Electron Scattering Studies of Nuclear Structure and Dynamics

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ECT* Doctoral Training Program
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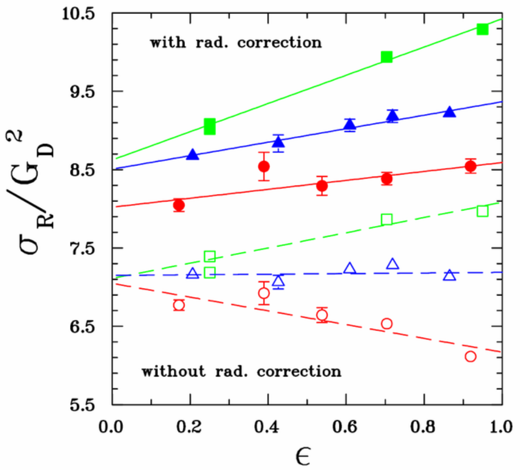
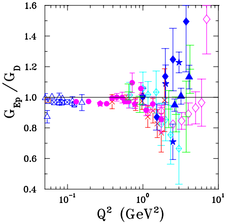
Rosenbluth Separation

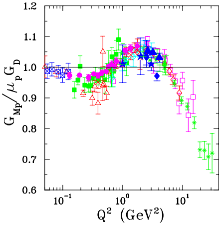
- $Q^2 = 1.75, 3.25$, and $5\ \text{GeV}^2$



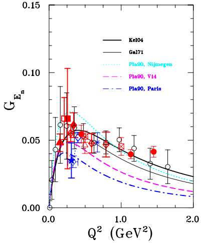
Vector Form Factors

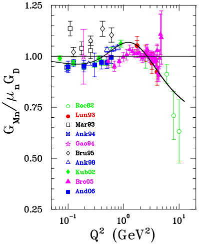
- ⋆ Proton data





- ⋆ Neutron (deuteron) data





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
- A quote from Blatt & Weiskopf (AD 1952): “The limitation of any independent particle model lies in its inability to encompass the correlation between the positions and spins of the various particles in the system”

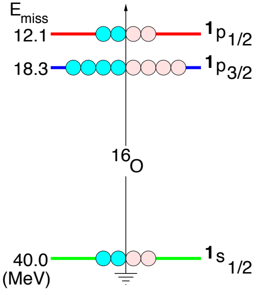
The Nuclear Ground State

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

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

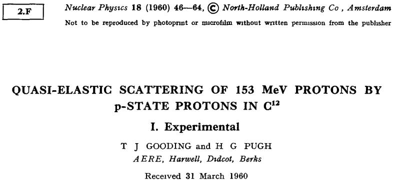
- Ground state of ^{16}O: $Z = N = 8$

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



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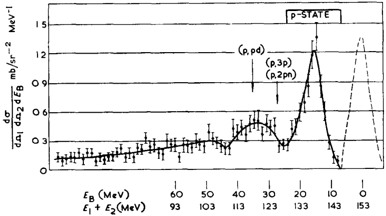
QUASI-ELASTIC SCATTERING OF 153 MeV PROTONS BY p-STATE PROTONS IN C^{12}

I. Experimental

T J GOODING and H G PUGH

AERE, Harwell, Didcot, Berks

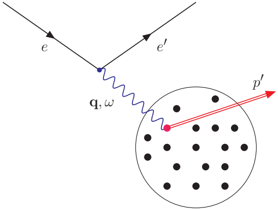
Received 31 March 1960



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

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



- 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

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

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

VOLUME 13, NUMBER 10 PHYSICAL REVIEW LETTERS 7 SEPTEMBER 1964

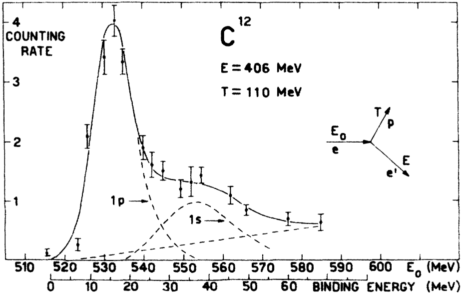
INNER-SHELL PROTON BINDING ENERGIES IN C^{12} AND Al^{27} FROM THE $(e, e'p)$REACTION USING 550-MeV ELECTRONS*†

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

SPECTRAL FUNCTION MEASUREMENTS AT SACLAY

2.L

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

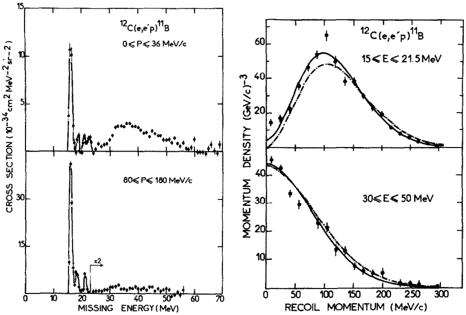
J. MOUGEY, M. BERNHEIM, A. BUSSIÈRE, A. GILLEBERT, PHAN XUAN HÔ,
M. PRIOU, D. ROYER, I. SICK † and G. J. WAGNER ††

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

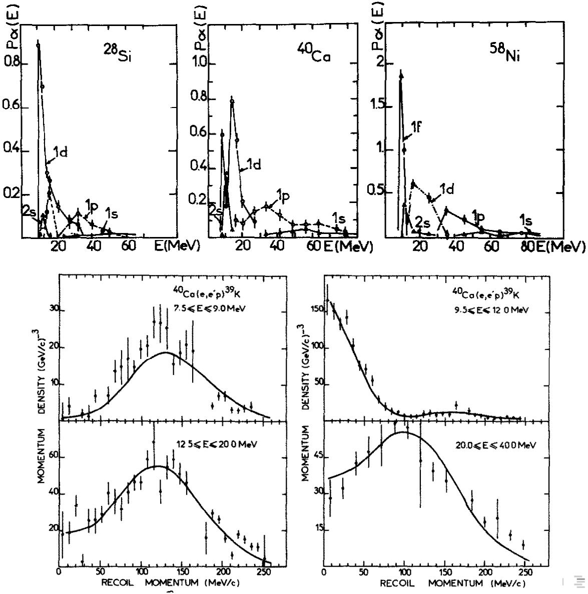
Received 29 August 1975
(Revised 19 January 1976)

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

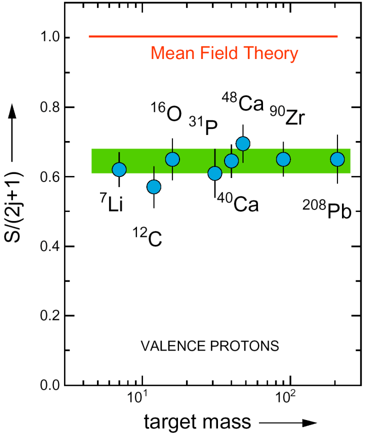
- The spectral functions extracted from the Saclay data, while exhibiting the spectral lines predicted by the nuclear shell model, provided unambiguous evidence of its limitations

		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

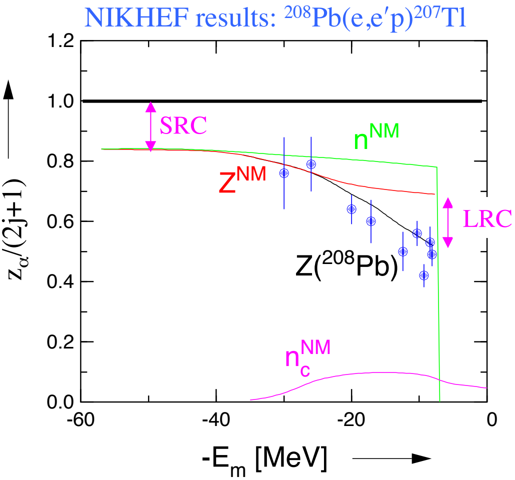
Spectroscopic Factors of Valence States

- 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.

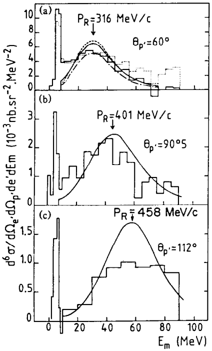


Fig. 5. Missing energy spectra form ^{3}He(e, e′p), showing evidence for an interaction on a two-nucleon correlated pair

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

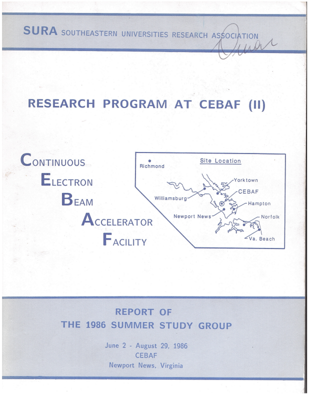
B. CONTACT PERSON: J. MOUGEY

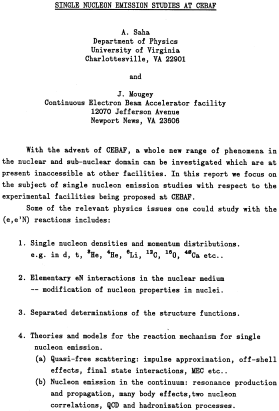
ADDRESS, PHONE AND BITNET: CEBAF, 12000 Jefferson Ave., Newport News, Va 23606 (804)249-7544 MOUGEY@CEBAFVAX

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

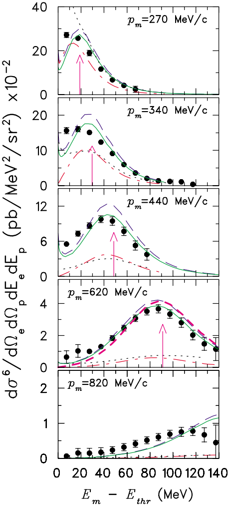
With the advent of CEBAF, a whole new range of phenomena in the nuclear and sub-nuclear domain can be investigated which are at present inaccessible at other facilities. In this report we focus on the subject of single nucleon emission studies with respect to the experimental facilities being proposed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

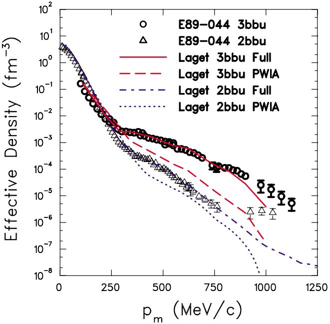
Some of the relevant physics issues one could study with the (e,e'N) reactions includes:

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

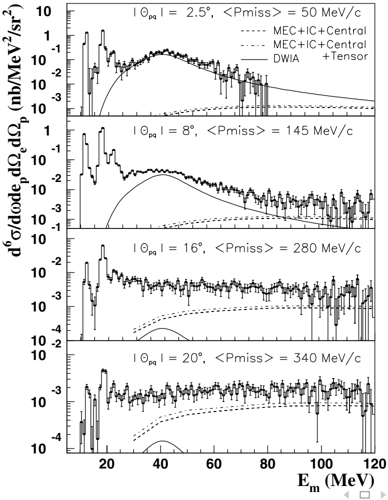
- ^{3}He$(e, e'p)$ at large $|\mathbf{p}_m|$ and E_m in hall A: strong energy-momentum correlation observed



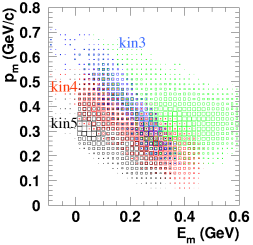


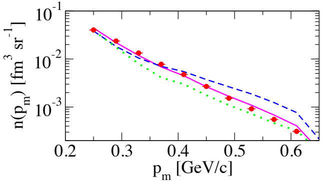
LARGE $|\mathbf{p}_m|$ AND E_m COMPONENTS IN COMPLEX NUCLEI

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



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

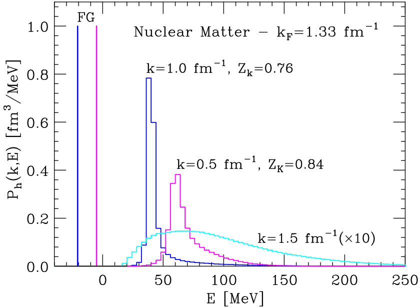


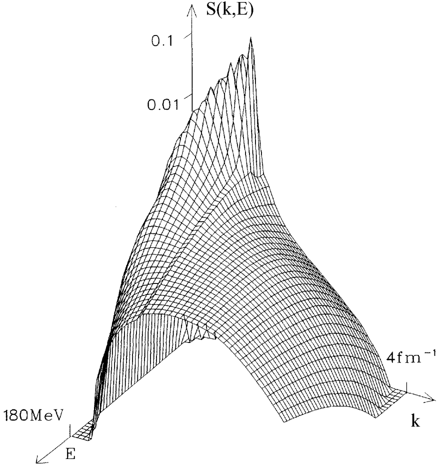


Experiment	0.61 ±0.06
Greens function theory [3]	0.46
CBF theory [2]	0.64
SCGF theory [4]	0.61

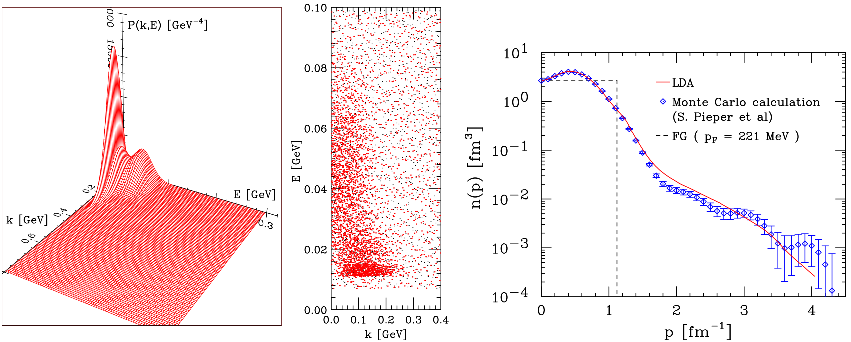
- Integrated correlation strength consistent with the measured quenching of spectroscopic factors

Hole States in Isospin-Symmetric Nuclear Matter



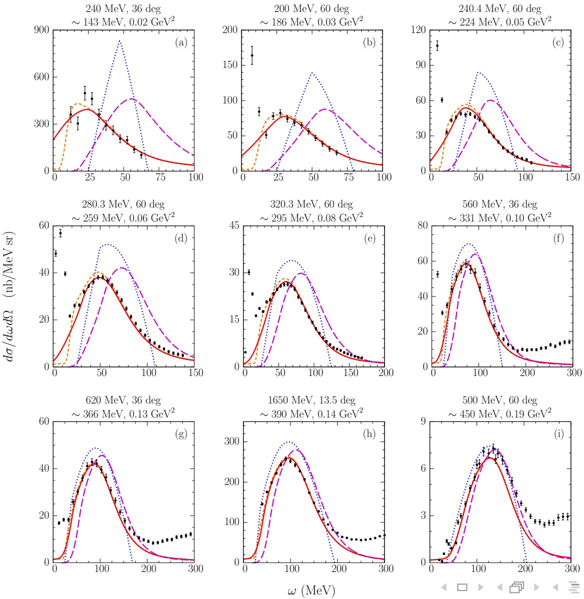


Oxygen Spectral Function



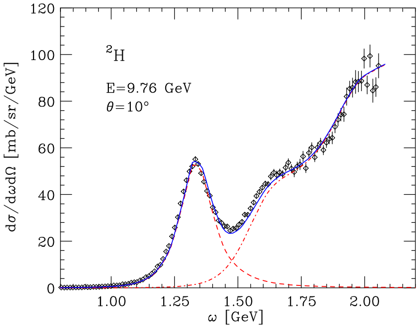
- FG model: $P(\mathbf{p},E) \propto \theta(p_F - |\mathbf{p}|)\,\delta(E - \sqrt{|\mathbf{p}|^2 + m^2} + \epsilon)$
- shell model states account for $\sim$ 80% of the strenght
- the remaining $\sim$ 20%, arising from NN correlations, is located at high momentum *and* large removal energy ($|\mathbf{p}| \gg p_F \sim 220$ MeV, $E \gg \epsilon$)

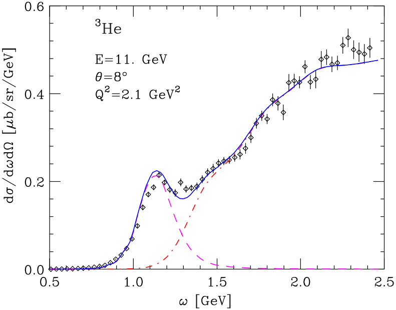
$e + {}^{12}\mathrm{C} \to e' + X$ IN THE QUASI ELASTIC CHANNEL (IA+FSI)



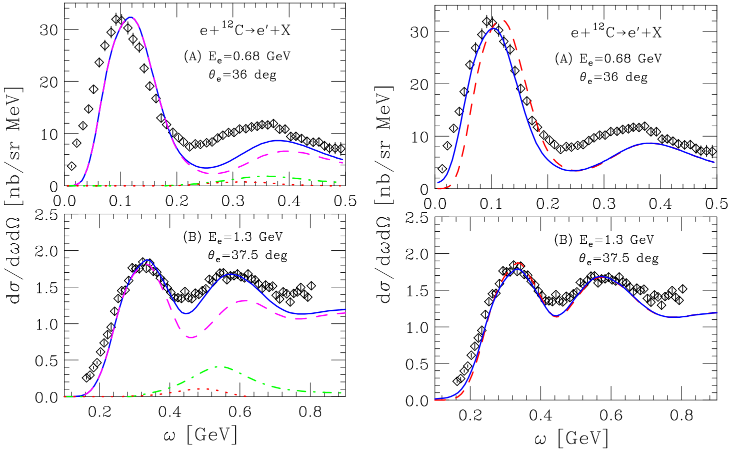
Electron Scattering off Deuteron and Tritium

⋆ Recall: theoretical calculations involve no adjustable parameters



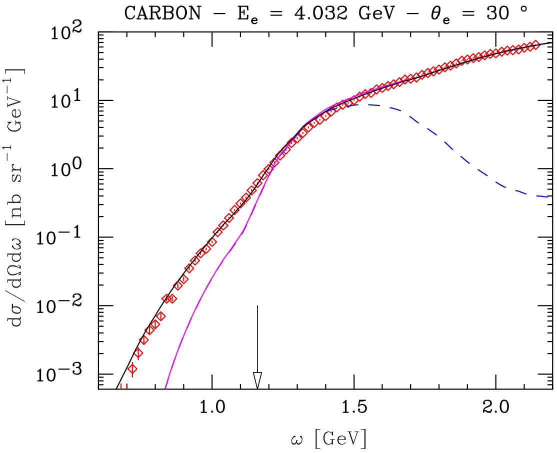


$e +^{12}\mathrm{C} \to e' + X$ (IA+FSI+MEC), Quasi Elastic + Inelastic

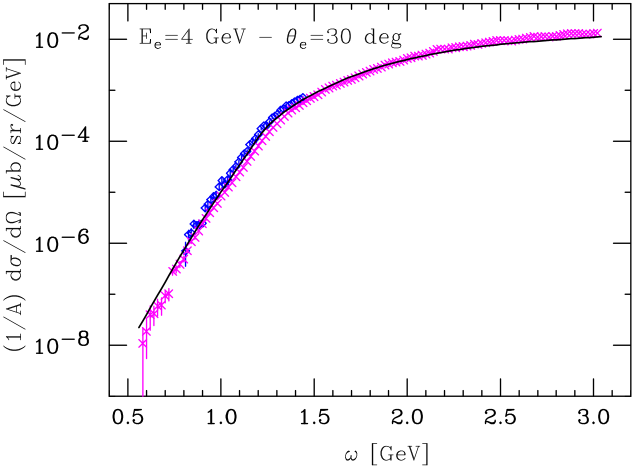


- ⋆ e-carbon x-section obtained within the extended spectral function formalism

$e + ^{12}\mathrm{C} \to e' + X$ (IA+FSI), Quasi Elastic + Inelastic



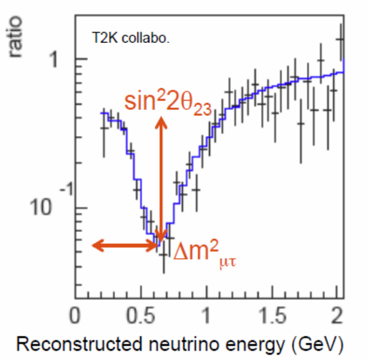
$e +^{56} \mathrm{Fe} \to e' + X$ (IA+FSI), Quasi Elastic + Inelastic



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

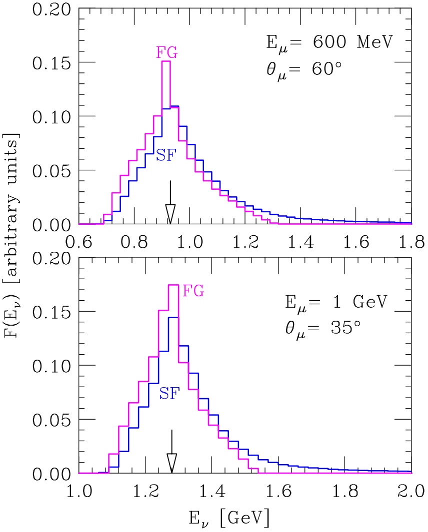
$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)} ,$$

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

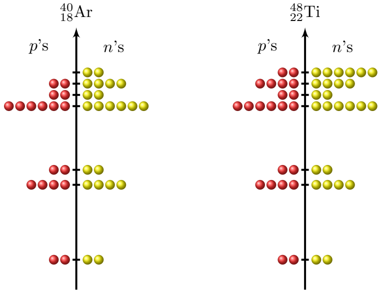
- Existing simulation codes routinely use $|\mathbf{p}_n| = 0$, $E_n = m_n - \epsilon$, with $\epsilon \sim 20$ MeV for carbon and oxygen, or the Fermi gas (FG) model

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



- ⋆ The data taking of Experiment JLab E12-14-012 was completed in March, and the analysis is under way

The End

Thank you for coming!