction reactions introduces Generalized Parton Distribution (GPDs)**

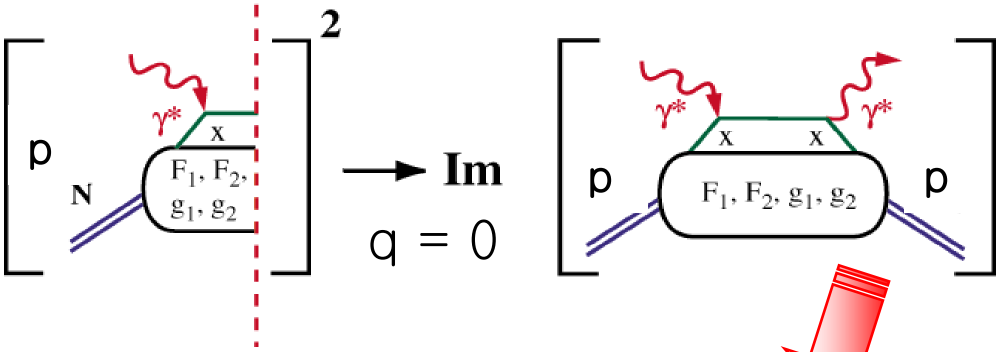
- **Carry new Information about the dynamical degrees of freedom inside the Nucleon**

- **In the Bjorken scaling regime($Q^2 \rightarrow \infty$, x_B finite), the amplitude for exclusive scattering reaction can be factorized into**

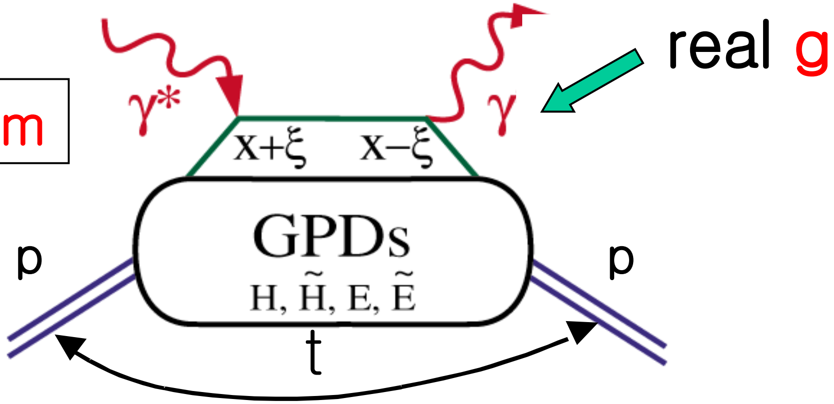
- **A hard scattering part (exactly calcluable in pQCD)**
- **A nucleon structure part (parameterized via GPDs – handbag approximations)**

From Inclusive to Exclusive Scattering

Inclusive Scattering ⇒ **Compton Scattering**



Deeply Virtual Compton Scattering (DVCS)



Handbag mechanism

2x – longitudinal momentum transfer

GPDs depend on 3 variables, e.g. *H(x, ξ, t)*. They probe the quark structure at the amplitude level.

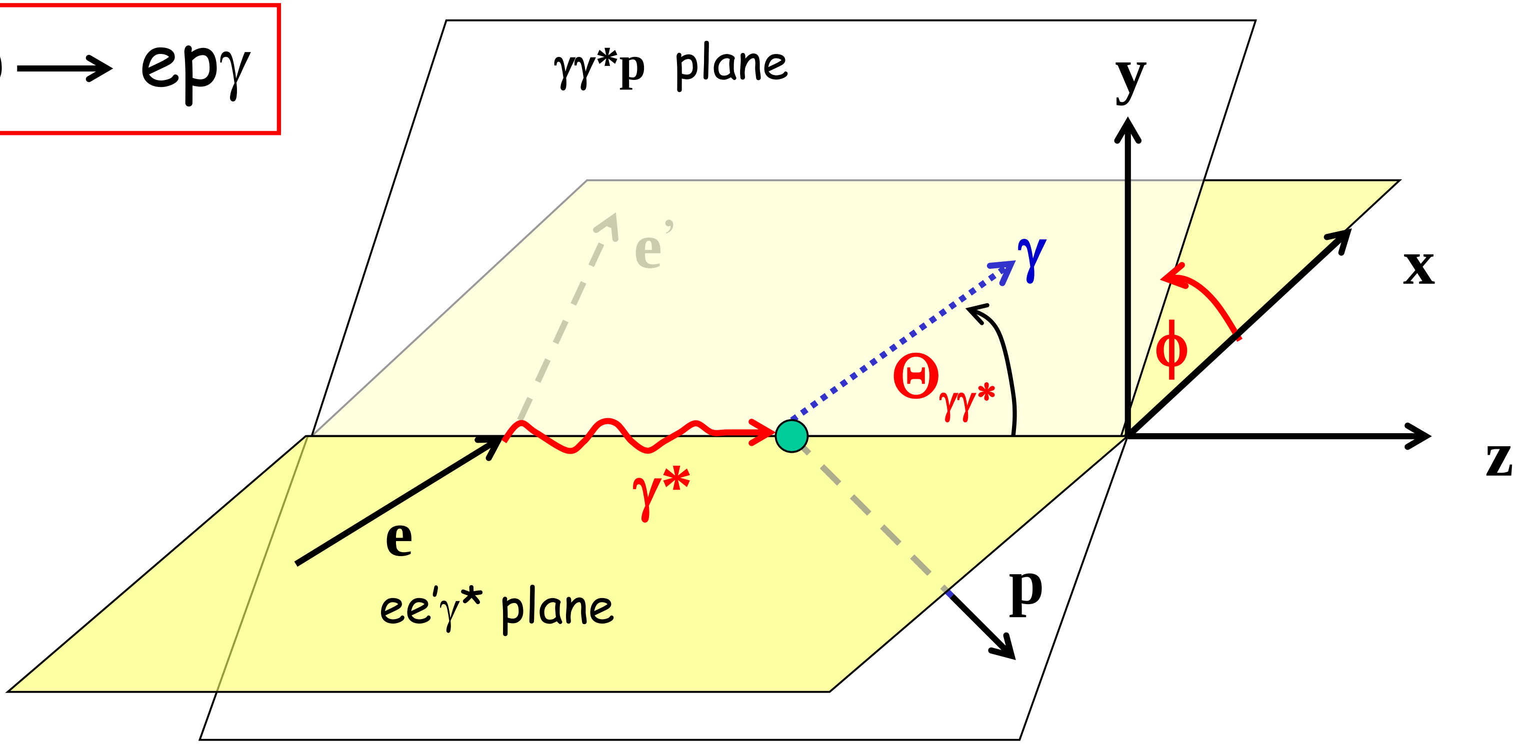
Deeply Virtual Compton Scattering

- **Virtual Compton Scattering in the Bjorken regime**
- **Virtual Compton Scattering : Electroproduction of photons from nucleons**
- **The cleanest way of gathering information on nucleon structure**
- **The simplest experiment for studying GPDs**

(W > 2GeV, $Q^2 > 1$ (GeV/c)^2)

Kinematics

$$\boxed{ep \longrightarrow ep\gamma}$$

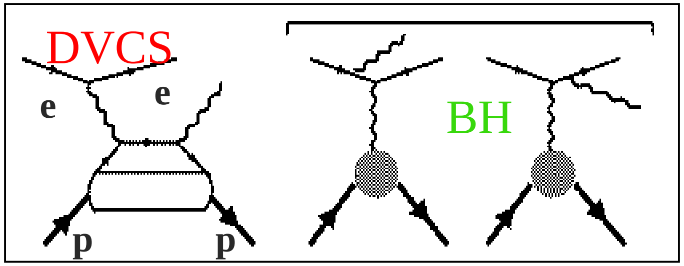


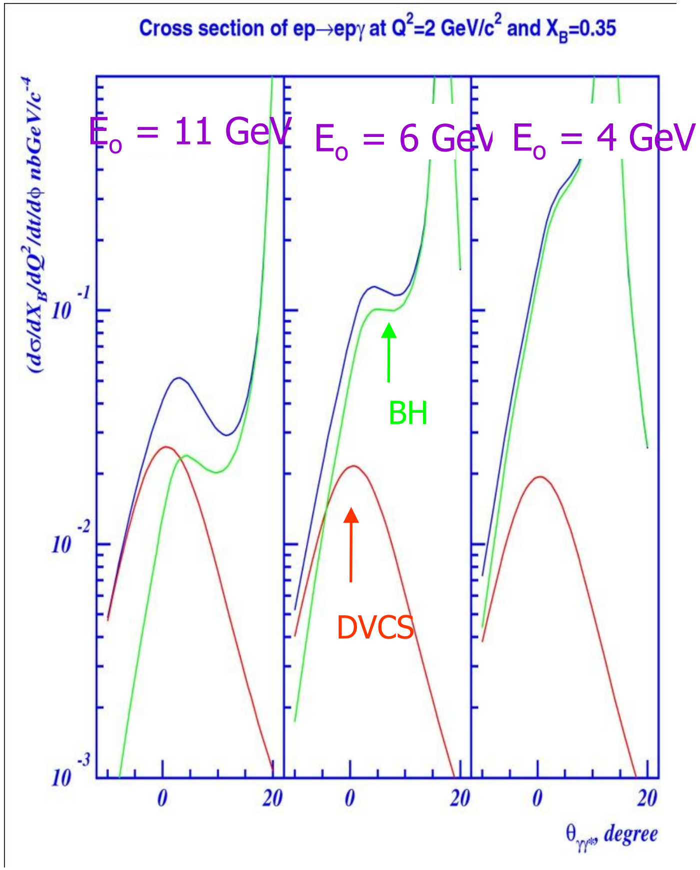
Accessing GPDs through DVCS

$$\frac{d^4\sigma}{dQ^2dx_Bdtd\phi} \propto |T^{DVCS}+T^{BH}|^2$$

$$\frac{d^4\sigma^+}{dQ^2dx_Bdtd\phi} - \frac{d^4\sigma^-}{dQ^2dx_Bdtd\phi} \propto \mathrm{Im}(T^{DVCS})T^{BH}$$

$$\propto a\cdot\mathrm{Im}\,\tilde{M}^{1,1}\sin\phi + b\cdot\mathrm{Im}\,\tilde{M}^{0,1}\sin 2\phi + O\left(\frac{1}{Q^2}\right)$$



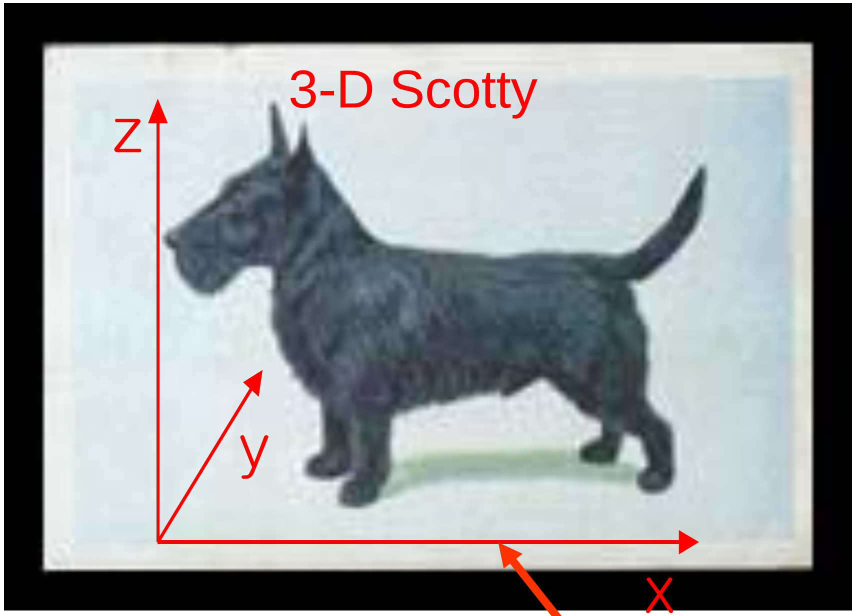


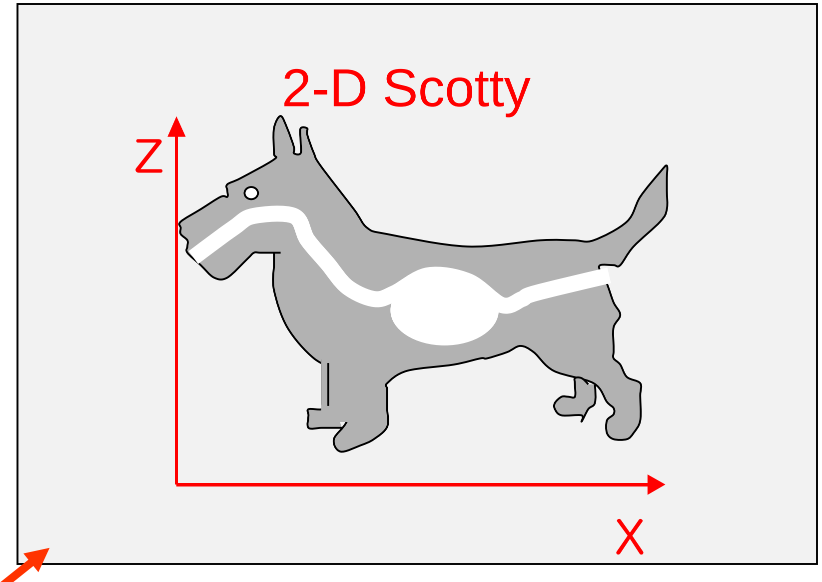
T^{BH} : given by elastic form factors F_1, F_2

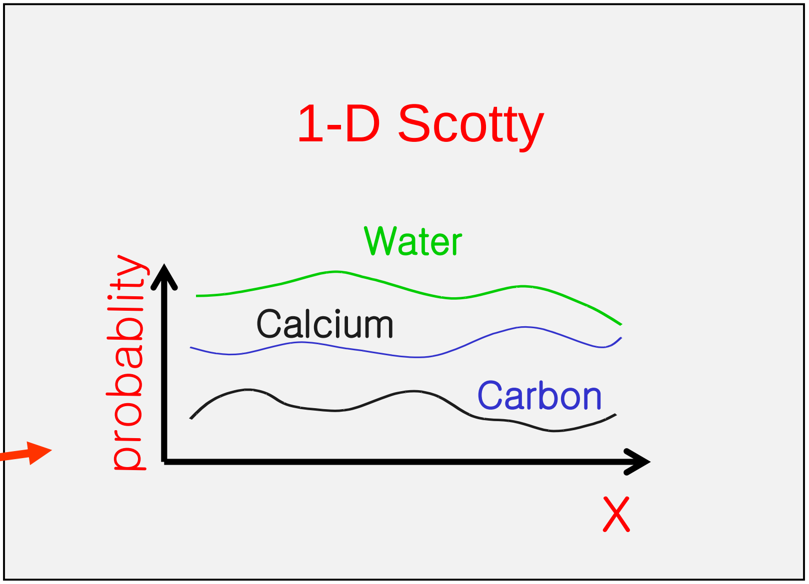
T^{DVCS}: determined by GPDs

BH-DVCS interference generates *beam and target polarization asymmetries* that carry the proton structure information.

GPDs & PDs





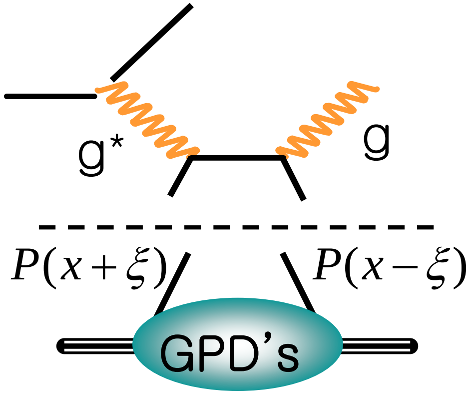


Deeply Virtual Exclusive Processes & GPDs

Deep Inelastic Scattering & PDs

DVCS and GPDs

GPDs: *H, E* unpolarized, $\widetilde{H}$, $\widetilde{E}$ polarized



e.g. $$H(\xi, t) = \int \frac{H^q(x, \xi, t)\,dx}{x-\xi + i\varepsilon}$$

$$= \int \frac{H^q(x, \xi, t)\,dx}{x-\xi} + i\pi H^q(\xi, \xi, t)$$

real part imaginary part

cross section difference

H^q: Probability amplitude for P to emit a parton q with $x+\xi$ and P' to absorb it with $x-\xi$.

Measuring GPDs through polarization

$$\boxed{A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}}$$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

$H(\xi,t)$

$\xi \approx x_B/(2-x_B)$

$k = t/4M^2$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H}+\xi(F_1+F_2)(H+\xi/(1+\xi)E) -.. \}d\phi$$

Kinematically suppressed

$\tilde{H}(\xi,t)$

Unpolarized beam, transverse target:

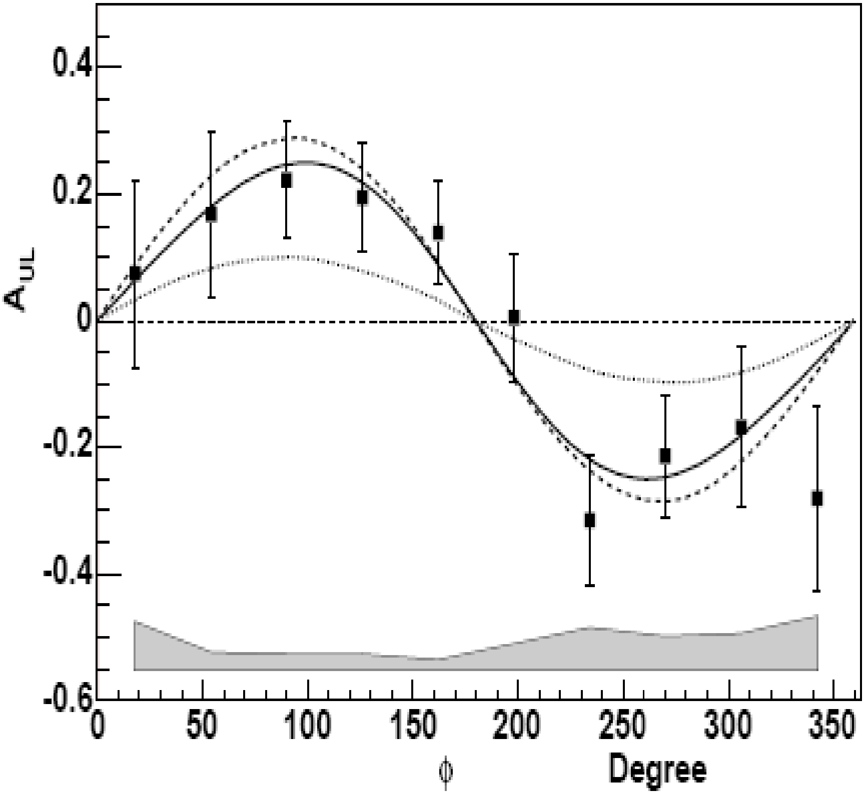
$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + ... \}d\phi$$

Kinematically suppressed

$H(\xi,t)$, $E(\xi,t)$

First DVCS measurement with spin-aligned target

S. Stepanyan et al.,
PRL 87, 182002 (2001)



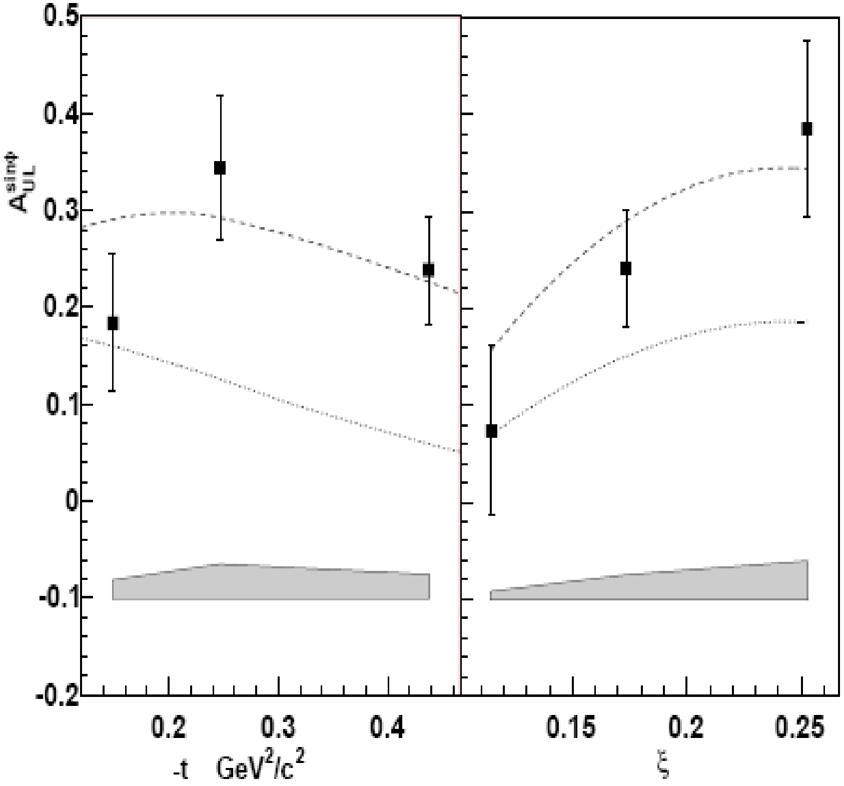
α = 0.252 ± 0.042
β = -0.022 ± 0.045

- **Longitudinal Target-Spin Asymmetry A_{uL} measured for $\overrightarrow{ep} \rightarrow e'p\Upsilon$ with 5.72 GeV electron beams**

Unpolarized beam, longitudinally spin-aligned target

S. Chen et al.,
PRL 97, 072002 (2006)

$Ds_{UL} \sim \text{sinfIm}\{F_1 H + x(F_1+F_2) H + \ldots\}\text{df}$



- **Theoretical calculations in good agreement with the magnitude and kinematic dependence of target-spin asymmetry, which is sensitive to GPDs $\tilde{H}$ and H**
- **Leading term A_{ul}^{sin} increases with f increasing ξ in agreement with model prediction**

Polarized Targets in Radioactive Ion Beams

Polarized Proton Beams

❑Extensively used in nuclear physics experiments.

❑Polarization observables provided us with rich information on spin-dependences of nuclear interactions, nuclear structure, and reaction mechanism.

Polarized Proton in RIB Experiments

❑will bring stiffer understanding of structure of unstable nuclei

Polarized d and 3He Target with RIB

❑will bring us similar contribution in spin physics

Why do we need polarized proton target? (I)

Spin-dependent Interactions

- Origin of fundamental properties of nuclei – Saturation, Shell, Cluster structure

Spin-orbit Couplings

- Phenomenologically modelled by spin-orbit potential.

Spin-orbit potential

- Localized at the nuclear surface

$$V_{LS} \sim \frac{1}{r}\frac{d\rho(r)}{dr}$$ where ρ(r) : density distribution

- Will be modified in neutron rich nuclei.
- Should be composed of two parts localized at different positions if p and n have different distributions.
- Would have extended shape correspondingly if n have extended distribution in skin or halo nuclei.

Why do we need polarized proton target? (II)

Measurement of Spin-dependent Asymmetry, Vector Analyzing Power: Direct approach to investigate modifications of spin-orbit potential in neutron rich nuclei.

❑**Ex 1** : Determination of a spin-orbit term in optical potential from vector analyzing power for p elastic scattering from a nucleus.

❑**Ex 2** : Spin-orbit splitting, energy difference between $j = l \pm \frac{1}{2}$ single particle states determined from vector analyzing power for transfer or p induced nuclear-knockout reactions.

Polarized Proton Target with RIB

- Need Solid Hydrogen target with high density for low RIB current
- Use single crystal of Naphthalene ($C_{10}H_8$) doped with a small amount of Pentacene ($C_{22}H_{14}$)
- Proton polarization produced at high temperature of 100K and in low magnetic field of 0.1 T allowing a detection of low-energy recoiled proton
- Use an electron alignment on the photo-excited triplet state of aromatic molecules
- A pulsed laser light with a wavelength of 532 nm from Ar-ion laser are used to induce an electron alignment in the triplet state of pentacene.
- The population difference in Zeeman sublevels of the triplet state is transferred to proton polarization by means of a cross polarization method.
- Proton polarization of about 20 % has been achieved.

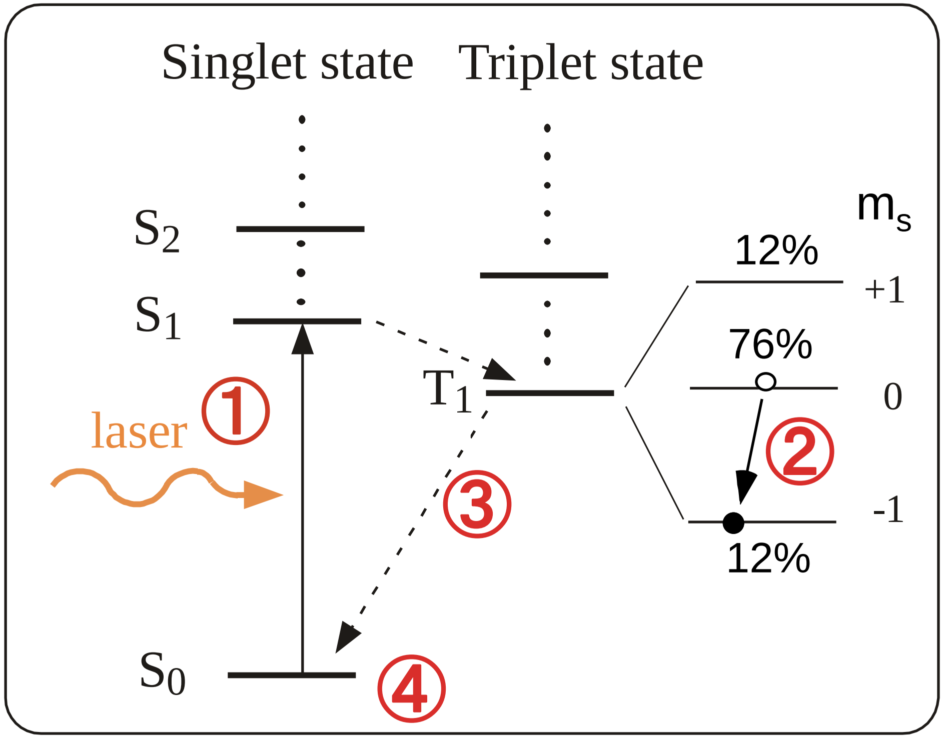
Excitation Scheme of Pentacene Molecules

① Optical Excitation
Electron Alignment

② Cross Polarization
Polarization Transfer

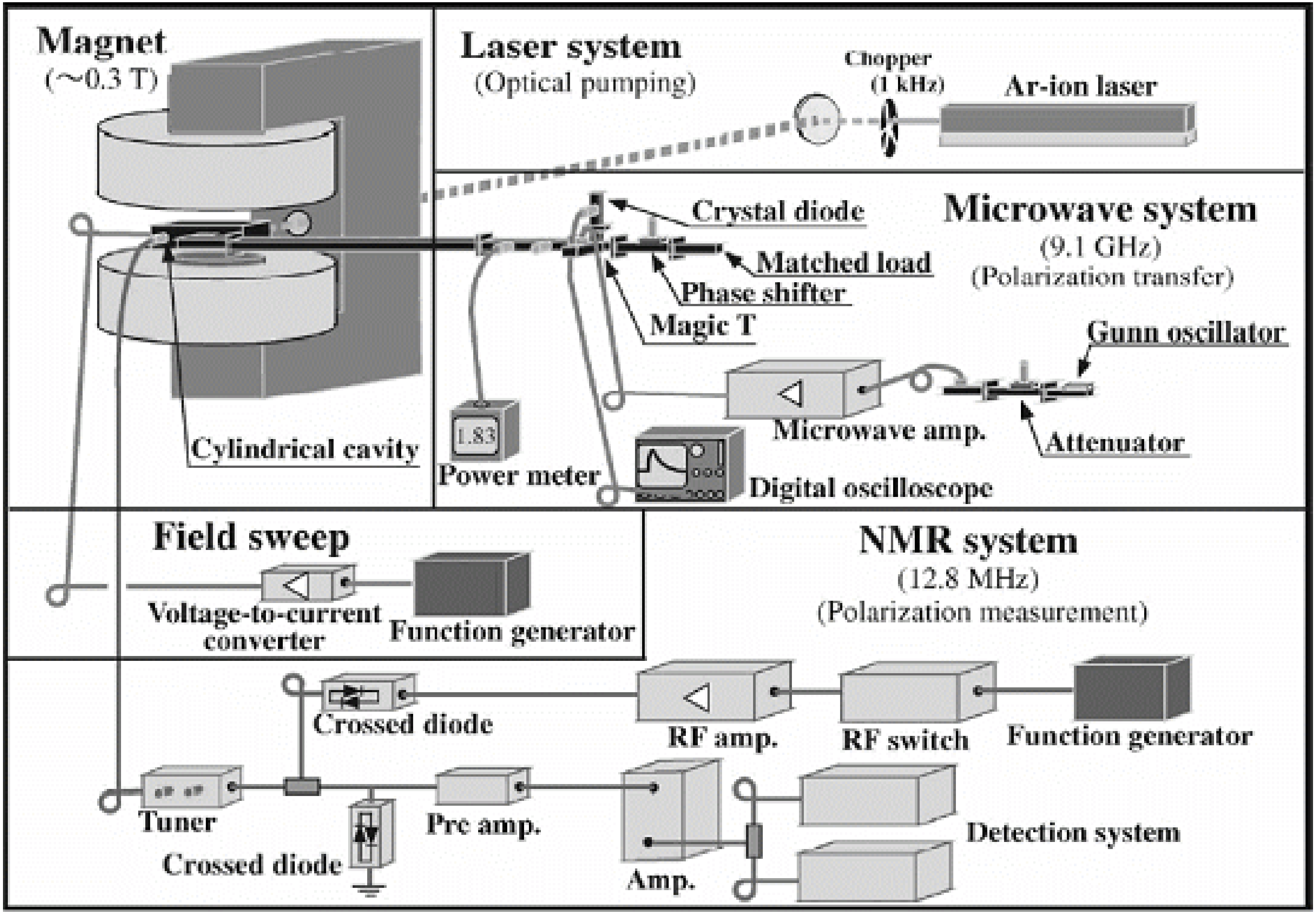
③ Decay to the Ground State

④ Diffuse the Polarization
to Protons in Host Molecules
by Dipolar Interaction

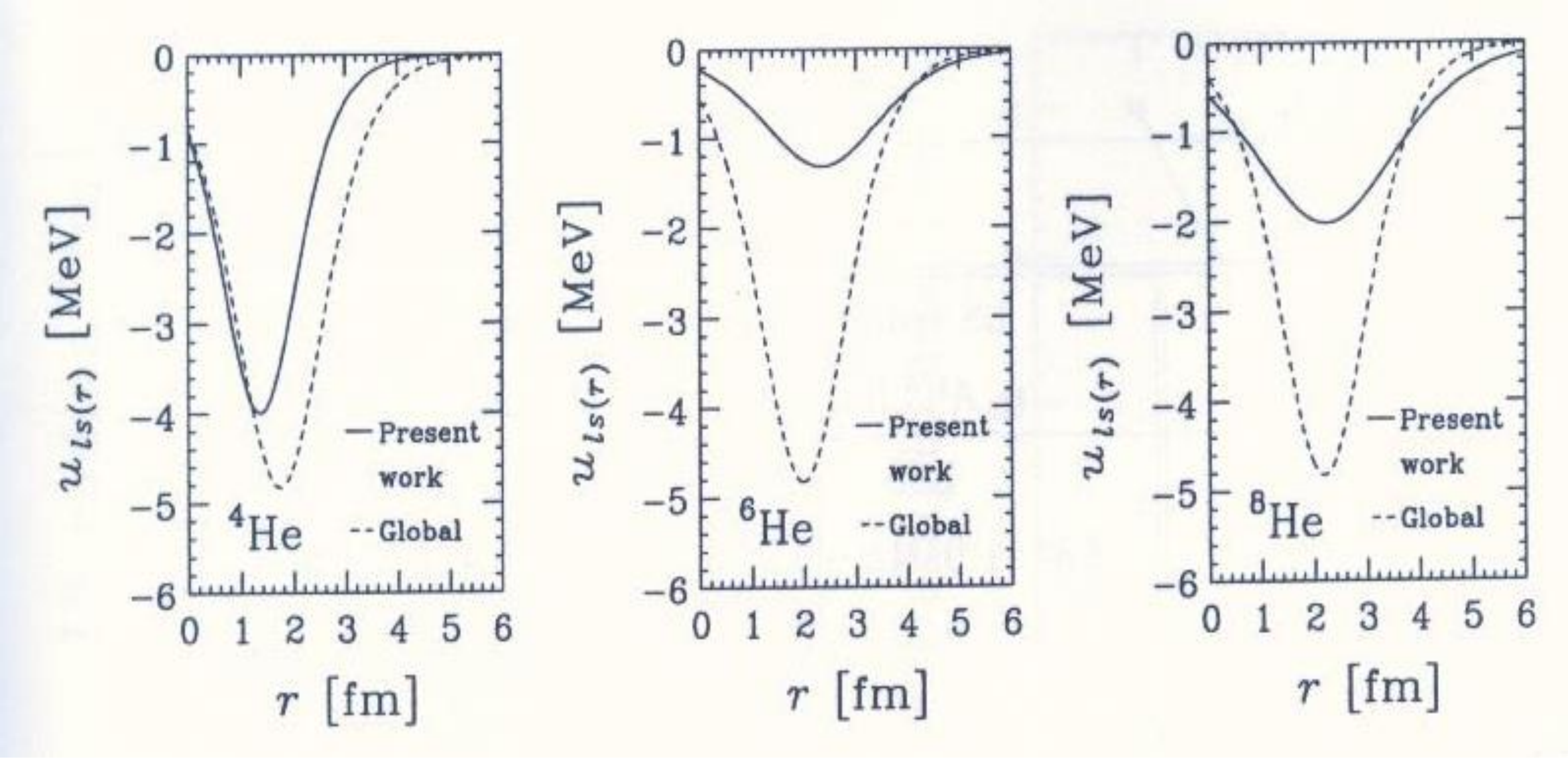


Repeating 1→ 4 ⇒ Protons are polarized

Complete Target System of RIKEN Polzrized p

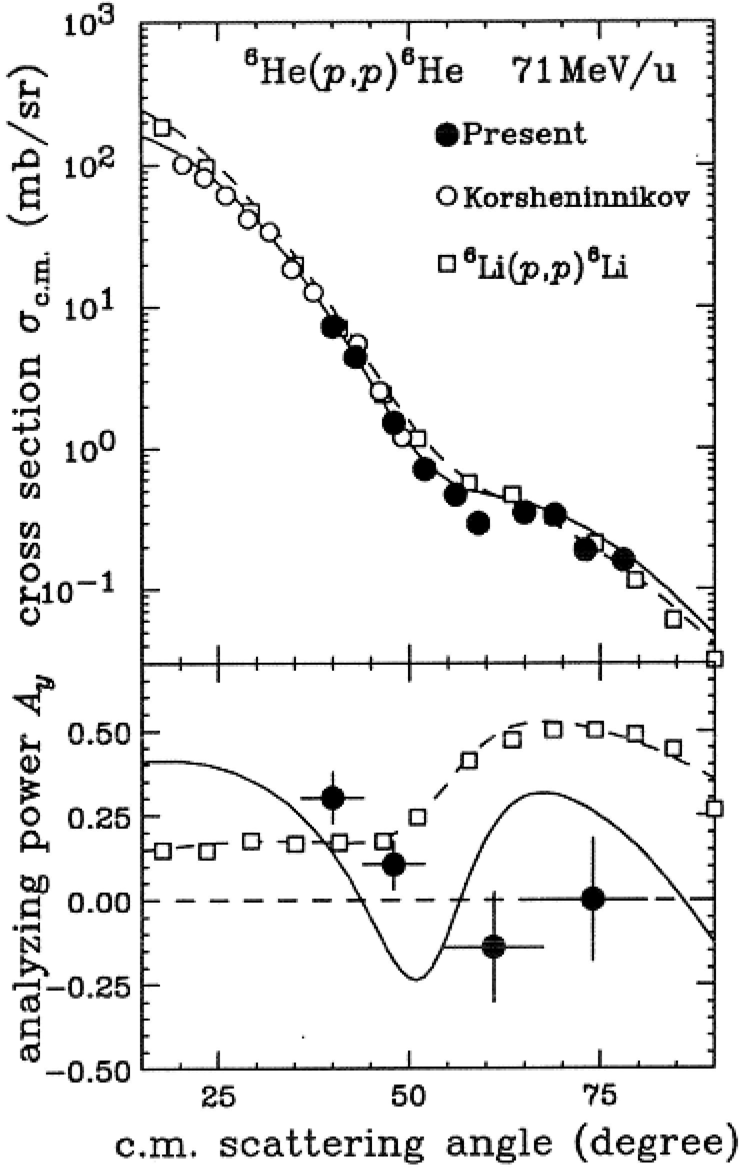


Present status: RIKEN

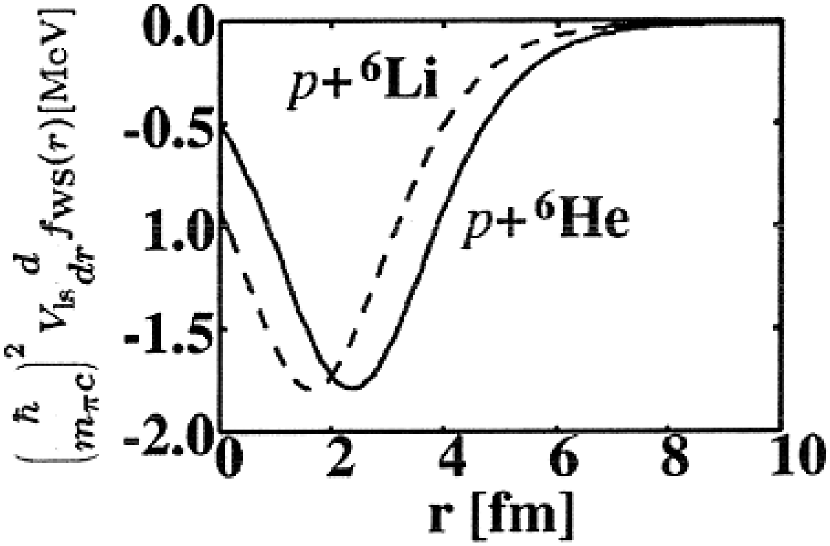


Radial dependence of spin-orbit potentials between a proton and helium isotopes.

^{6}He-p Cross-section & Analyzing Power Results

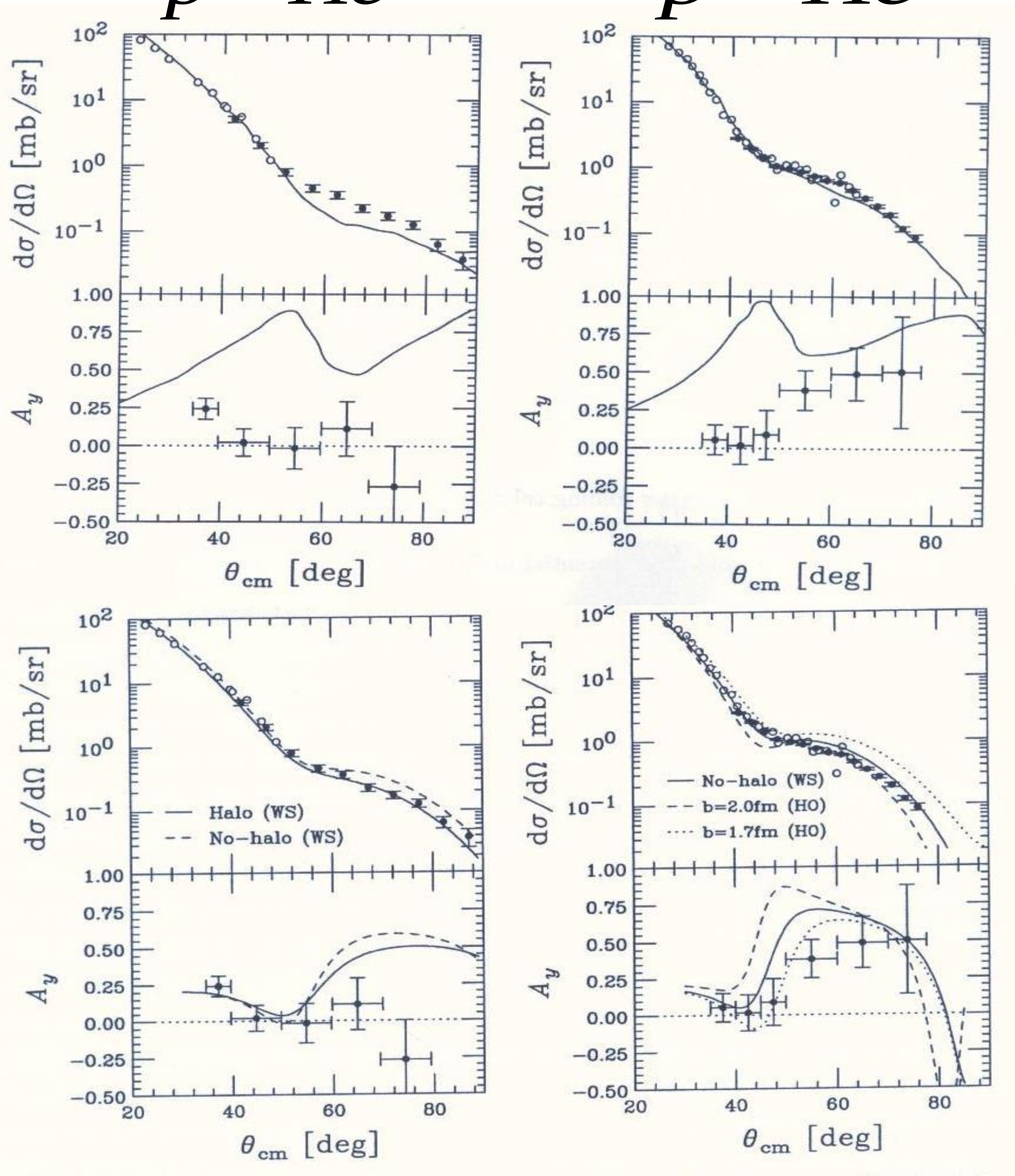


M. Hatao et al.,
Eur. Phys. J. A
S01, 255 (2005)



p – ^{6}He , p – ^{8}He Elastic Scattering in 71 MeV/A

$\vec{p}-{}^6He$ $\vec{p}-{}^8He$



S. Sakaguchi Ph.D. Thesis
Univesity of Tokyo(2008)

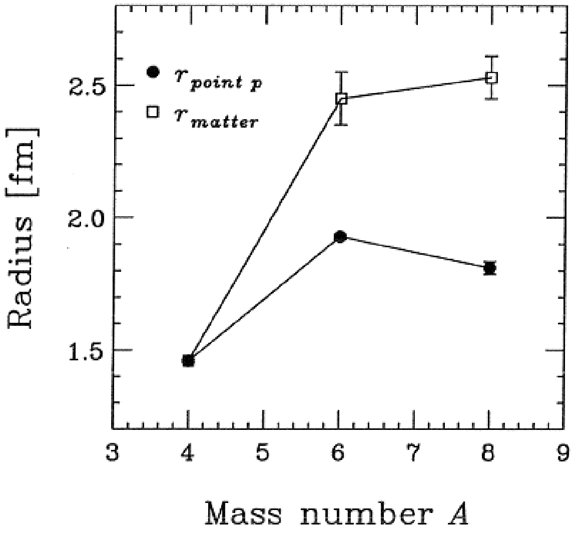
t-matrix folding calculation.
S. P. Weppner et al.,
PRC 61, 044601 (2000)

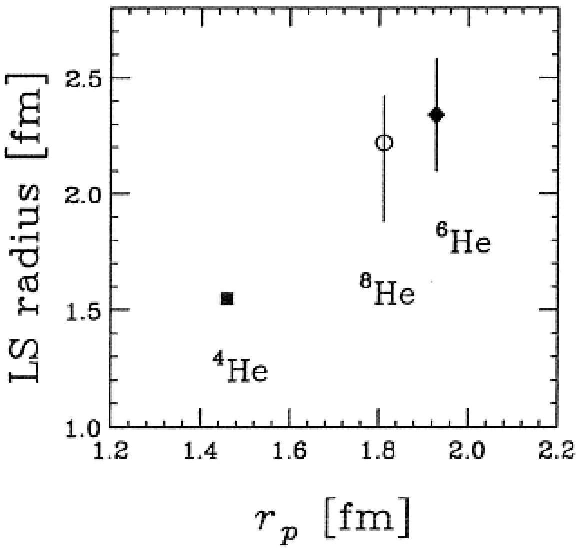
Non-local g-matrix folding calculation.
K. Amos et al., Adv. in N. P. A 25, 275 (2000)

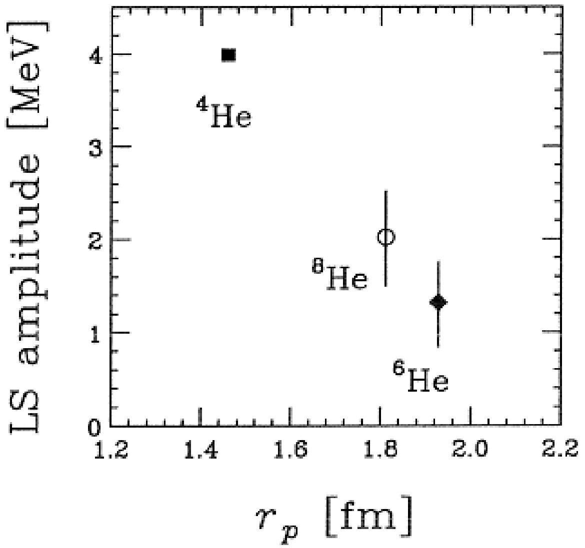
g-matrix as an Effective Interaction

- t-matrix : Effective Two-body Interaction in free space
- g-matrix : Complicated Medium Effects are taken into account.
- Full treatment of Exchange Amplitudes is important to describe the proton elastic scattering.
- As an effective interaction the Melbourne g-matrix was used.
- Contains Density-dependent Spin-orbit Interaction

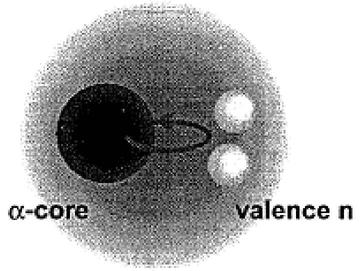
A-dependence & Correlation between point proton radius and LS







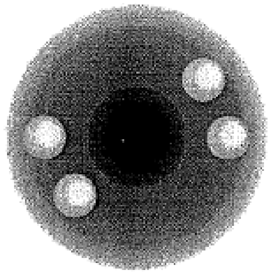
^{6}He



1. Di-neutron structure
→ Large recoil motion of α-core
→ Large charge radius (2.068 fm)

2. Two valence neutrons
→ Small matter radius (2.45 fm)

^{8}He



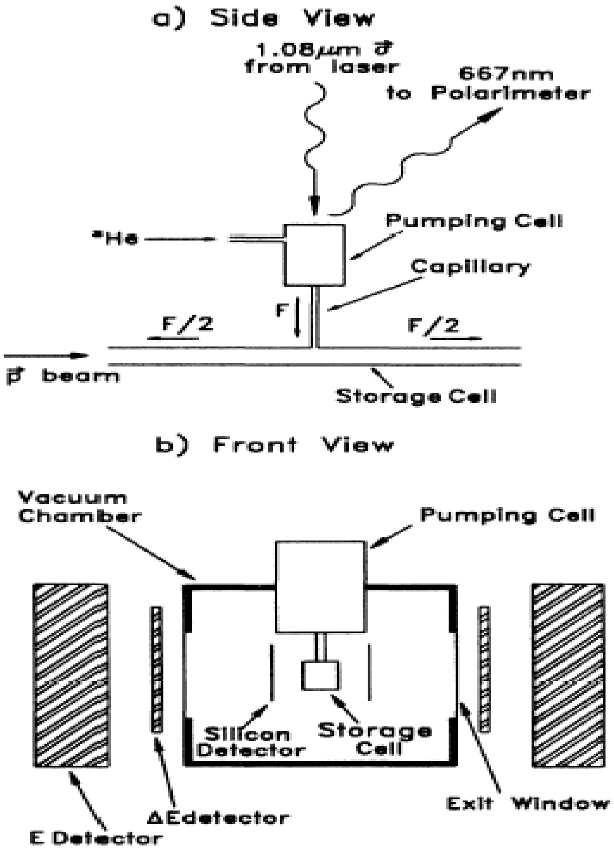
1. Isotropically distributed neutrons
→ Small recoil motion of α-core
→ Small charge radius (1.929 fm)

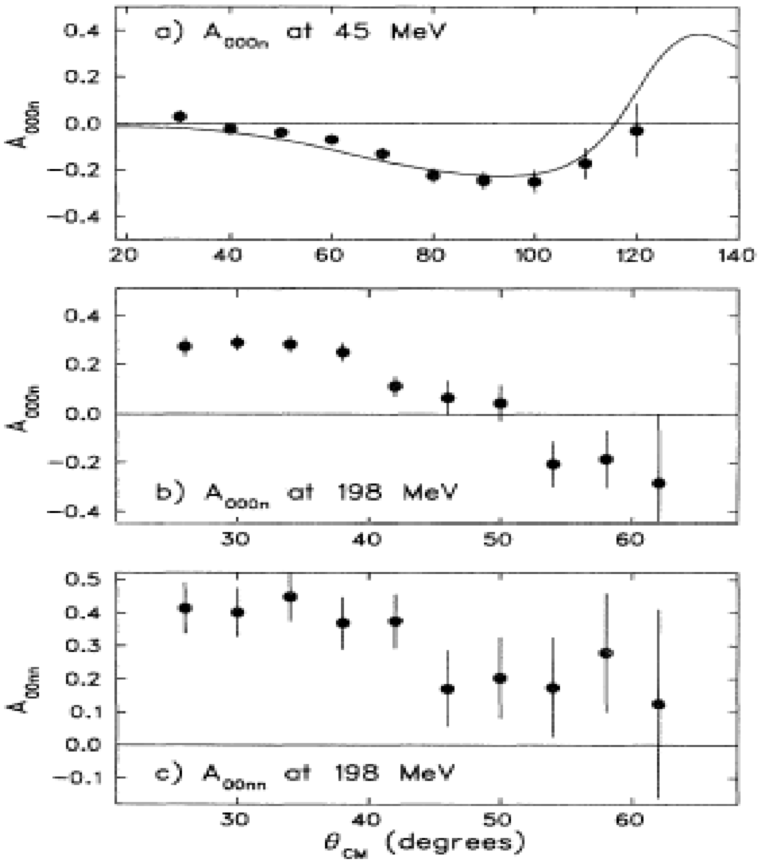
2. Four valence neutrons
→ Large matter radius (2.53 fm)

- Microscopic $\alpha + 2n$ calculation was carried out
- Reduction of the spin-orbit potential in 6He was found to be due to the diffuseness of the density.
- The spin-orbit potential in 6He is dominated by the contribution of the α core.

Measurement of Spin Observables Using a Storage Ring with Polarized Beam and Polarized Internal Gas Target

$\overrightarrow{{}^3He}\,(\vec{p},p')$ **IUCF K. Lee et al., PRL 70, 738 (1993)**

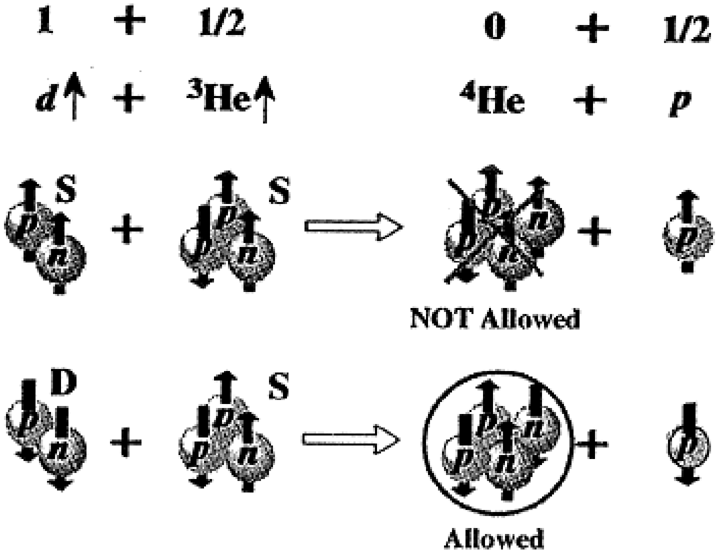


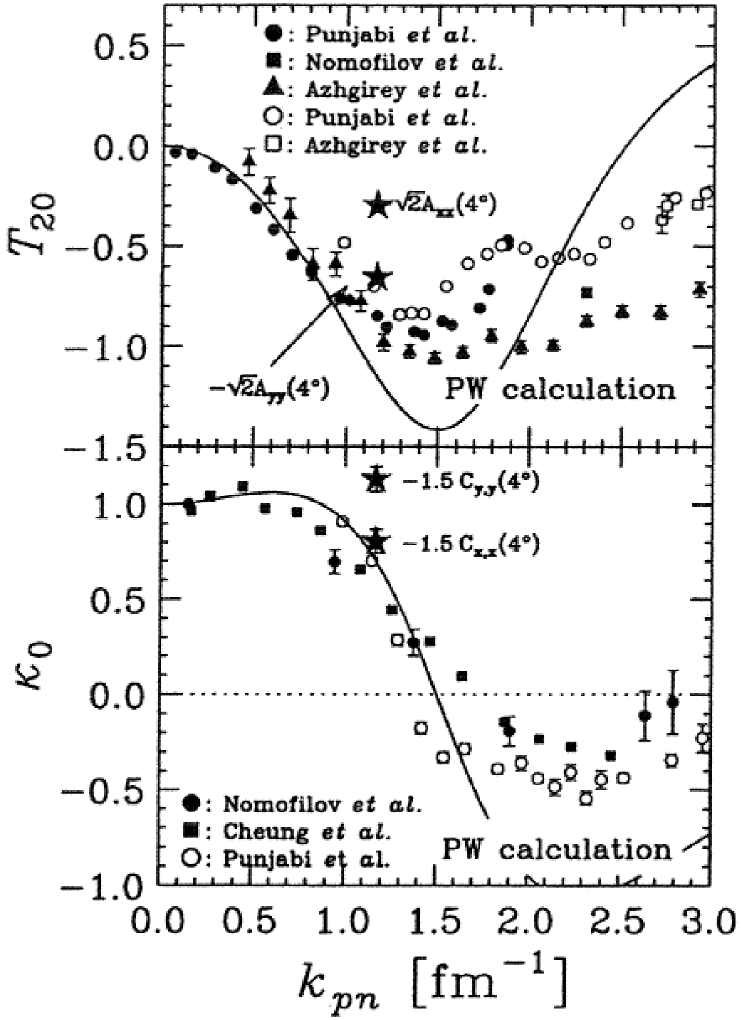


Polarization Correlation Coefficient

T. Uesaka et al.,
PL B 467 (1999)

$$^{3}\vec{He}\left(\vec{d},p\right)\,^{4}He$$



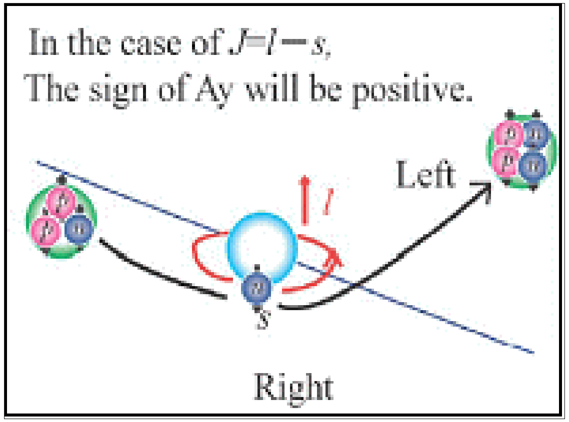


Physics Motivation with Polarized ^{3}He and RIB

Study of unstable nuclei by performing (^{3}He, α) scattering experiments with RI beams

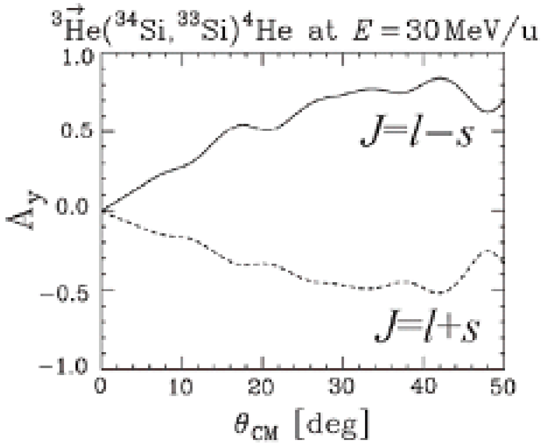
Analyzing Power A_y in (^{3}He, α) Reaction becomes in PWIA

$$A_Y = \begin{cases} +1 & (J = l - s) \\ -\dfrac{1}{l+1} & (J = l + s) \end{cases}$$



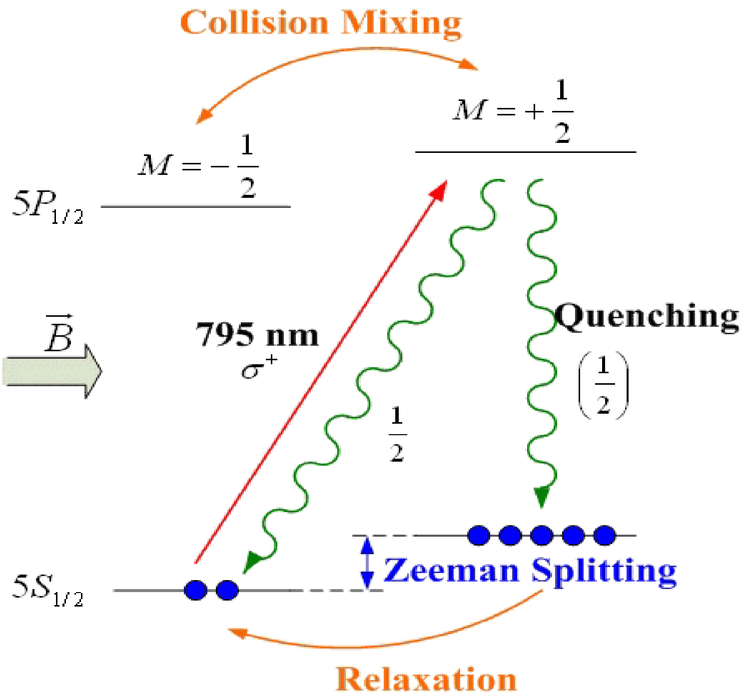
In the case of $J=l-s$,
The sign of Ay will be positive.

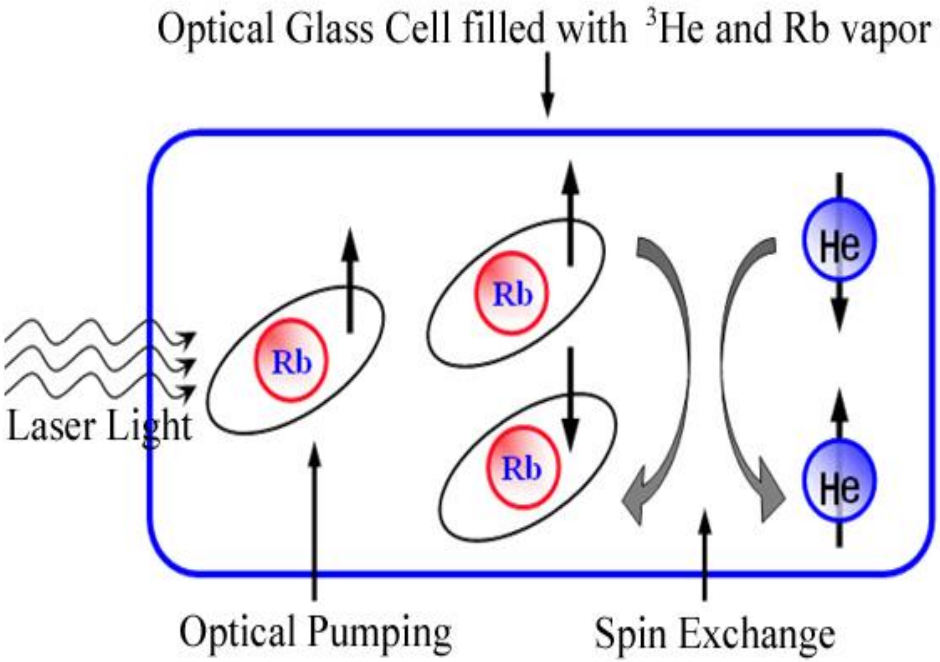
Measure A_y and assign J^π



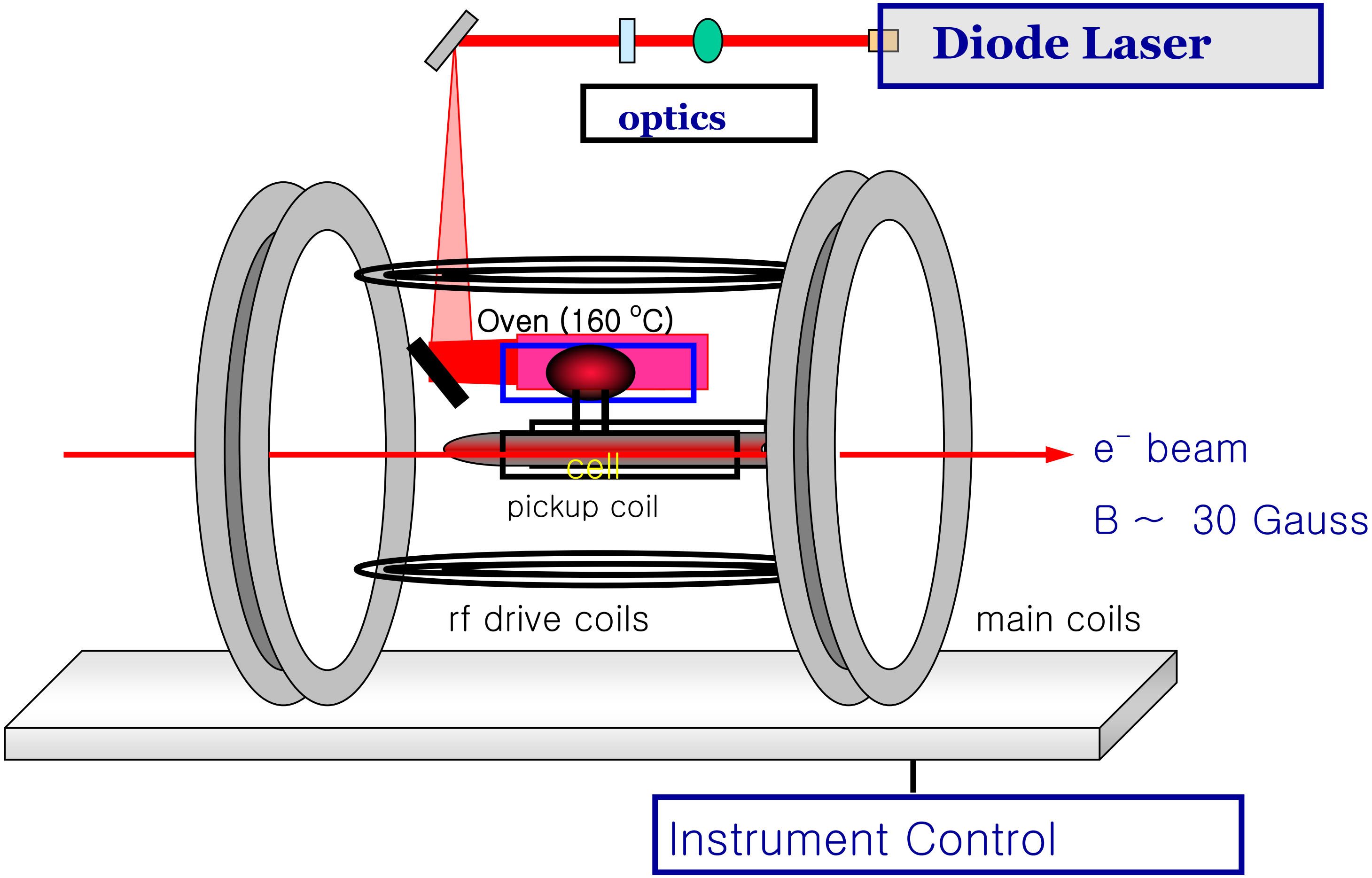
Ex. Perform ^{34}Si(^{3}He, Alpha)^{33}Si and study the excited state of ^{33}Si

Optical Pumping and Spin Exchange



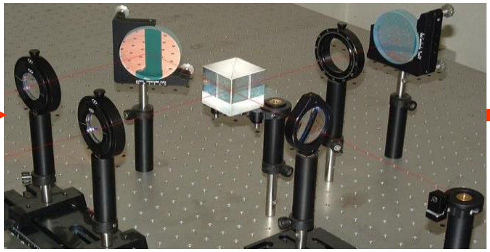


Polarized ^{3}He Setup with Electron Beams



Experimental Setup

Laser



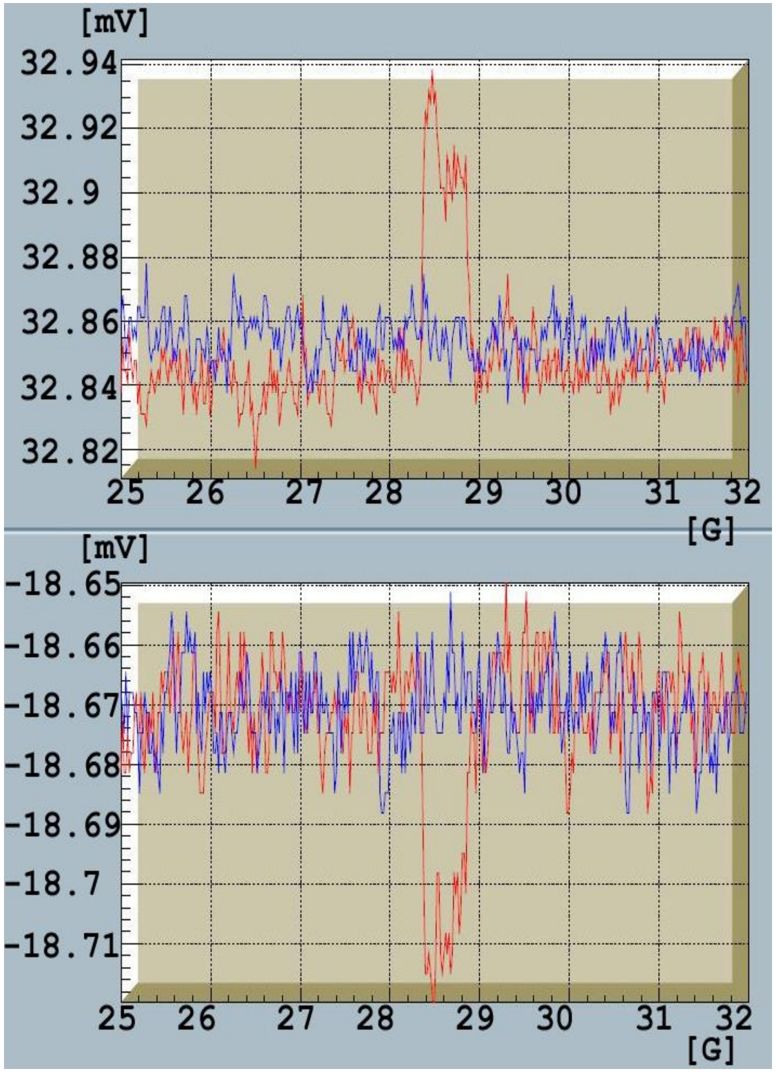
Optics system

Oven, coils and heaters

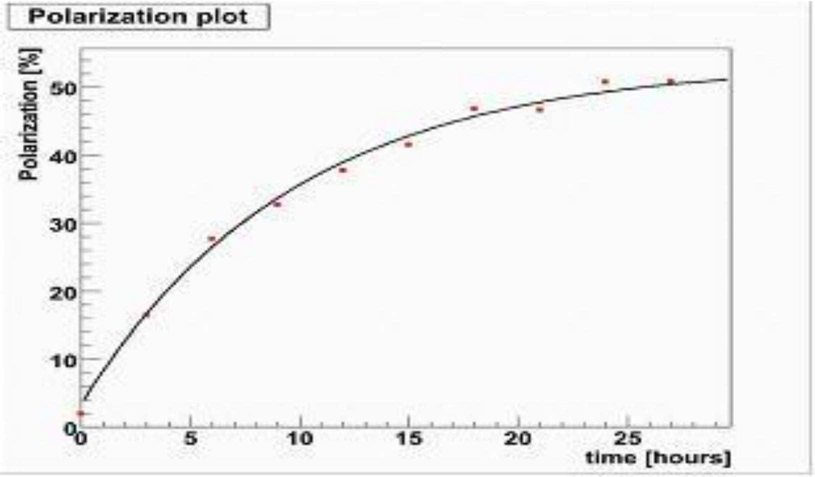
Ion pump and gas panel

500^0C Oven to bake cell assembly

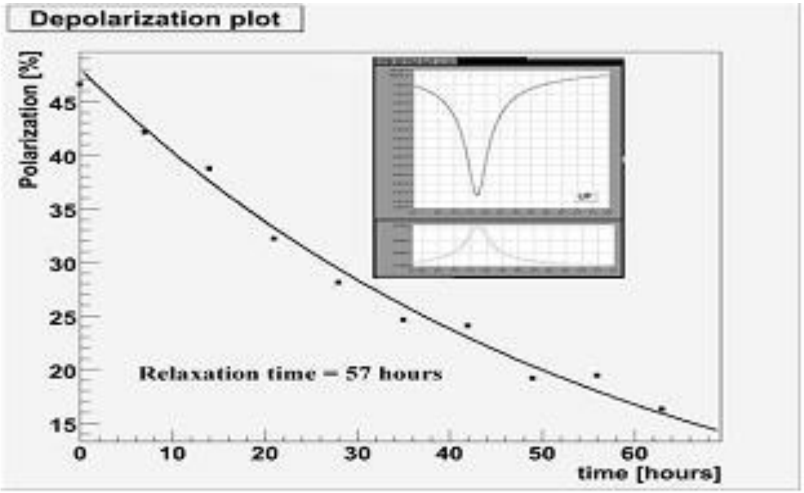
Results : Polarized ^{3}He



^{3}He NMR Signal



Polarization Dependence on time



Exponential Decay of polarization

2007.9.5 Polarized ^{3}He achieved in Korea for the first time

Summary

- RIB Accelerator will provide us with world's forefront Physics in unstable nuclei

- Demonstrated the effectiveness of polarized p, d, ^{3}He in exploring new aspects of nuclei far from the stability line

- RI beam experiment with polarized p, d, ^{3}He targets will be a powerful tool to shed a light on the spin-orbit coupling in unstable nuclei