Outstanding Physics Questions We Can Address

Single Particle Structure in Nuclei
Short-Range Correlations in Nuclei
} Strongly related

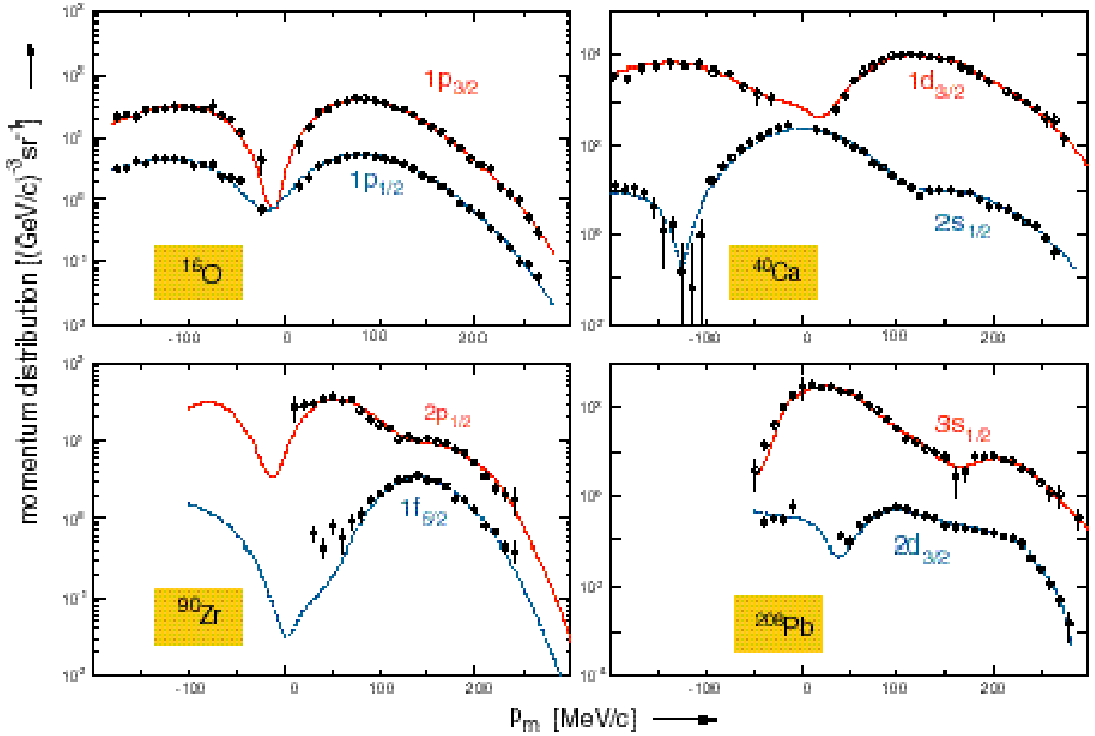
Modification of Meson and Nucleon properties in Nuclear Medium

One of the most direct way of investigating such questions
Is via quasi-free scattering using hadronic and leptonic probes

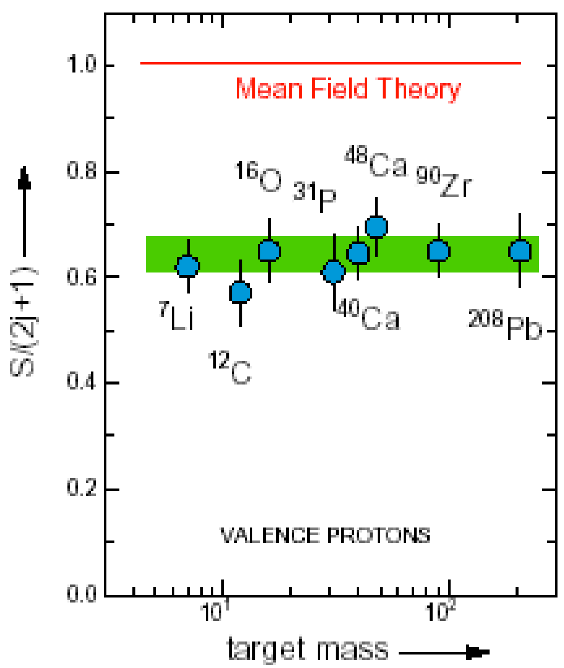
Ideally suited to GSI/FAIR energies

Our Picture of the Nucleus

Independent Particle Shell Model - very successful. BUT !!!



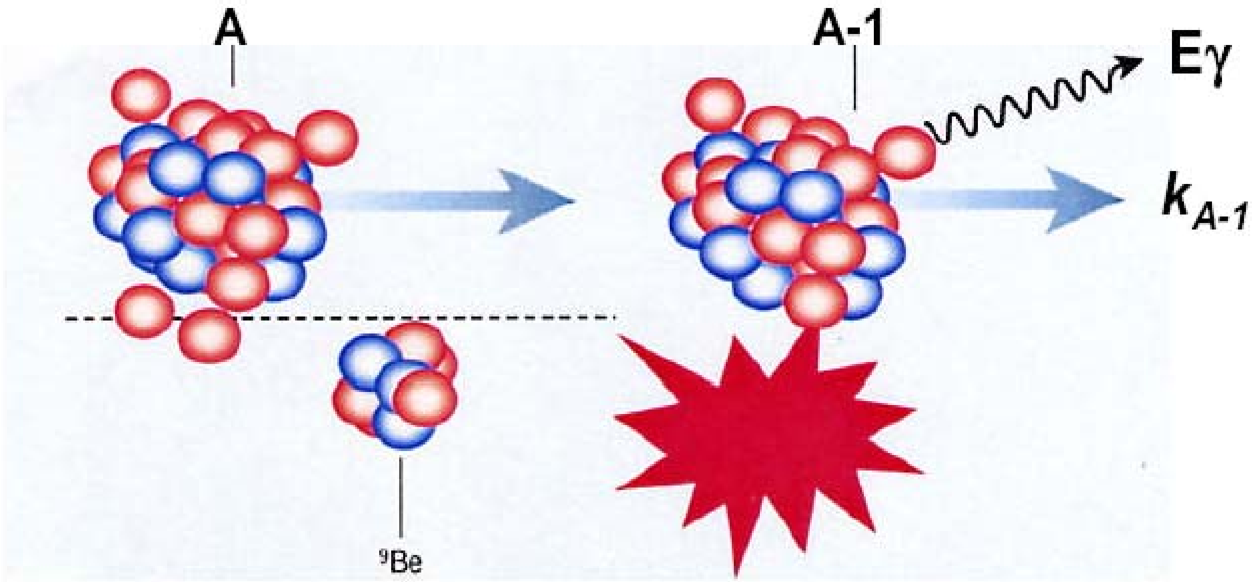
Data from NIKHEF : (e,e'p)

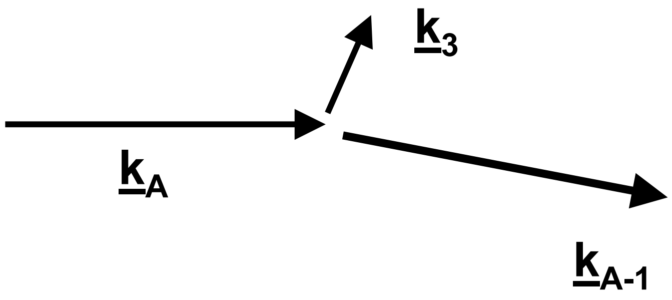


L. Lapikas, Nucl. Phys. A553 (1993) 297c.

Effect of long-range and short-range correlations

One-Neutron Removal Reaction in Inverse Kinematics



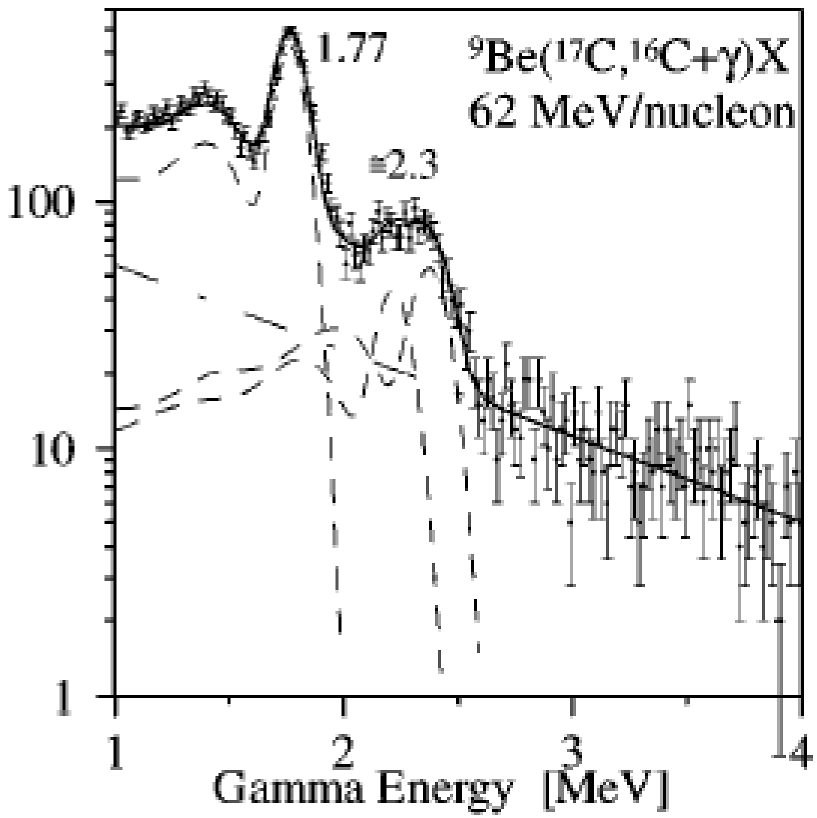


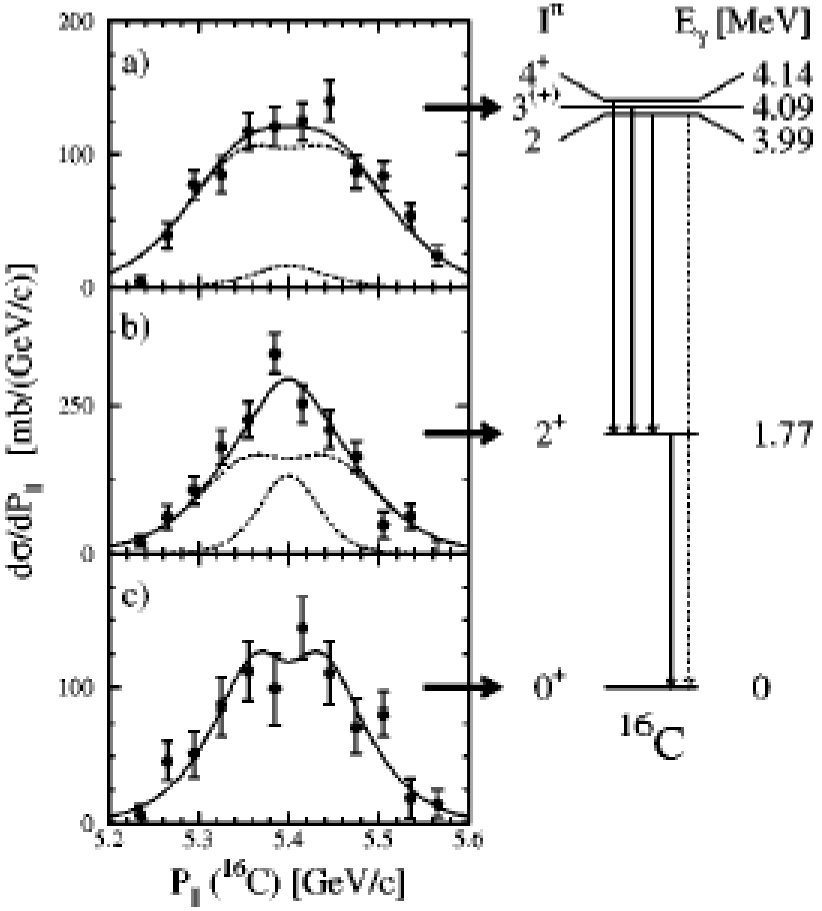
Directly measure momentum distribution k_{A-1}. Related to momentum of struck nucleon k_3 by :

$$k_3 = \frac{A-1}{A} k_A - k_{A-1}$$

- **l-value from momentum distribution of core**
- **tag excited core states with γ-rays**

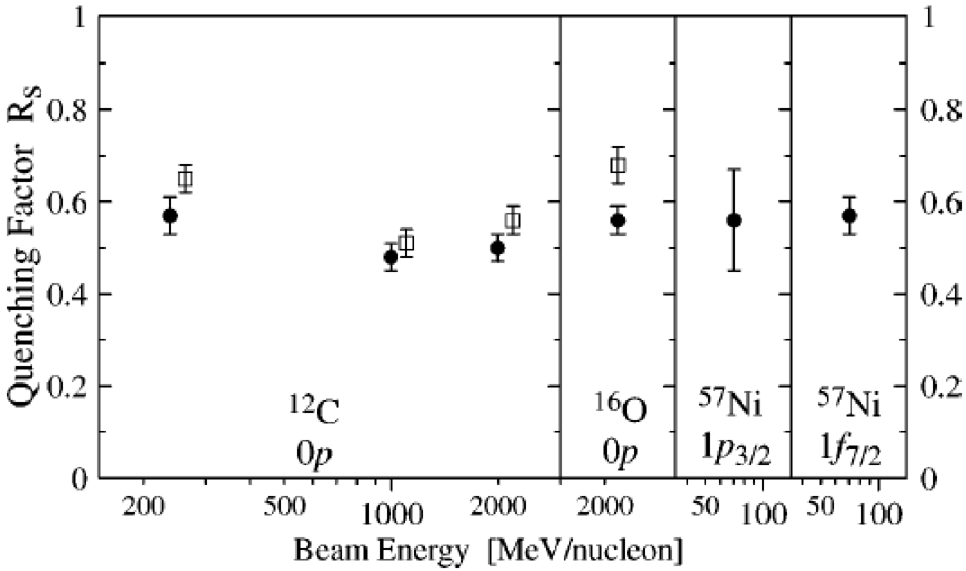
Example : $^{9}Be(^{17}C,^{16}C+\gamma)X$





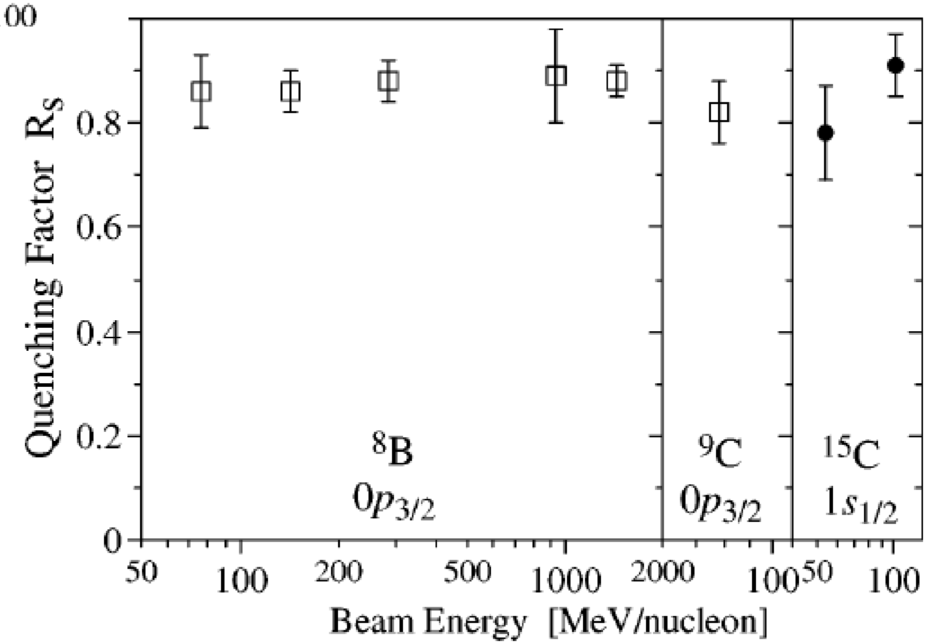
V. Maddalena et al., Phys. Rev. C 63 (2001) 024613.

Quenching Factors R_S From Knockout Reactions



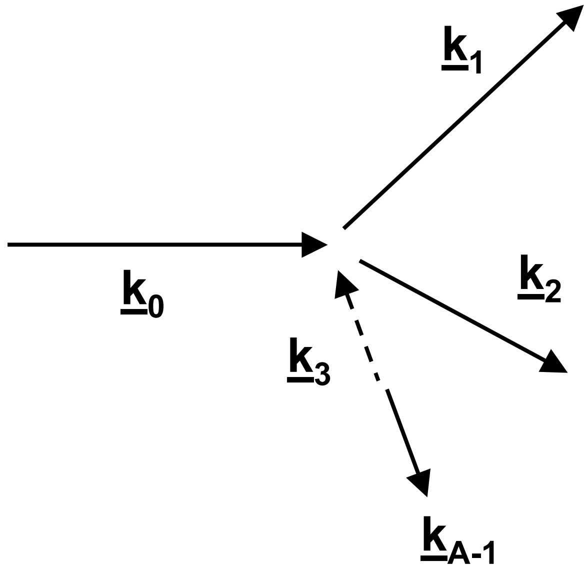
Strongly bound nucleons

Weakly bound nucleons



P.G. Hansen and J.A. Tostevin,
Ann. Rev. Nucl. Part. Sci 53 (2003) 219.

Quasi-Free Scattering (QFS) : Kinematics



Nuclear recoil momentum :

$$k_{A-1} = k_0 - k_1 - k_2 = -k_3$$

Separation energy of knocked-out nucleon

$$E_S = E_0 - E_1 - E_2 - \frac{k_{A-1}^2}{2(A-1)}$$

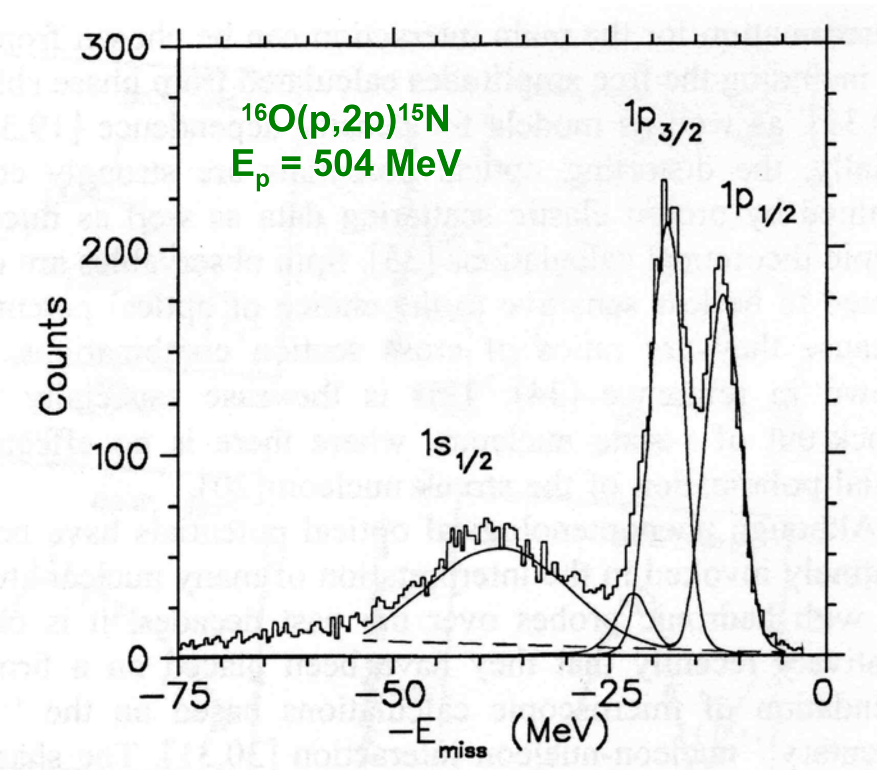
Coplanar geometry

Correlation cross-section in the factorized DWIA :

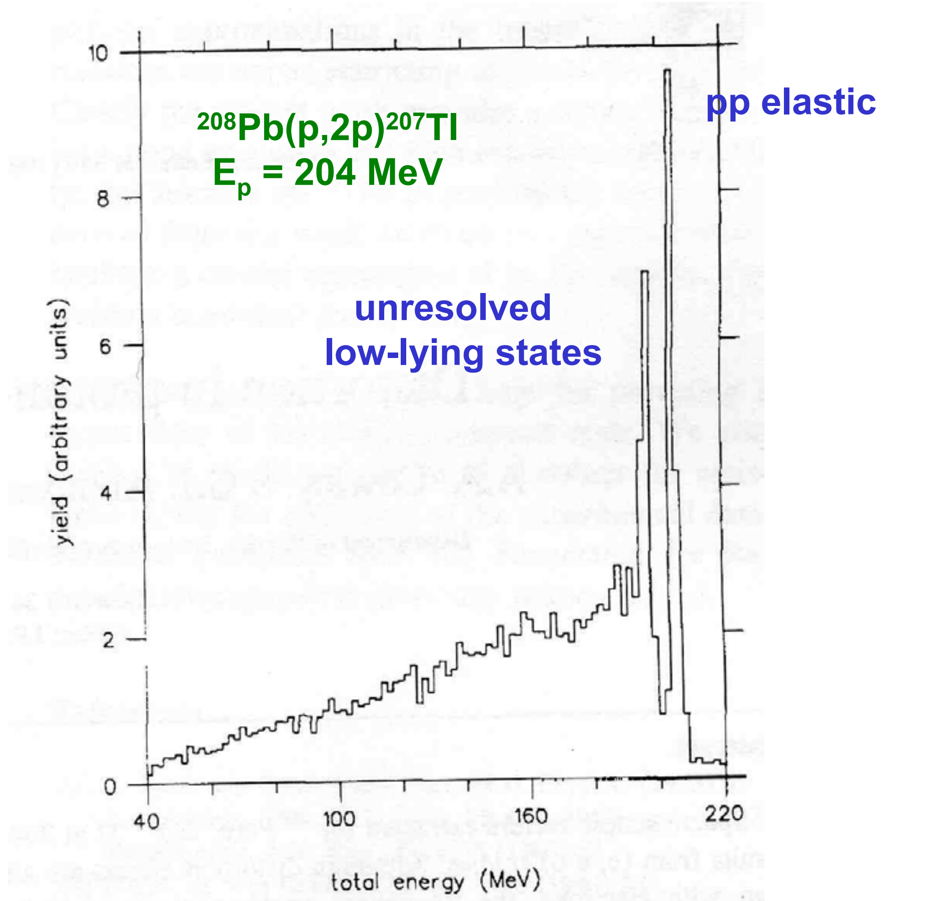
$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE} = \underbrace{S_3 F_k}_{\text{spectroscopic factor}} \underbrace{\frac{d\sigma_{pp}}{d\Omega}\left(E_0, \theta, P_{eff}\right)}_{\text{free n-n cross-section}} \underbrace{G\left(\vec{k}_3\right)}_{\text{distorted momentum distribution}}$$

spectroscopic factor — free n-n cross-section — distorted momentum distribution

QFS : Binding Energy Spectra



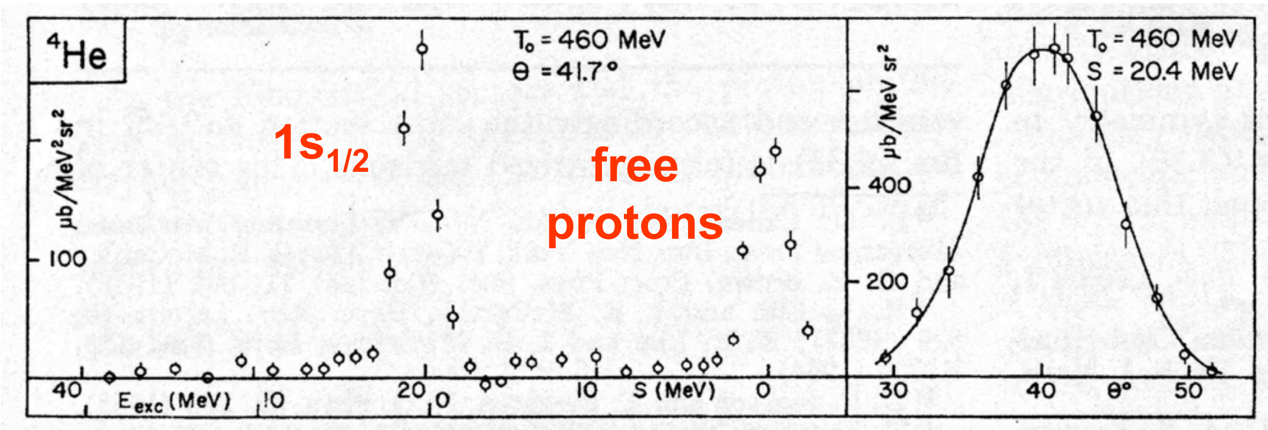
C.A. Miller et al., Phys. Rev. C 57 (1998) 1756.



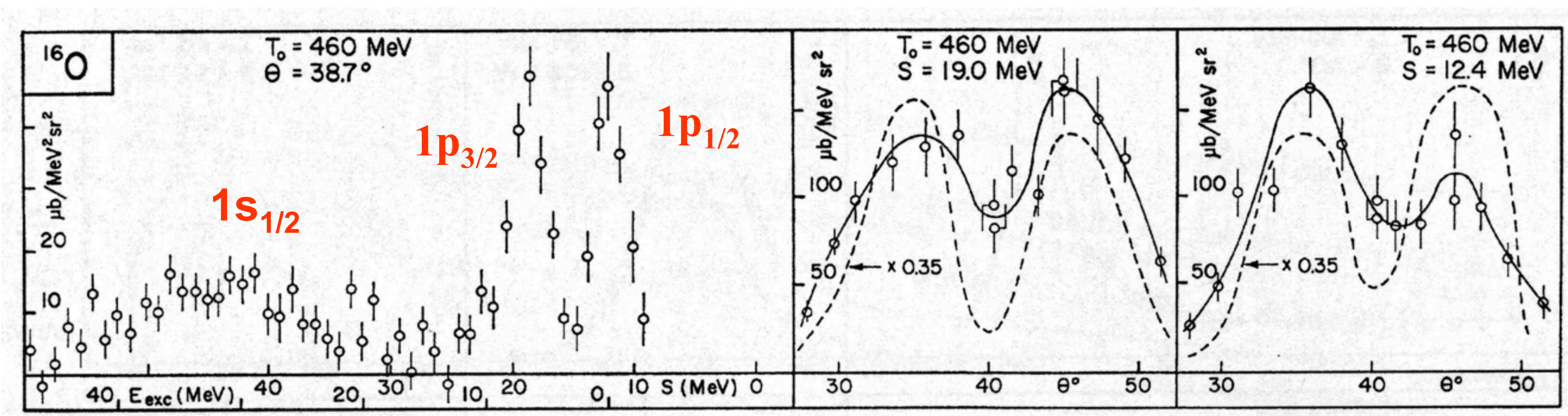
A.A. Cowley et al., Phys. Lett. B 359 (1995) 300.

Energy resolution ~ few MeV

QFS : Angular Correlation Spectra



$^{4}He(p,2p)^{3}H$



$^{16}O(p,2p)^{15}N$

G. Jacob and Th. A.J. Maris, Rev. Mod. Phys. 38 (1966) 121.

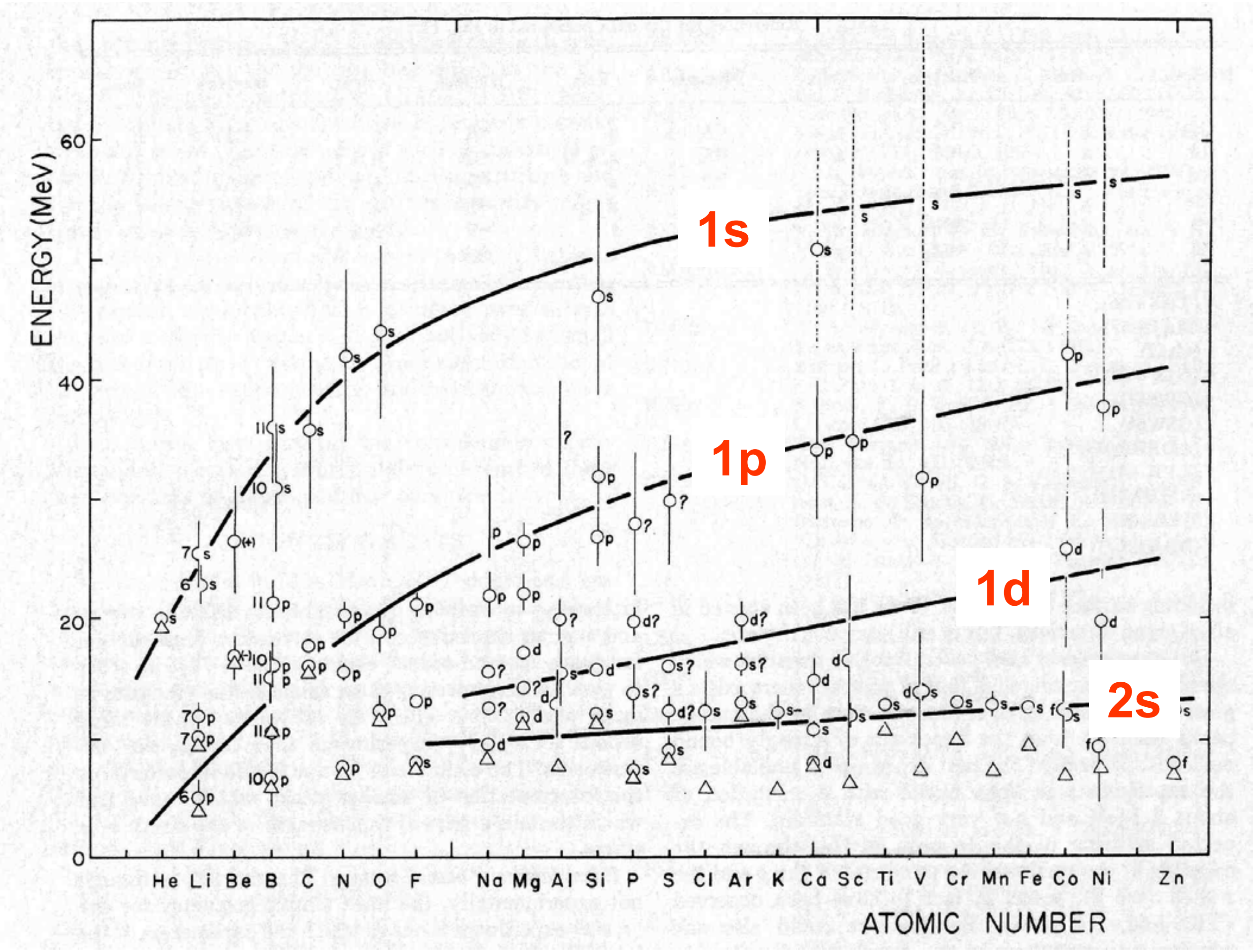
QFS : Energy Sharing Correlation Spectra

E_p = 101.3 MeV

(a) 41.0°/ -41.0°
(b) 46.7°/ -35.0°
(c) 52.2°/ -29.0°
(d) 57.0°/ -23.0°

C. Samanta et al., Phys. Rev. C 34 (1986) 1610.

Summary of QFS Spectroscopic Results c. 1973



G. Jacob and Th. A.J. Maris, Rev. Mod. Phys. 45 (1973) 6.

Comparison of (p,2p) and (e,e′p)

^{16}O(p,2p)^{15}N
E_p = 151 MeV

TABLE II. Average spectroscopic factors.

Reaction	Incident energy (MeV)	Reference	Spectroscopic factors $^{15}N_{g.s.}(\frac{1}{2}^-)$	$^{15}N_{6.3}(\frac{3}{2}^-)$
$(p,2p)$	101	2	2.2	3.1
	101	2[a]	1.9	2.5
	151	This work	1.3	2.4
	200	17	1.3	2.7
$(e,e'p)$	500	18[b]	1.2	2.3
$(d,{}^3\mathrm{He})$	29	20	2.2–2.3	2.8–3.7
	34	21	2.1	3.7
Theory		19	1.5	2.9

[a]Our reanalysis of the results of Ref. 2. [b]Values from Ref. [18] corresponding to Elton-Swift [14] bound state, and with spin-orbit interaction in distorting potentials.

A.A. Cowley et al., Phys. Rev. C 44 (1991) 329.

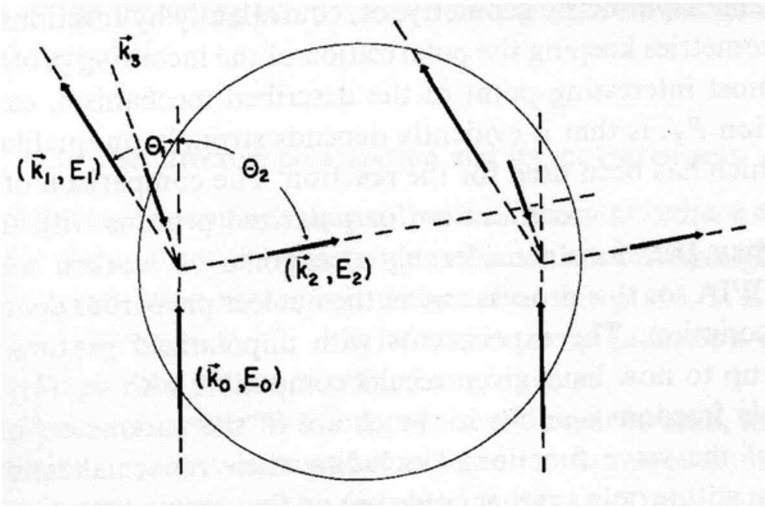
^{208}Pb(p,2p)^{207}Tl
E_p = 204 MeV

Table 2
Comparison between spectroscopic factors extracted in this work and existing values

Spectroscopic factor	Reference
0.7–0.8	this work (p, 2p)
0.65	[4] (e, e′p)
0.71	[5] (e, e′p)
0.65–0.73	[6] (e, e′p)
0.70	[14] theory

R. Neveling et al., Phys. Rev. C 66 (2002) 034602.
A.A. Cowley et al., Phys. Lett. B 359 (1995) 300.

Spin-Dependence in Quasi-Free Scattering



Free nucleon-nucleon cross-section

$$\frac{d\sigma}{d\Omega}(\theta) = I_0(\theta)\left[1 + \left(P_0 + P_{eff}\right)P(\theta) + P_0 P_{eff} C_{nn}(\theta)\right]$$

- $I_0(\theta)$ is free unpolarized nn cross-section
- P_0 is polarization of incoming nucleon
- P_{eff} is effective polarization of knocked out nucleon
- $P(\theta)$, $C_{nn}(\theta)$ are spin observables for free polarized nn scattering

Absorption and spin-orbit coupling gives an effective polarization to knocked out nucleon.

With experimental asymmetry defined as :

$$A_{exp} = \frac{d\sigma^{(+)} - d\sigma^{(-)}}{d\sigma^{(+)} + d\sigma^{(-)}}$$

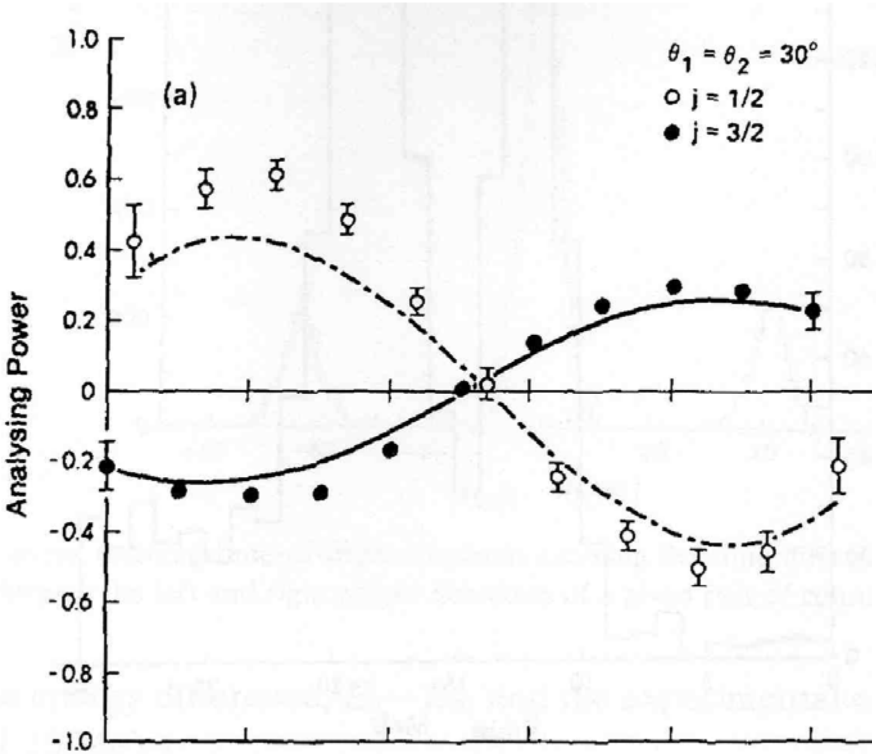
$$= \frac{P(\theta) + P_{eff} C_{nn}(\theta)}{1 + P_{eff} P(\theta)} P_0$$

If $P_{eff} = 0$ (e.g. s-state nucleon) and $P_0 = 1$:

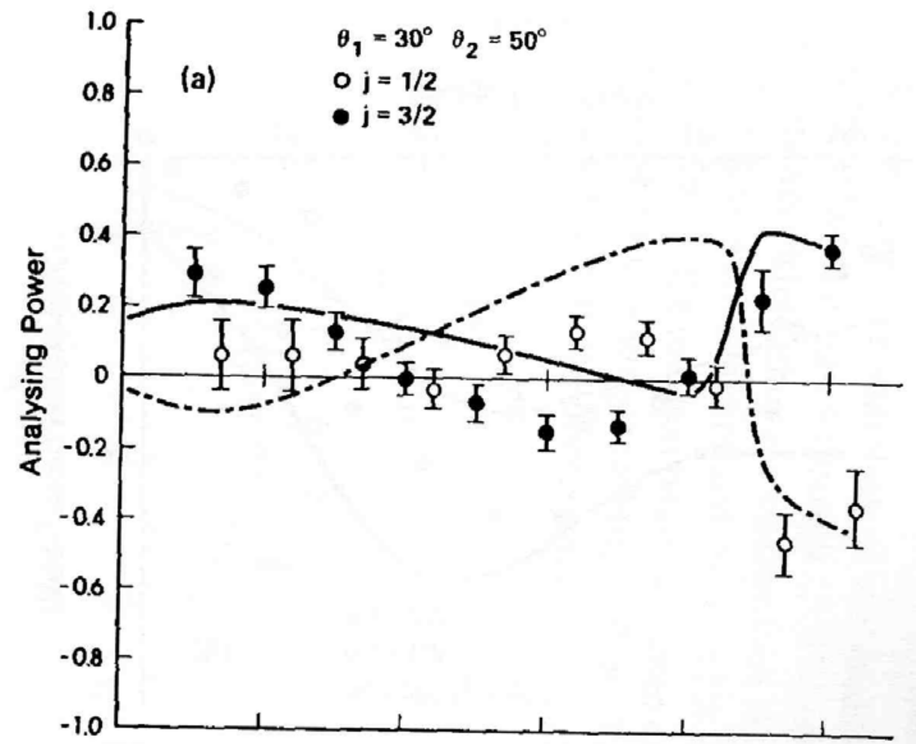
$$P(\theta) = A_{exp}$$

➡ **nn analysing power in-medium**

Analysing Powers For $^{16}O(p,2p)^{15}N$

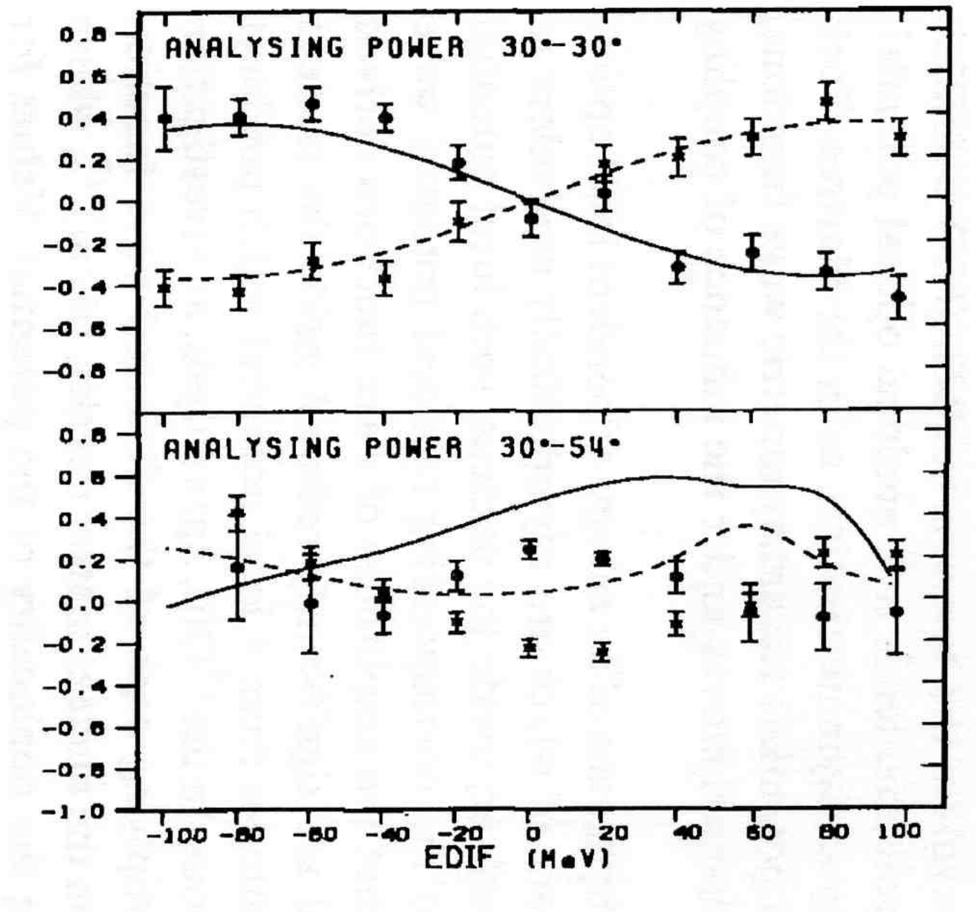


Knockout from
$p_{1/2}$ and $p_{3/2}$ states
$E_p = 200$ MeV



P. Kitching et al., Nucl. Phys. A 340 (1980) 423.

Analysing Powers For $^{40}Ca(p,2p)^{39}K$



Knockout from d-states
E_p = 200 MeV

—— $1d_{3/2}$
- - - $1d_{5/2}$

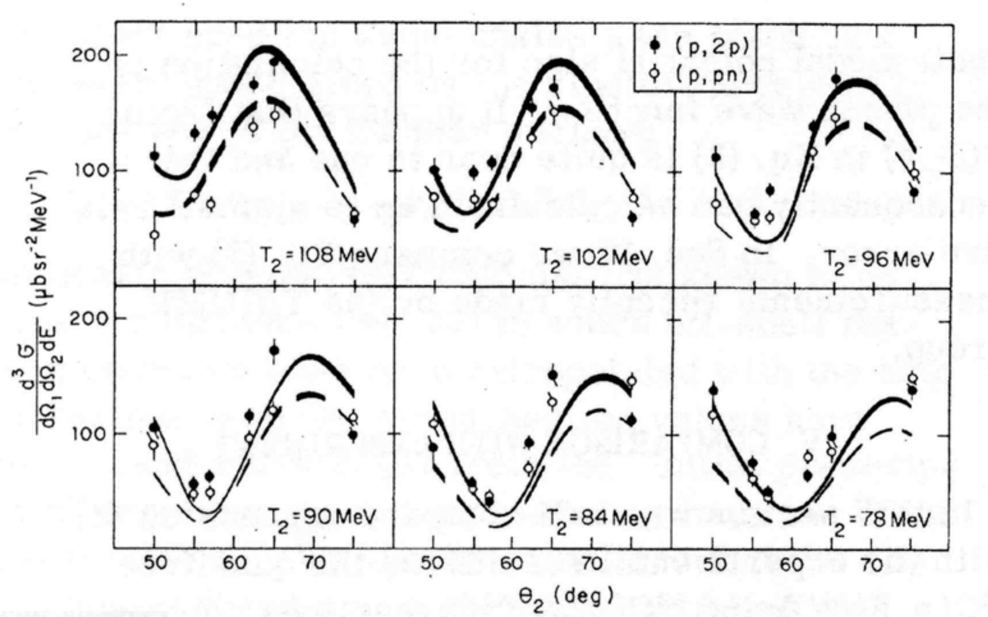
L. Antonuk et al., Nucl. Phys. A 370 (1981) 389.

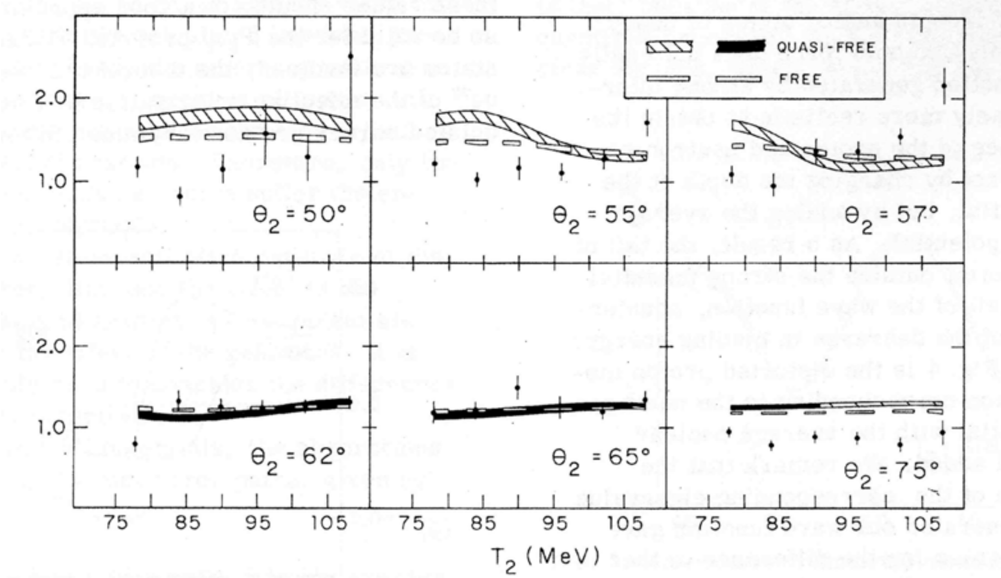
Isospin Dependence in Quasi-Free Scattering

For $^{12}C(p,2p)^{11}B$ and $^{12}C(p,pn)^{11}C$ with E_p = 400 MeV

$$\frac{d\sigma(p,2p)}{d\sigma(p,pn)} = \frac{d\sigma_{free}(p,2p)}{d\sigma_{free}(p,pn)} C(E,\theta)$$

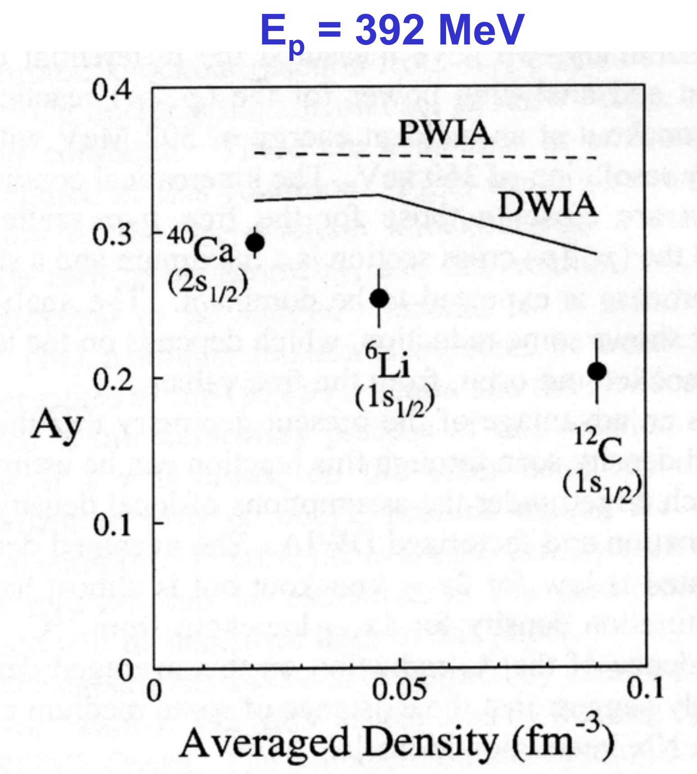
where $$C(E,\theta) = \frac{G_p(\vec{k}_3)}{G_n(\vec{k}_3)} \frac{F_k^{(p,2p)}}{F_k^{(p,pn)}}$$



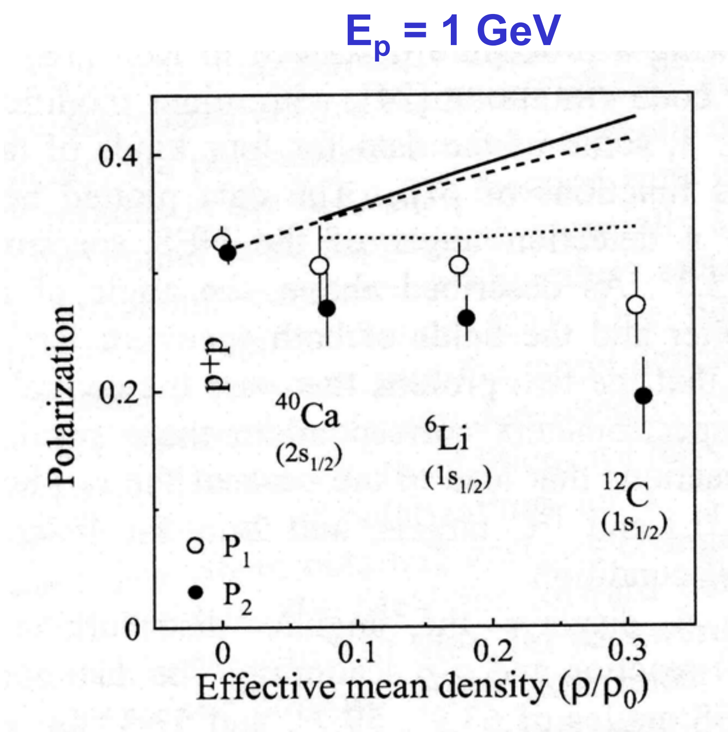


Validity of impulse approximation

Nuclear Medium Effects



K. Hatanaka et al., Phys. Rev. Lett. 78 (1997) 1014.



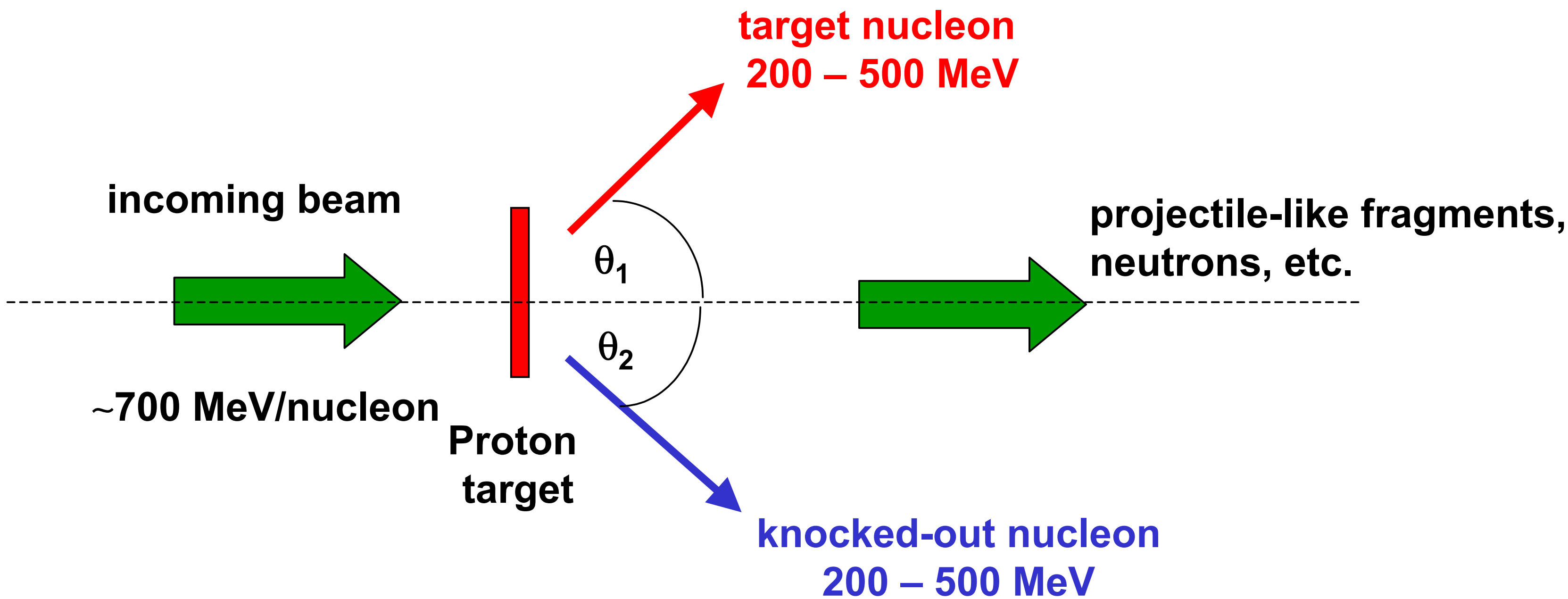
V.A. Andreev et al., Phys. Rev. C 69 (2004) 024604.

Chiral symmetry restoration, quark deconfinement :

Modification of
- nucleon and meson masses
- sizes
- meson-nucleon coupling constants

→ **modified n-n interaction**

Experimental Setup for External Target



SuperFRS-R3B is ideal with addition of target recoil detector

Complete kinematics :

- detect/reconstruct projectile-like fragment, neutrons
- detect target and knocked-out nucleon(s)
- tag excited states with gamma-rays
- polarised target

A Possible Experimental Programme

PHASE 1 – Unpolarized QFS

- (p,2p) and (p,pn) measurements
- first attempt using ^{12}C
- compare 1n removal and (p,pn) reactions
- (p,2p)/(p,pn) tests of impulse approximation
- physics measurements using light n-rich nuclei, e.g. He, C, O, Si etc.
- extraction of spectroscopic factors
- parallel development of theoretical programme crucial !!!

PHASE 2 – Polarized QFS

- measure experimental asymmetrys
- first measurements of polarized (p,pn)
- probe spin-orbit properties
- examine in-medium effects
- extend measurements to heavier nuclei, e.g. Ca and upwards