Why Ar,Ti$(e, e'p)$?

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E12-14-012 Collaboration Meeting
Jefferson Lab, Newport News, VA
April 10-11, 2017

Outline

- Why $(e, e'p)$?
  - Nuclear dynamics: the shell model and beyond
  - $(e, e'p)$ cross section and nuclear spectral function
  - 50 years of $(e, e'p)$ data
- Why Ar and Ti targets?
  - Neutrino energy reconstruction in accelerator based searches of neutrino oscillations
  - Neutrino and antineutrino interactions in liquid argon detectors
- What needs to be done

Why $(e, e'p)$?

The Paradigm of Nuclear Many-Body Theory

- To a remarkably large extent, atomic nuclei can be described as non relativistic systems consisting of point-like particles, whose dynamics are dictated by a phenomenological Hamiltonian

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{j>i} v_{ij} + \sum_{k>j>i} v_{ijk}$$

  - v_{ij} provides a very accurate descritpion of the observed properties of the two-nucleon system, in both bound and scettering states, and reduces to Yukawa's one-pion-exchange potential at large distances
  - inclusion of v_{ijk} needed to explain the ground-state energies of the three-nucleon systems
  - v_{ij} is spin and isospin dependent, non spherically symmetric, and strongly repulsive at short distance
  - nuclear interactions can not be treated in perturbation theory in the basis of eigenstates of the non interacting system

THE MEAN-FIELD APPROXIMATION

- Nuclear systematics offers ample evidence supporting the further assumption, underlying the nuclear shell model, that the potentials appearing in the Hamiltonian can be eliminated in favour of a mean field

$$H \to H_{MF} = \sum_i \left[\frac{\mathbf{p}_i^2}{2m} + U_i \right]$$

$$\left[\frac{\mathbf{p}_i^2}{2m} + U_i \right] \phi_{\alpha_i} = \epsilon_{\alpha_i} \phi_{\alpha_i} \quad , \quad \alpha \equiv \{n, \ell, j\}$$

- For proposing and developing the nuclear shell model, E. Wigner, M. Goeppert Mayer and J.H.D. Jensen have been awarded the 1963 Nobel Prize in Physics

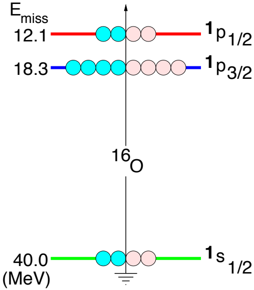
THE NUCLEAR GROUND STATE

- According to the shell model, in the nuclear groud state protons and neutrons occupy the A lowest energy eigenstates of the mean field Hamiltonian

$$H_{MF}\Psi_0 = E_0\Psi_0 \quad , \quad \Psi_0 = \frac{1}{A!}\det\{\phi_\alpha\} \quad , \quad E_0 = \sum_{\alpha\in\{F\}} \epsilon_\alpha$$

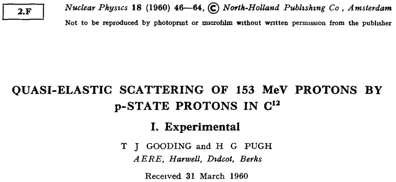
- Ground state of ^{16}O: $Z = N = 8$

$$(1S_{1/2})^2 \quad , \quad (1P_{3/2})^4 \quad , \quad (1P_{1/2})^2$$



Nucleon Knockout Reactions

- Nucleon knockout reactions, in which the outgoing nucleon and the scattered beam particle are detected in coincidence, have been readily recognized as a powerful tool for investigating the validity of the shell model



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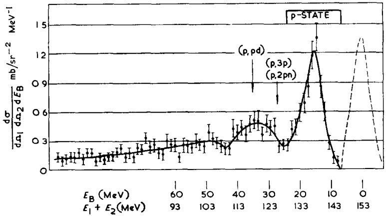
Nuclear Physics 18 (1960) 46—64, © North-Holland Publishing Co., Amsterdam

QUASI-ELASTIC SCATTERING OF 153 MeV PROTONS BY p-STATE PROTONS IN C^{12}

I. Experimental

T J GOODING and H G PUGH
AERE, Harwell, Didcot, Berks

Received 31 March 1960



- Early attempts with proton beams were plagued by the strong distortion of both the incoming and outgoing particles

From Proton to Electron Beams

- In 1962, it was argued that much cleaner information could be obtained from electron-nucleus scattering in the kinematical region corrsponding to momentum transfer $|\mathbf{q}| \ll d^{-1}$—d being the average ucleon-nucleon distance in the target nucleus —in which the reaction predominantly involves individual nucleons

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Nuclear Physics **32** (1962) 139—151;

QUASI-FREE ELECTRON-PROTON SCATTERING (I)

GERHARD JACOB † and TH. A. J. MARIS ††

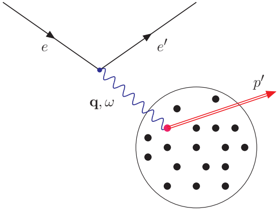
Instituto de Física and Faculdade de Filosofia, Universidade do Rio Grande do Sul, Pôrto Alegre, Brasil

Received 6 July 1961

Abstract: It is shown that, from angular and energy correlation measurements on electron-proton pairs emerging from the scattering of high energy (300-1000 MeV) electrons on nuclei, detailed information on the energy levels and structures of the upper and lower shells of light and medium nuclei could be obtained. A calculation in which the distortion of the outgoing proton wave is taken into account has been performed for C^{12}. As compared to the result for zero distortion, the absolute magnitude of the correlation cross section is reduced, but the shape of its angular distribution is practically unchanged. Consequently the observed energy and angular correlations would immediately give both the binding energy and the momentum distribution of the nuclear proton in the shell model state out of which it has been ejected. From an extrapolation to other nuclei of the calculated value of the reduction factor for the cross section, it is expected that this situation prevails at least up to nuclei with $A = 50$. Finally some corrections are qualitatively discussed.

THE $(e, e'p)$ REACTION

- Consider the process $e + A \to e' + p + (A-1)$ in which both the outgoing electron and the proton, carrying momentum p', are detected in coincidence, and the recoiling nucleus can be left in either a bound or a continuum state



- Assuming that there are no final state interactions (FSI), the initial energy and momentum of the knocked out nucleon can be identified with the *measured* missing momentum and energy, respectively

$$\mathbf{p}_m = \mathbf{p}' - \mathbf{q} \quad , \quad E_m = \omega - T_{\mathbf{p}'} - T_{A-1} \approx \omega - T_{\mathbf{p}'}$$

$(e, e'p)$ Cross Section and Nuclear Spectral Function

- In the absence of FSI (to be discussed at a later stage)

$$\frac{d\sigma_A}{dE_{e'} d\Omega_{e'} dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- Kállën-Lehman representation of the spectral function

$$P_(\mathbf{p}_m, E_m) = P_{\rm MF}(\mathbf{p}_m, E_m) + P_{\rm corr}(\mathbf{p}_m, E_m)$$

- In the kinematical region corresponding to knock-out from the shell-model states ($E_m \lesssim 50$ MeV and $|\mathbf{p}_m| \lesssim 250$ MeV)

$$P_{\rm MF}(\mathbf{p}_m, E_m) = \sum_{\alpha \in \{F\}} Z_\alpha \, |\phi_\alpha(\mathbf{p}_m)|^2 \, F_\alpha(E_m - \epsilon_\alpha)$$

- According to the nuclear shell model

$$Z_\alpha \to 2j_\alpha + 1 \quad , \quad F_\alpha(E_m - \epsilon_\alpha) \to \delta(E_m - \epsilon_\alpha)$$

THE FIRST $(e, e'p)$ MEASUREMENT AT LNF, A.D. 1964

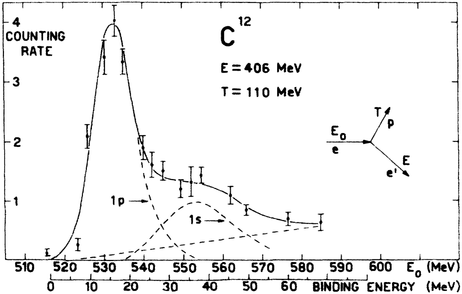
VOLUME 13, NUMBER 10 PHYSICAL REVIEW LETTERS 7 SEPTEMBER 1964

INNER-SHELL PROTON BINDING ENERGIES IN C^{12} AND Al^{27} FROM THE $(e, e'p)$REACTION USING 550-MeV ELECTRONS*†

U. Amaldi, Jr., G. Campos Venuti, G. Cortellessa, C. Fronterotta, A. Reale, and P. Salvadori
Physics Laboratory, Istituto Superiore di Sanità, Rome, Italy

and

P. Hillman‡
Laboratori Nazionali di Frascati, Rome, Italy
(Received 3 August 1964)



- The peak arising from knockout of the four protons in the $1P_{3/2}$ level is clearly visible
- The contribution of the two $1S_{1/2}$ protons is not well resolved

PRE-JLAB ERA: THE $(e, e'p)$ PROGRAM AT SACLAY

- The *Accelerateur Lineaire de Saclay*, or ALS (late 1960s)

THE SACLAY LINEAR ACCELERATOR (ALS)

A.M.L. MESSIAH

Department of Nuclear Physics, Saclay

France

The station in HE 1 will comprise two very big spectrometers, the so-called "600" and "900" rotating around the same vertical axis. Their characteristics are compared in the Table below with those of other big magnets in use at present for electron spectroscopy.

Magnet "900" is fit for (e,e') reactions at a resolution of 2×10^{-4}. The ensemble "900"+"600" is fit for (e,e'X) reactions - notably (e,e'p) - at a resolution of 2×10^{-3}. The two spectrometers are now

Spectral Function Measurements at Saclay

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Nuclear Physics **A262** (1976) 461—492; © *North-Holland Publishing Co., Amsterdam*

QUASI-FREE (e, e′p) SCATTERING ON ^{12}C, ^{28}Si, ^{40}Ca AND ^{58}Ni

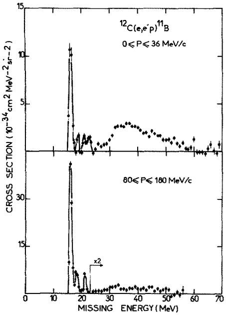
J. MOUGEY, M. BERNHEIM, A. BUSSIÈRE, A. GILLEBERT, PHAN XUAN HÔ,
M. PRIOU, D. ROYER, I. SICK † and G. J. WAGNER ††

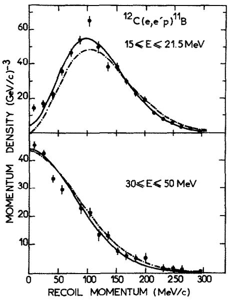
Département de Physique Nucléaire, CEN Saclay, BP 2, 91190 Gif-sur-Yvette, France

Received 29 August 1975
(Revised 19 January 1976)

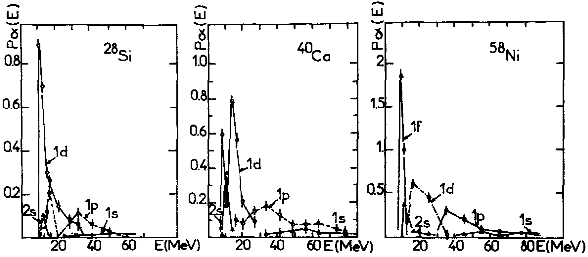
Abstract: The (e, e′p) reaction on ^{12}C, ^{28}Si, ^{40}Ca and ^{58}Ni has been measured at 497 MeV incident electron energy. The experiment covered the region $E \leqq 80$ MeV for the separation energy and $P \leqq 250$ MeV/c for the recoil momentum. Cross sections, calculated in the distorted wave impulse approximation, have been utilized in a shell-model expansion of the spectral function. Average separation and kinetic energies of protons in individual shells are extracted from the data. The validity of Koltun's sum rule is discussed.

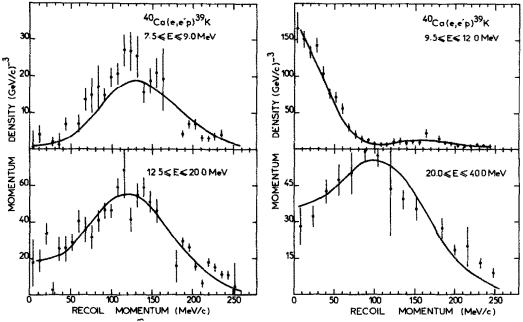
- Carbon data (to be compared to the LNF data of 1964)





Systematics of Energy and Momentum Distributions





Exposing the Limits of the Independent Particle Model

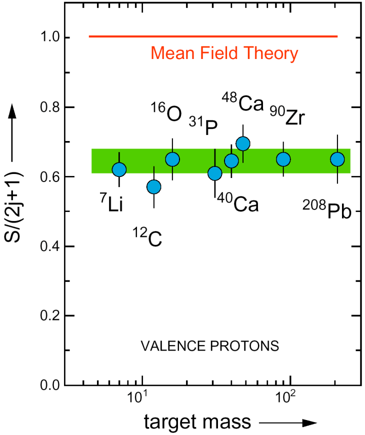
- The spectral functions extracted from the Saclay data, while exhibiting the spectral lines predicted by the nuclear shell model, provided unambiguous evidence of its limitations

		η_α	ΔT_α	N_α	$\langle E\rangle_\alpha$	$\langle T\rangle_\alpha$
^{12}C	1p	0.66	2.1	2.5	17.5±0.4	18.3
	1s	0.52	1.9	1.0	38.1±1.0	12.7
^{28}Si	2s	0.46	3.2	0.4	13.8±0.5	18.6
	1d	0.46	2.2	5.5	16.1±0.8	19.5
	1p	0.39	2.0	2.9	32	14.1
	1s	0.28	1.1	0.9	(51)	8.5
^{40}Ca	2s	0.38	3.2	1.3	11.2±0.3	19.7
	1d	0.38	2.1	7.7	14.9±0.8	19.6
	1p	0.32	2.4	5.7	41	14.0
	1s	0.23	1.2	1.5	(56)	8.0
^{58}Ni	1f	0.32	2.4	7.6	9.3±0.3	23.4
	2s	0.31	3.2	1.9	14.7±0.5	18.6
	1d	0.32	2.2	8.9	21	19.4
	1p	0.27	2.0	6.8	45	14.4
	1s	0.19	1.1	1.0	(62)	9.1

- The systematic deviation of the spectroscopic factors from the shell model prediction is a clear signature of strong correlation effects, not taken into account within the independent particle model

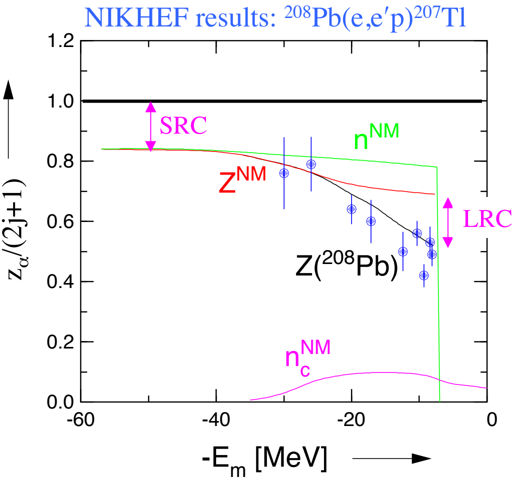
Spectroscopic Factors of Valence States

- The quenching of the spectroscopic factor of valence states has been confirmed by a number of high-resolution $(e, e'p)$ experiments carried out at NIKHEF-K using a 700 MeV high duty factor electron beam



- quenching is large and independent of target mass
- both short- and long-range correlations contribute

SPECTROSCOPIC FACTORS OF ^{208}Pb



⋆ Deep hole states largely unaffected by finite size and shell effects

WHERE IS THE MISSING STRENGTH?

- The $(e, e'p)$ cross section at large E_m and p_m , tipically $E_m \gtrsim 50$ MeV and $p_m \gtrsim 250$ MeV give direct access to the *missing strength*. Strong energy–momentum correlation clearly observed.

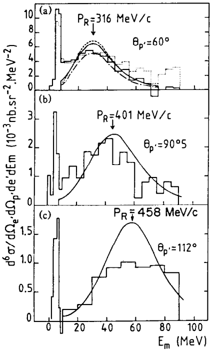


Fig. 5. Missing energy spectra form ^{3}He(e, e′p), showing evidence for an interaction on a two-nucleon correlated pair

CEBAF PROPOSAL COVER SHEET

This Proposal must be mailed to:

CEBAF
Scientific Director's Office
12000 Jefferson Avenue
Newport News, VA 23606

and received on or before OCTOBER 31, 1989

A. TITLE: Selected studies of the ^{3}He and ^{4}He nuclei through electrodisintegration at high momentum transfer

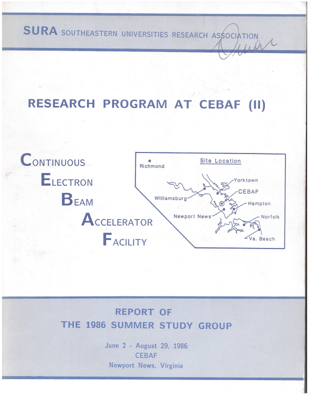
B. CONTACT PERSON: J. MOUGEY

ADDRESS, PHONE AND BITNET: CEBAF, 12000 Jefferson Ave., Newport News, Va 23606 (804)249-7544 MOUGEY@CEBAFVAX

We propose to use the CEBAF Hall A High Resolution Spectrometer pair to study selective aspects of the electromagnetic response of ^{3}He and ^{4}He through (e,e'p) coincidence measurements at Q^2 values from 0.4 to 4.1$(\mathrm{GeV}/c)^2$. In Part I, we propose to study the single nucleon structure of the He isotopes with special emphasis on high momenta (up to ~ 0.6 GeV/c) by the separation of the R_L, R_T and R_{LT} response functions. The Q^2 dependence of the reaction will be examined in Part II by performing longitudinal/transverse (L/T) separations for protons emitted along $\vec{q}$, up to $Q^2 = 4.11(\mathrm{GeV}/c)^2$ at quasifree kinematics ($p_m = 0$) and for $Q^2 = 0.5$ and $1.(\mathrm{GeV}/c)^2$ at $p_m = \pm 0.3\mathrm{GeV}/c$. In Part III, we focus on the continuum region to study correlated nucleon pairs. Measurements at $Q^2 = 1.\ (\mathrm{GeV}/c)^2$ and recoil momenta up to 1 GeV/c are proposed, including separations of the in-plane structure functions for $p_m < 680$ MeV/c.

The JLab Era

- In the 1980s, the planning of CEBAF—designed to reach a beam energy of 4 GeV and 100% duty-cycle—begun
- CEBAF was ideally suited to perform the next generation of $(e, e'p)$ experiments, to investigate nuclear dynamics beyond the shell model, and much more …



SINGLE NUCLEON EMISSION STUDIES AT CEBAF

A. Saha
Department of Physics
University of Virginia
Charlottesville, VA 22901

and

J. Mougey
Continuous Electron Beam Accelerator facility
12070 Jefferson Avenue
Newport News, VA 23606

With the advent of CEBAF, a whole new range of phenomena in the nuclear and sub-nuclear domain can be investigated which are at present inaccessible at other facilities. In this report we focus on the subject of single nucleon emission studies with respect to the experimental facilities being proposed at CEBAF.

Some of the relevant physics issues one could study with the (e,e'N) reactions includes:

1. Single nucleon densities and momentum distributions.
   e.g. in d, t, ^{3}He, ^{4}He, ^{6}Li, ^{12}C, ^{16}O, ^{40}Ca etc..

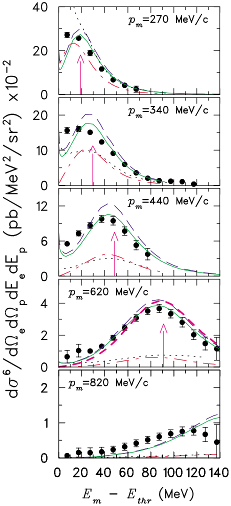
2. Elementary eN interactions in the nuclear medium
   -- modification of nucleon properties in nuclei.

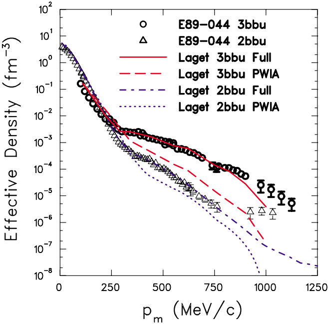
3. Separated determinations of the structure functions.

4. Theories and models for the reaction mechanism for single nucleon emission.
   (a) Quasi-free scattering: impulse approximation, off-shell effects, final state interactions, MEC etc..
   (b) Nucleon emission in the continuum: resonance production and propagation, many body effects, two nucleon correlations, QCD and hadronization processes.

$(e,e'p)$ Studies at JLab

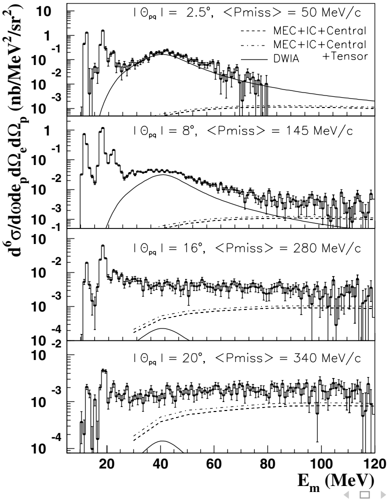
- ^{3}He$(e,e'p)$ at large $|\mathbf{p}_m|$ and E_m in hall A: strong energy-momentum correlation observed



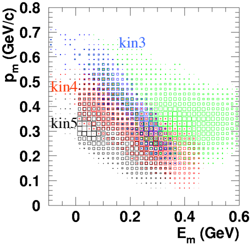


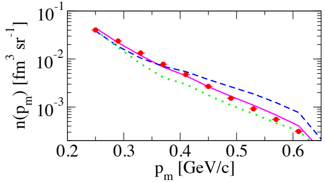
LARGE $|\mathbf{p}_m|$ AND E_m COMPONENTS IN COMPLEX NUCLEI

- $|\mathbf{p}_m|$-evolution of missing energy spectrum in Oxygen. Hall A data



- Direct measurement of correlation strength in carbon. Hall C data



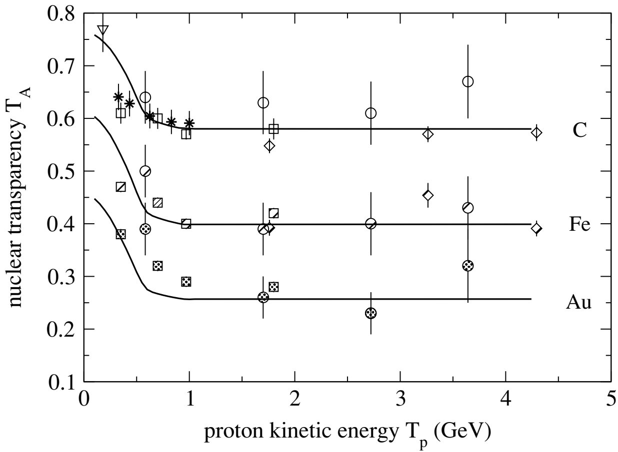


Experiment	0.61 ±0.06
Greens function theory [3]	0.46
CBF theory [2]	0.64
SCGF theory [4]	0.61

- Integrated correlation strength consistent with the measured quenching of spectroscopic factors

$(e, e'p)$ Measurements of Nuclear Transparency

- Nuclear transparency, measured by the ratio $\sigma_{\text{exp}}/\sigma_{\text{PWIA}}$

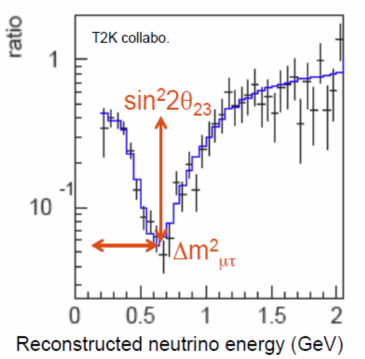


Why Ar and Ti targets?

THE ISSUE OF NEUTRINO ENERGY RECONSTRUCTION

- Oscillation probability after traveling a distance L (two neutrino flavors, for simplicity)

$$P_{\alpha\to\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



- The energy of the incoming neutrino, E_ν is not precisely known, but broadly distributed according to a flux $\Phi(E_\nu)$

Kinematic Neutrino Energy Reconstruction

- In the charged current quasi elastic (CCQE) channel, assuming single nucleon single knock, the relevant elementary process is

$$\nu_\ell + n \to \ell^- + p$$

- The *reconstructed* neutrino energy is

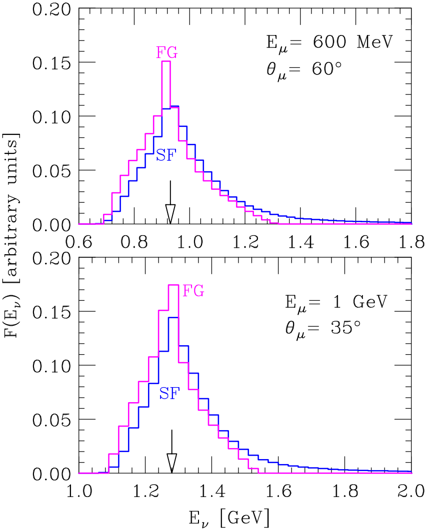
$$E_\nu = \frac{m_p^2 - m_\mu^2 - {E_n}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |{\mathbf{p}_n}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)} ,$$

  where $|\mathbf{k}_\mu|$ and θ_μ are measured, while $\mathbf{p}_n$ and E_n are the *unknown* momentum and energy of the interacting neutron

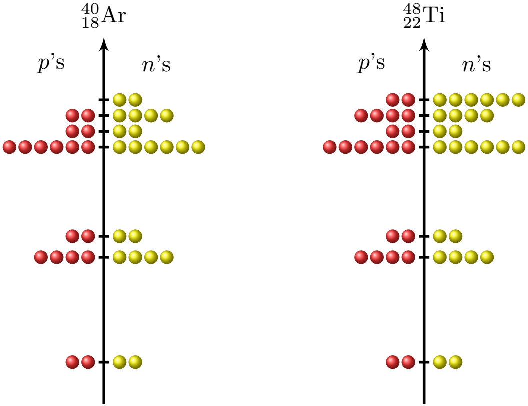
- Existing simulation codes routinely use $|\mathbf{p}_n| = 0$, $E_n = m_n - \epsilon$, with $\epsilon \sim 20 \text{ MeV}$ for carbon and oxygen, or the Fermi gas (FG) model

RECONSTRUCTED NEUTRINO ENERGY IN THE CCQE CHANNEL

- Neutrino energy reconstructed using 2×10^4 pairs of $(|\mathbf{p}|, E)$ values sampled from realistic (SF) and FG oxygen spectral functions
- The average value $\langle E_\nu \rangle$ obtained from the realistic spectral function turns out to be shifted towards larger energy by ~ 70 MeV



- ⋆ The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both protons and neutrons
- ⋆ The $\mathrm{Ar}(e, e'p)$ cross section only provides information on proton interactions. The information on neutrons can be obtained from the $\mathrm{Ti}(e, e'p)$, exploiting the pattern of shell model levels



WHAT NEEDS TO BE DONE

- ⋆ Extracting the spectral function from the measured cross sections will require
  - ▸ A quantitative description of the effects of FSI, leading to a "distortion" of the spectral function
  - ▸ A model suitable to describe the spectral function in the energy–momentum region not covered by the E12-14-012 data
- ⋆ A consistent framework—based on a combination of accurate theoretical calculations and experimental input and tested in the analyses of the available $(e, e'p)$ data—appears to be available.

Final State Interactions

- In the presence of FSI, the distorted spectral function describing the mean field region can be written in the form

$$P^D_{MF}(\mathbf{p}_m, \mathbf{p}, E_m) = \sum_\alpha Z_\alpha |\phi^D_\alpha(\mathbf{p}_m, \mathbf{p})|^2 F_\alpha(E_m - E_\alpha)$$

with

$$\sqrt{Z_\alpha}\, \phi^D_\alpha(\mathbf{p}_m, \mathbf{p}) = \int d^3p_i \, \chi^\star_p(\mathbf{p}_i + \mathbf{q})\phi(\mathbf{p}_i)$$

where $\chi^\star_p(\mathbf{p}_i + \mathbf{q})$ describes the distortion arising from FSI effects

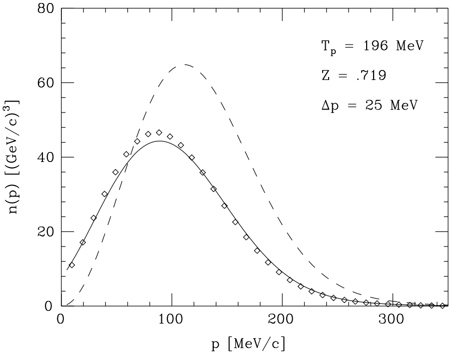
- The large body of existing work on $(e, e'p)$ data suggests that the effects of FSI can be strongly reduced measuring the cross section in *parallel kinematics*, that is with $\mathbf{p} \parallel \mathbf{q}$.
- in parallel kinematics, the distorted momentum distribution at fixed $|\mathbf{p}|$ becomes a function of missing momentum only

$$n^D_\alpha(p_m) = Z_\alpha \, |\phi^D(p_m)|^2 \, ,$$

and the effects FSI can be easily identified.

Distorted Momentum Distribution

- Knock out of a P-shell protons in oxygen. Proton energy $T_p = 196$ MeV
- Distortion described by a complex optical potential (OP)



- FSI lead to a shift in missing momentum (real part of the OP), and a significant quenching, typically by a factor ~ 0.7 (imaginary part of the OP).

MODELING THE NUCLEAR SPECTRAL FUNCTION

- Local density approximation

$$P(\mathbf{k}, E) = P_{MF}(\mathbf{k}, E) + P_{corr}(\mathbf{k}, E)$$

  - $P_{MF}(\mathbf{k}, E) \rightarrow$

$$P_{MF}(\mathbf{k}, E) = \sum_n Z_n |\phi_n(\mathbf{k})|^2 \, F_n(E - E_n)$$

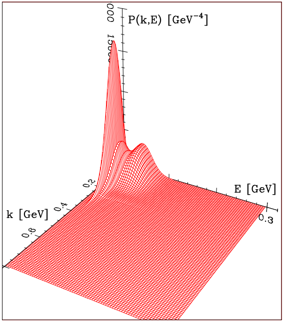
  - $P_{corr}(\mathbf{p}, E) \rightarrow$ from uniform nuclear matter calculations at different densities:

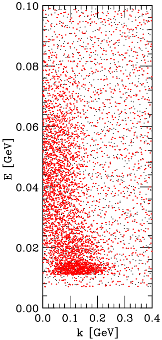
$$P_{corr}(\mathbf{k}, E) = \int d^3r \; \rho_A(r) \; P^{NM}_{corr}(\mathbf{k}, E; \rho = \rho_A(r))$$

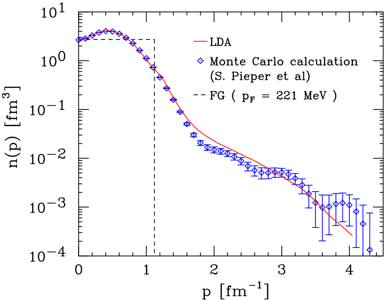
- Widely and successfully employed to analize (e, e') data at beam energies $\sim 1GeV$
- Warning: model dependence, chance of double counting

Spectral Function of ^{16}O

- The spectral function of medium-mass nuclei has obtained combining $(e, e'p)$ data and results of accurate nuclear matter calculations within the Local Density Approximation (LDA)







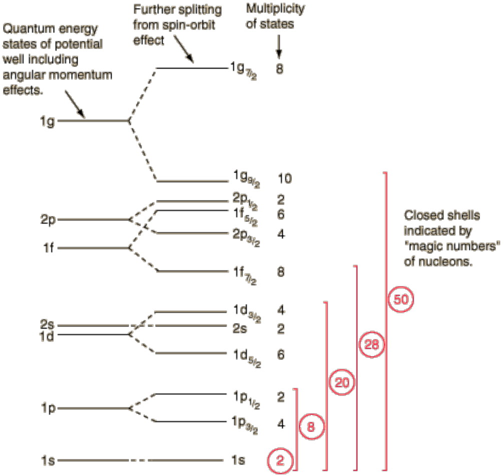
- shell model states account for $\sim 80\%$ of the strenght
- the remaining $\sim 20\%$, arising from NN correlations, is located at high momentum and large removal energy ($\mathbf{k} \gg k_F, E \gg \epsilon$)

Thank you!

Backup slides

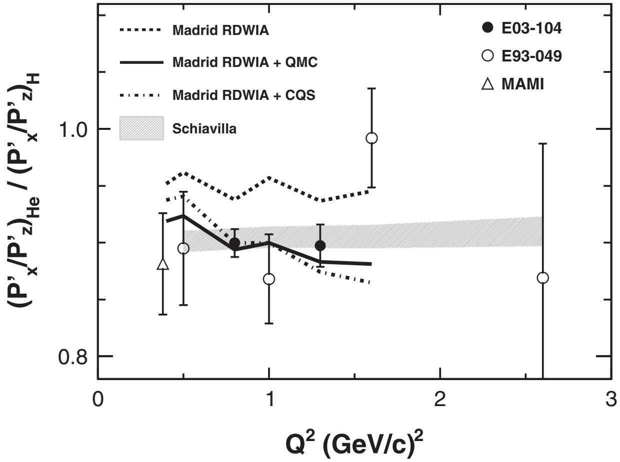
EVIDENCE OF NUCLEAR SHELL STRUCTURE

- Energy spectra and emergence of *magic numbers*



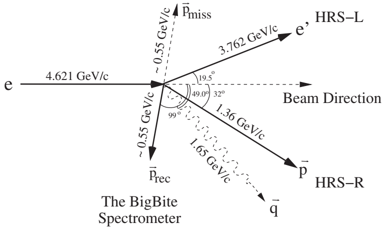
EXPLOITING POLARISATION DEGREES OF FREEDOM: $^4\mathrm{He}(\vec{e}, \vec{e}\,'p)$

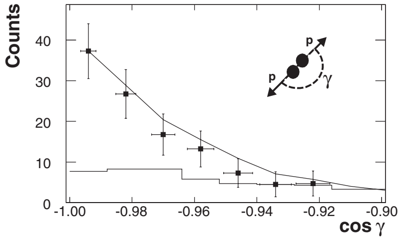
- Looking for possible medium modifications of the proton electromagnetic structure



Coincidence Experiments Beyond $(e, e'p)$

- Studies of the $^{12}\mathrm{C}(e, e'pp)$ reactions Hall A.





- The detection of back-to-back outgoing protons is a clearcut signature of nucleon-nucleon correlations