Fifty Years of $(e, e'p)$ Experiments and the Legacy of Jean Mougey (1935-2015)

Omar Benhar

INFN and Department of Physics, "Sapienza" University
I-00185 Roma, Italy

Users Group Workshop and Annual Meeting
Jefferson Lab, Newport News, VA
June 20-22, 2016

OUTLINE

- Fifty years of $(e, e'p)$: from Frascati to Jefferson Lab[1]
- Jean Mougey's legacy to the community of Electro-Nuclear Physics

[1] Nuclear Physics News **26**, 15 (2016)

The Nuclear Shell Model

- 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

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

- 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

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

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

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

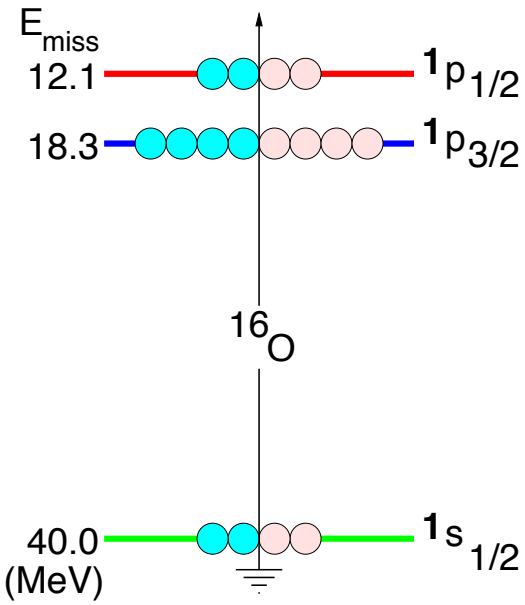
The Nuclear Ground State

- 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

2.F

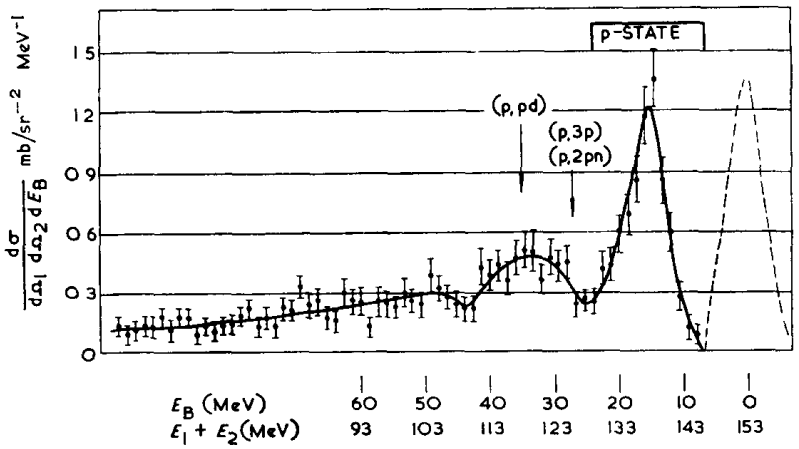
Nuclear Physics **18** (1960) 46—64, © *North-Holland Publishing Co, Amsterdam*

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

2.L

Nuclear Physics **32** (1962) 139—151; © *North-Holland Publishing Co., Amsterdam*

QUASI-FREE ELECTRON-PROTON SCATTERING (I)

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

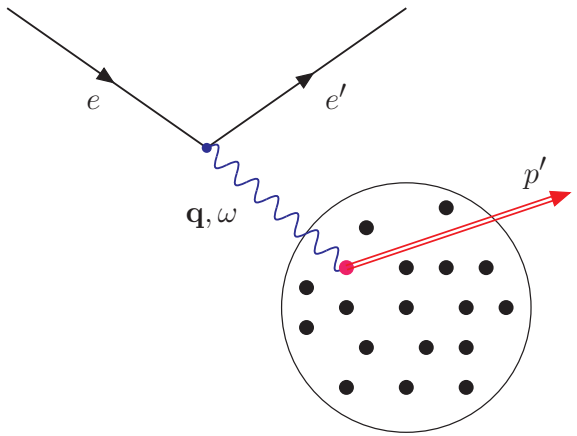
Instituto de Física and Faculdade de Filosofia, Universidade do Rio Grande do Sul, Pôrto Alegre, Brasil

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 any bound state



- In the absence of 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[2]

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

- Kállën-Lehman representation of the spectral function

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

- In the kinematical region corresponding to knock-out from the shell-model states ($E_m \lesssim 50$ MeV and $|\mathbf{p}_m| \lesssim 350$ MeV)

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

- According to the nuclear shell model

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

[2] Note: the effects of FSI are included as corrections

The First $(e, e'p)$ Measurement at LNF, A.D. 1964

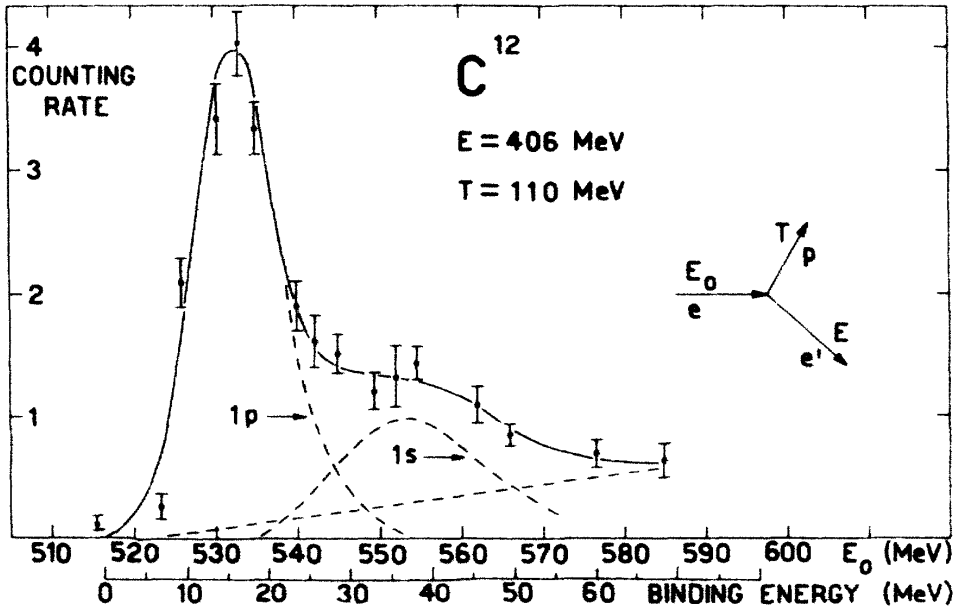
Volume 13, Number 10 PHYSICAL REVIEW LETTERS 7 September 1964

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

Enter Jean Mougey: 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.

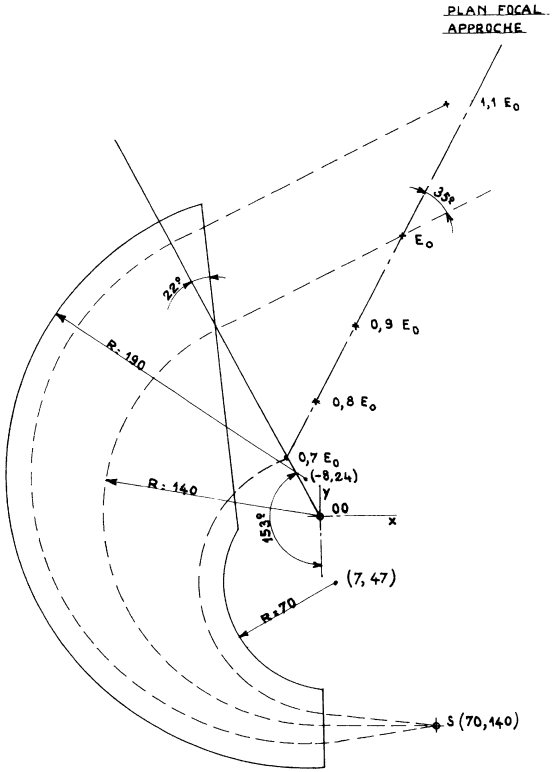
Magnet "900" is fit for (e,e') reactions at a resolution of 2×10^{-4}. The ensemble "900"+"600" is fit for (e,e'X) reactions - notably (e,e'p) - at a resolution of 2×10^{-3}. The two spectrometers are now

The HE1 Experimental Hall at Saclay

REVUE DE PHYSIQUE APPLIQUÉE TOME 4, JUIN 1969, PAGE 209.

UN SPECTROMÈTRE A DOUBLE FOCALISATION DE GRANDE ACCEPTANCE EN ÉNERGIE

P. BOUNIN et J. MOUGEY,
Service de Physique Nucléaire à Haute Énergie, C.E.N., Saclay.



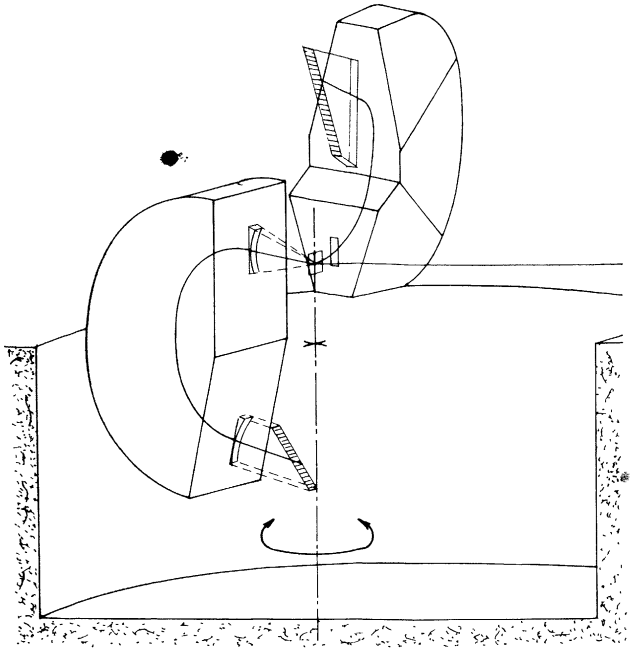


FIG. 2. — Ensemble des deux spectromètres dans la fosse de la salle HE1 de l'accélérateur linéaire de Saclay.

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

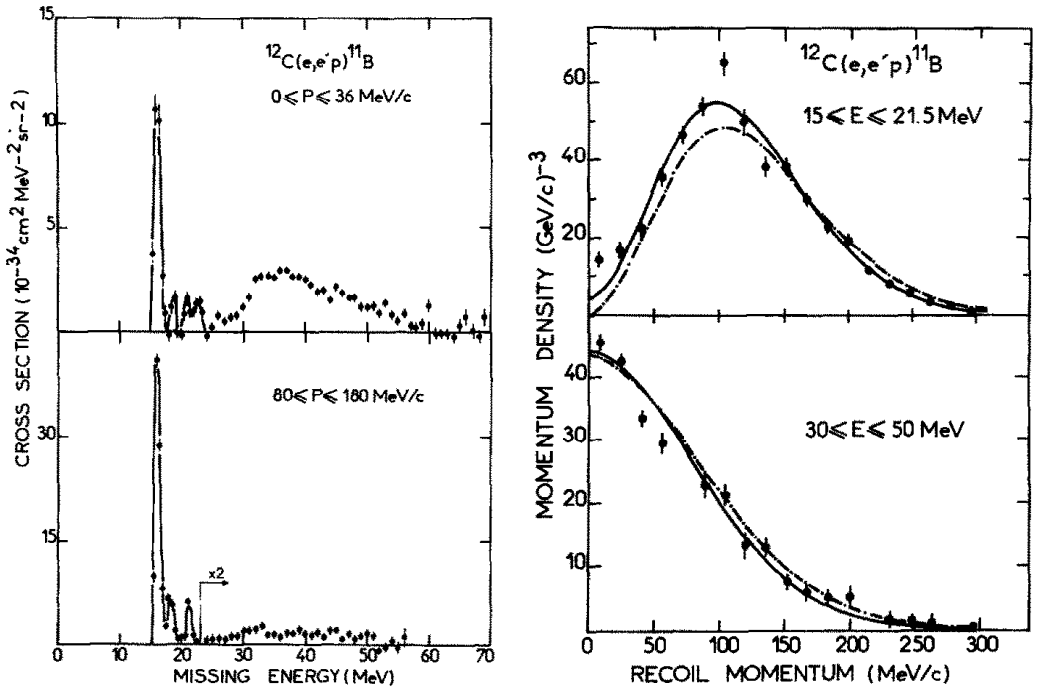
J. MOUGEY, M. BERNHEIM, A. BUSSIÈRE, A. GILLEBERT, PHAN XUAN HÔ,
M. PRIOU, D. ROYER, I. SICK† and G. J. WAGNER††

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

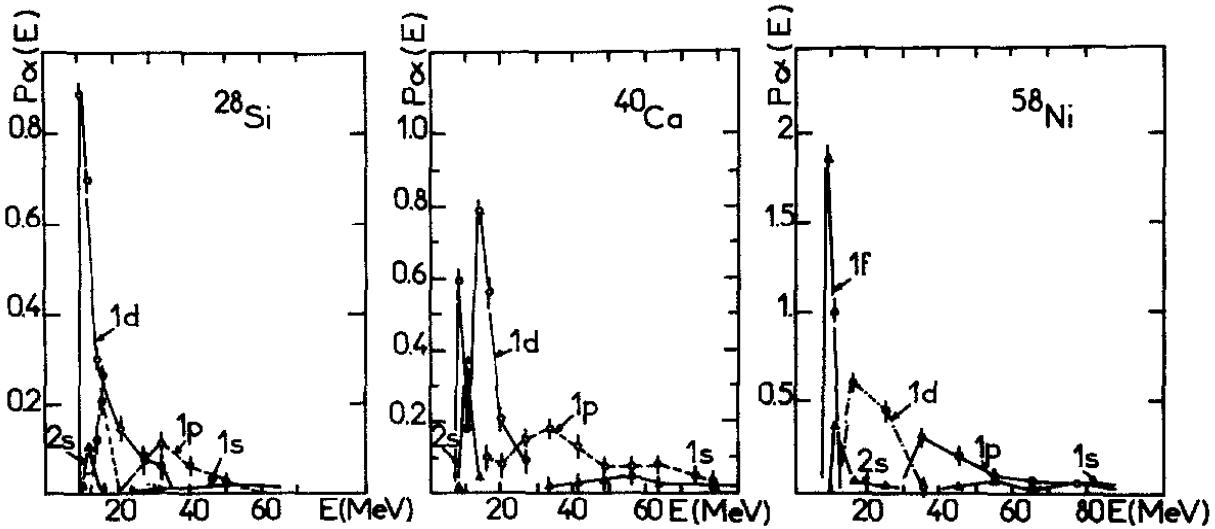
Received 29 August 1975
(Revised 19 January 1976)

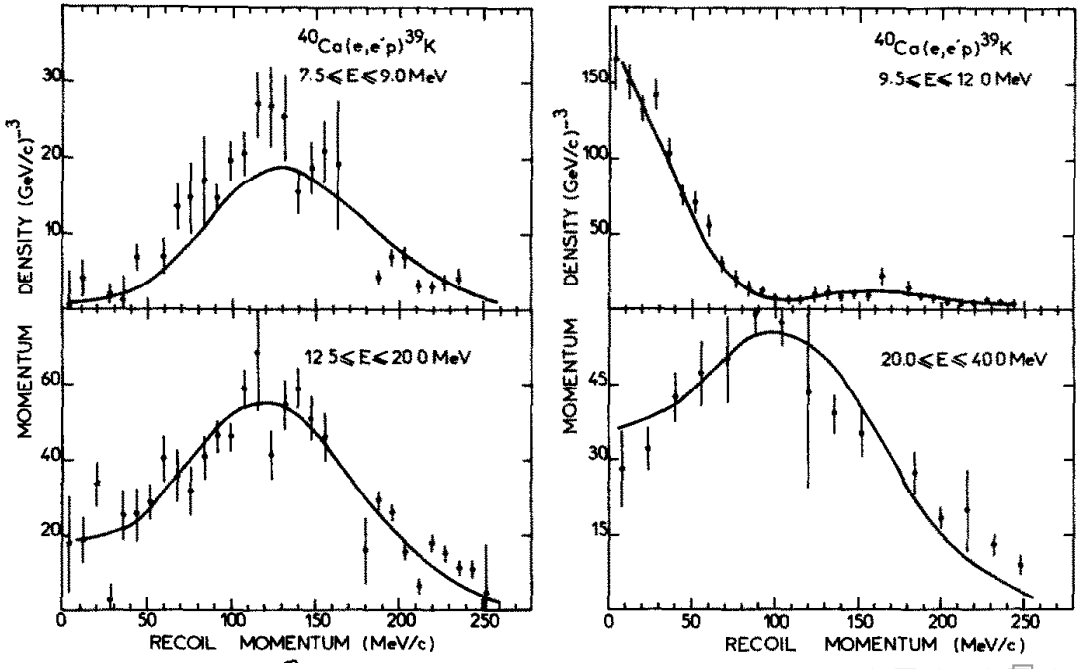
Abstract: The (e, e′p) reaction on ^{12}C, ^{28}Si, ^{40}Ca and ^{58}Ni has been measured at 497 MeV incident electron energy. The experiment covered the region $E \leqq 80$ MeV for the separation energy and $P \leqq 250$ MeV/c for the recoil momentum. Cross sections, calculated in the distorted wave 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 $Z_\alpha = 2j_\alpha + 1$ is a clear signature of strong nucleon-nucleon correlations, not taken into account within the independent particle model

THE 1984 ISSUE OF *Advances in Nuclear Physics*

ADVANCES IN NUCLEAR PHYSICS

Edited by

J.W. Negele

Center for Theoretical Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts

Erich Vogt

Department of Physics
University of British Columbia
Vancouver, B.C., Canada

VOLUME 14

PLENUM PRESS • NEW YORK-LONDON

SINGLE-PARTICLE PROPERTIES OF NUCLEI THROUGH (*e, e'p*) REACTIONS

Salvatore Frullani

Istituto Superiore di Sanità
Physics Laboratory
Rome, Italy

Istituto Nazionale di Fisica Nucleare
Sezione Sanità
Rome, Italy

and

Jean Mougey

Institut de Recherche Fondamentale
Commisariat à l'Energie Atomique, DRF/CPN
85X-38041 Grenoble Cedex, France

Institut Max von Laue–Paul Langevin
38042 Grenoble Cedex, France

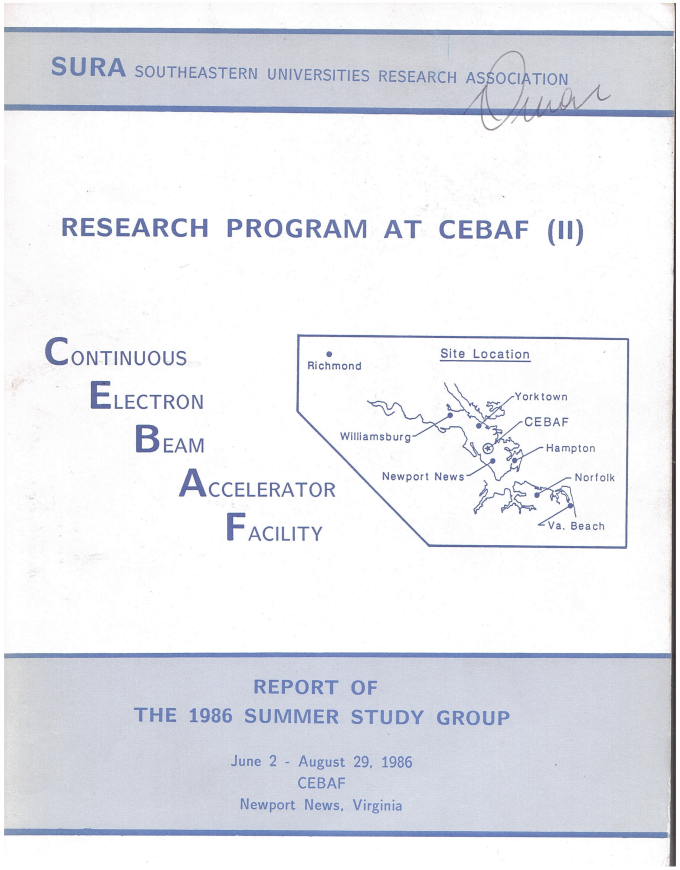
1. INTRODUCTION

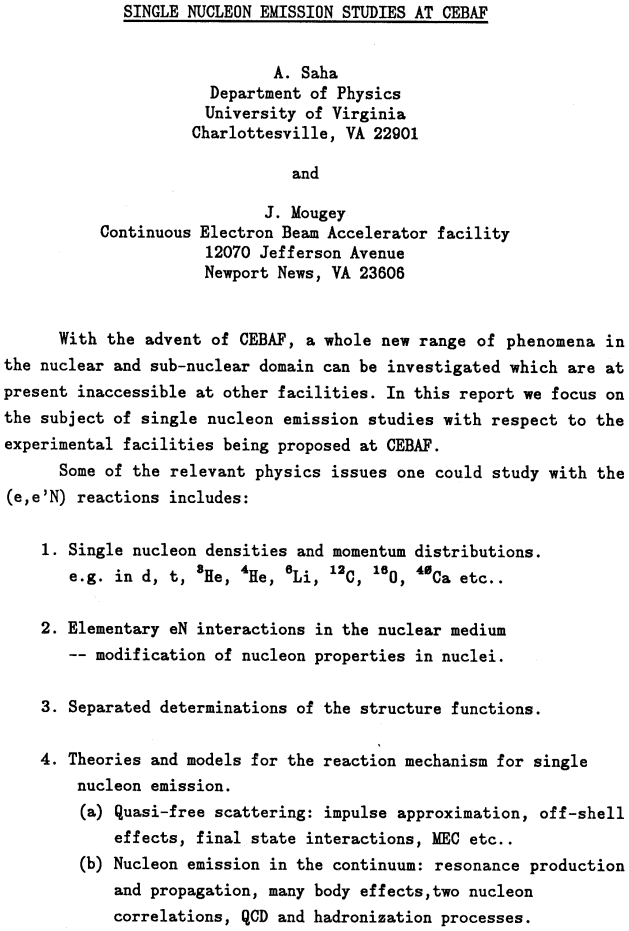
High-energy inclusive electron scattering experiments on nuclei reveal a wealth of nuclear structure information. As an example, the energy spectrum of 280-MeV electrons scattered at 60° from ^{12}C nuclei is shown in Fig. 1. In order of increasing energy loss, different regions of the spectrum may be distinguished and associated with distinct physical processes. First, the elastic peak corresponds to processes in which the target nucleus remains in its ground state. Next, discrete inelastic peaks arise from the excitation of

1

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.

- In 1986, Jean was appointed leader of the hall A. In this capacity, he played a key role in the design and construction of the High Resolution Spectrometers, which are still in use.

Nuclear Instruments and Methods in Physics Research B40/41 (1989) 441–446
North-Holland, Amsterdam

COINCIDENCE EXPERIMENTS AT CEBAF

Jean MOUGEY

Continuous Electron Beam Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, USA

With the 4 GeV Continuous Electron Beam Accelerator Facility (CEBAF) presently under construction in Newport News, Virginia, a new range of nuclear and subnuclear phenomena can be investigated, mostly through coincidence experiments. The accelerator characteristics, some examples of its physics programs, and the related experimental equipment are briefly reviewed.

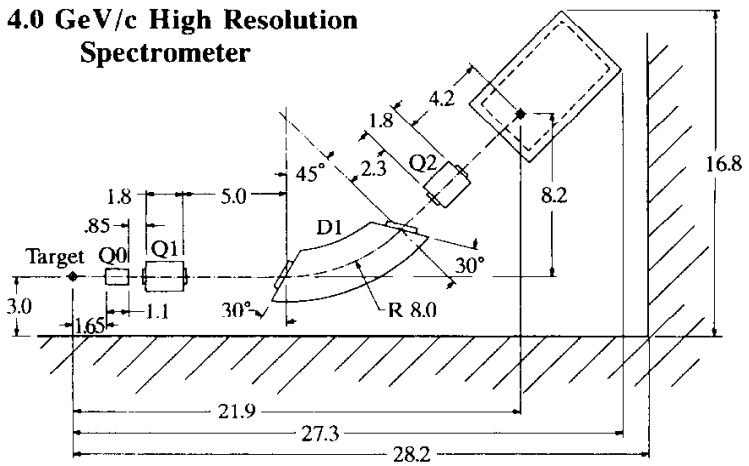


Fig. 6. Sketch of the 4 GeV/c high resolution spectrometer planned for Hall A (distance in meters). Its optical length is 25 m and its total weight is about 400 tons.

- In addition to leading the effort to assemble hall A, Jean continued to pursue the Physics studies initiated in Saclay. A notable example are the investigations of short range correlations in few-nucleon systems

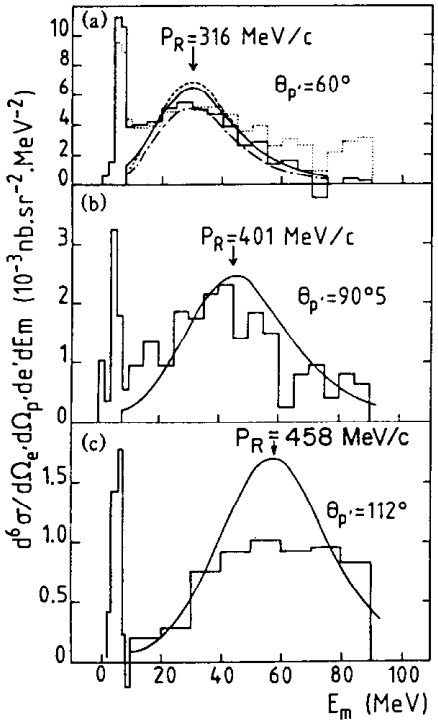


Fig. 5. Missing energy spectra form ^{3}He(e, e′p), showing evidence for an interaction on a two-nucleon correlated pair

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

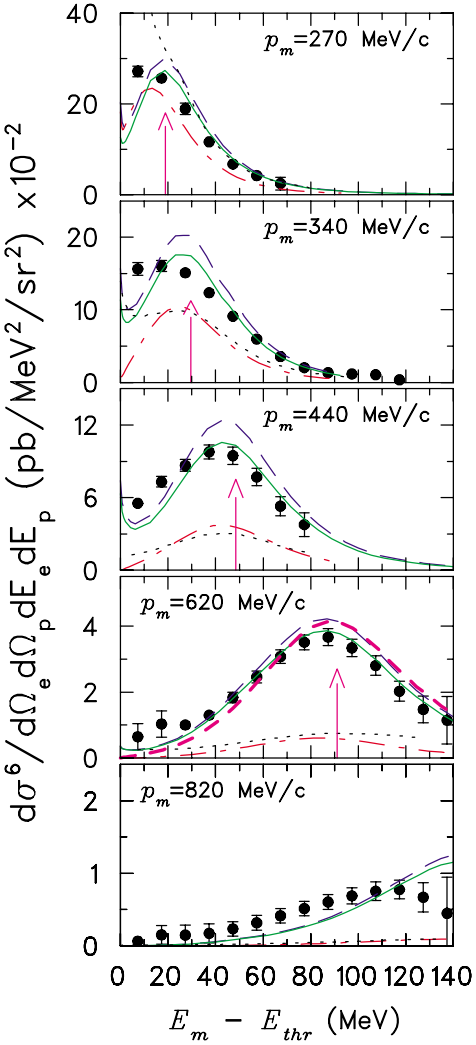
B. CONTACT PERSON: J. MOUGEY

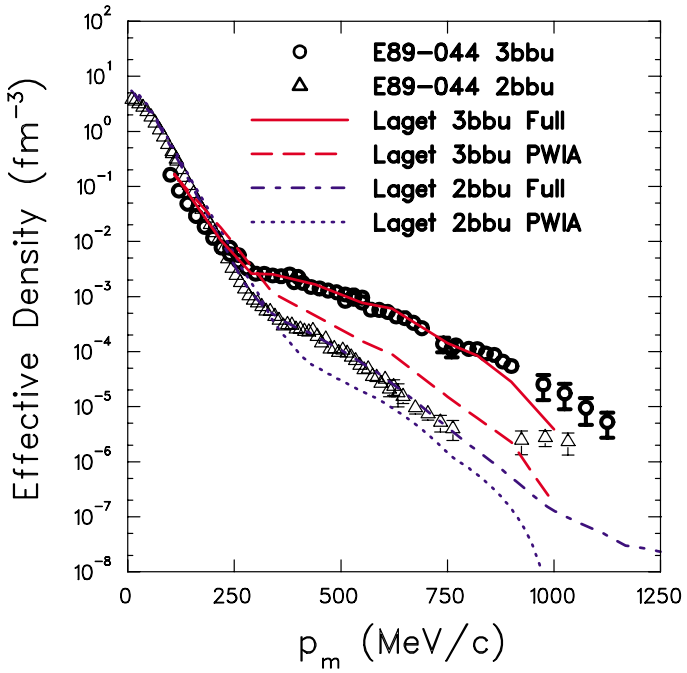
ADDRESS, PHONE AND BITNET: CEBAF, 12000 Jefferson Ave., Newport News, Va 23606 (804)249-7544 MOUGEY@CEBAFVAX

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(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 $\sim$ 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 $Q^2 = 4.11$(GeV/c)^2 at quasifree kinematics ($p_m = 0$) and for $Q^2 = 0.5$ and 1.(GeV/c)^2 at $p_m = \pm 0.3$GeV/c. In Part III, we focus on the continuum region to study correlated nucleon pairs. Measurements at $Q^2 = 1.$ (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.

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

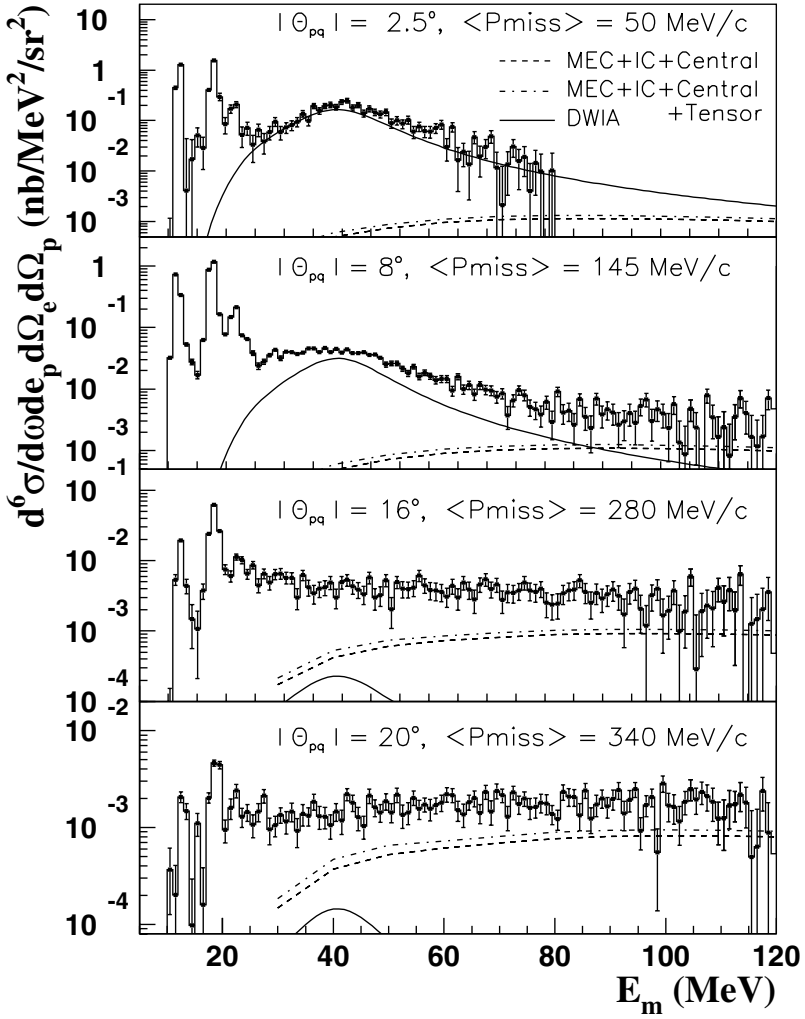
- ^{3}He$(e, e'p)$ at large $|\mathbf{p}_m|$ and E_m in hall A: strong energy-momentum correlation observed



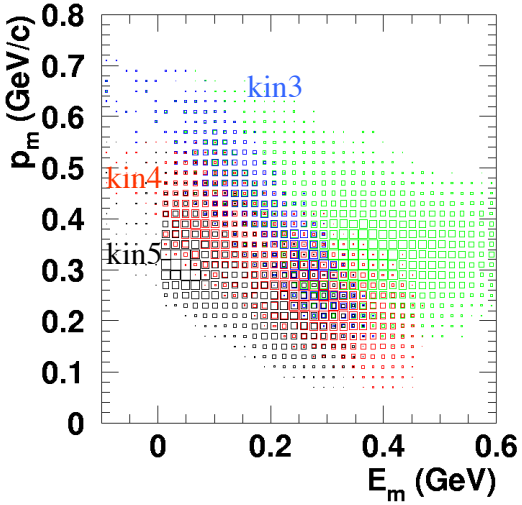


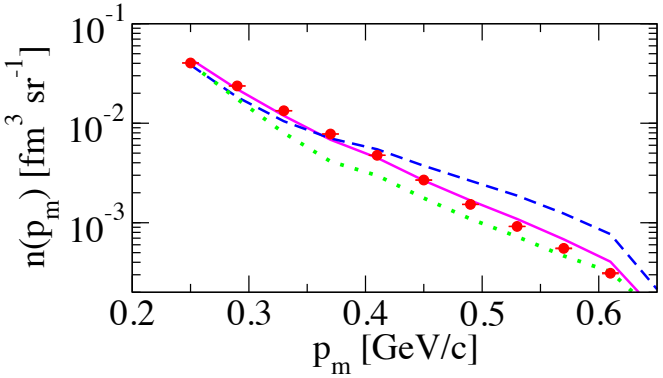
Large $|\mathbf{p}_m|$ and E_m Components in Complex Nuclei

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



- Measurement of correlation strength in carbon. Hall C data



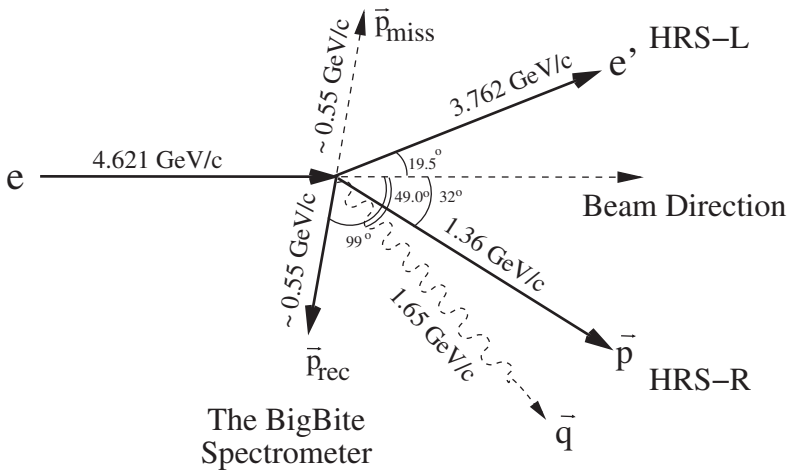


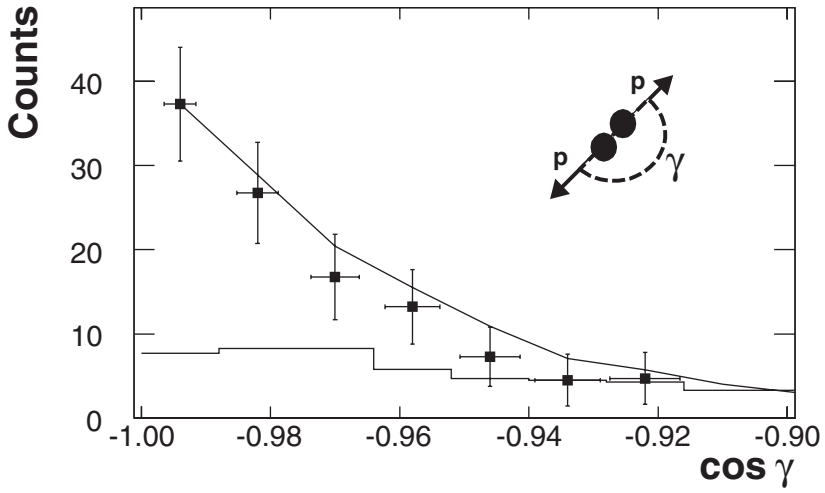
Experiment	0.61 ±0.06
Greens function theory [3]	0.46
CBF theory [2]	0.64
SCGF theory [4]	0.61

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

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

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

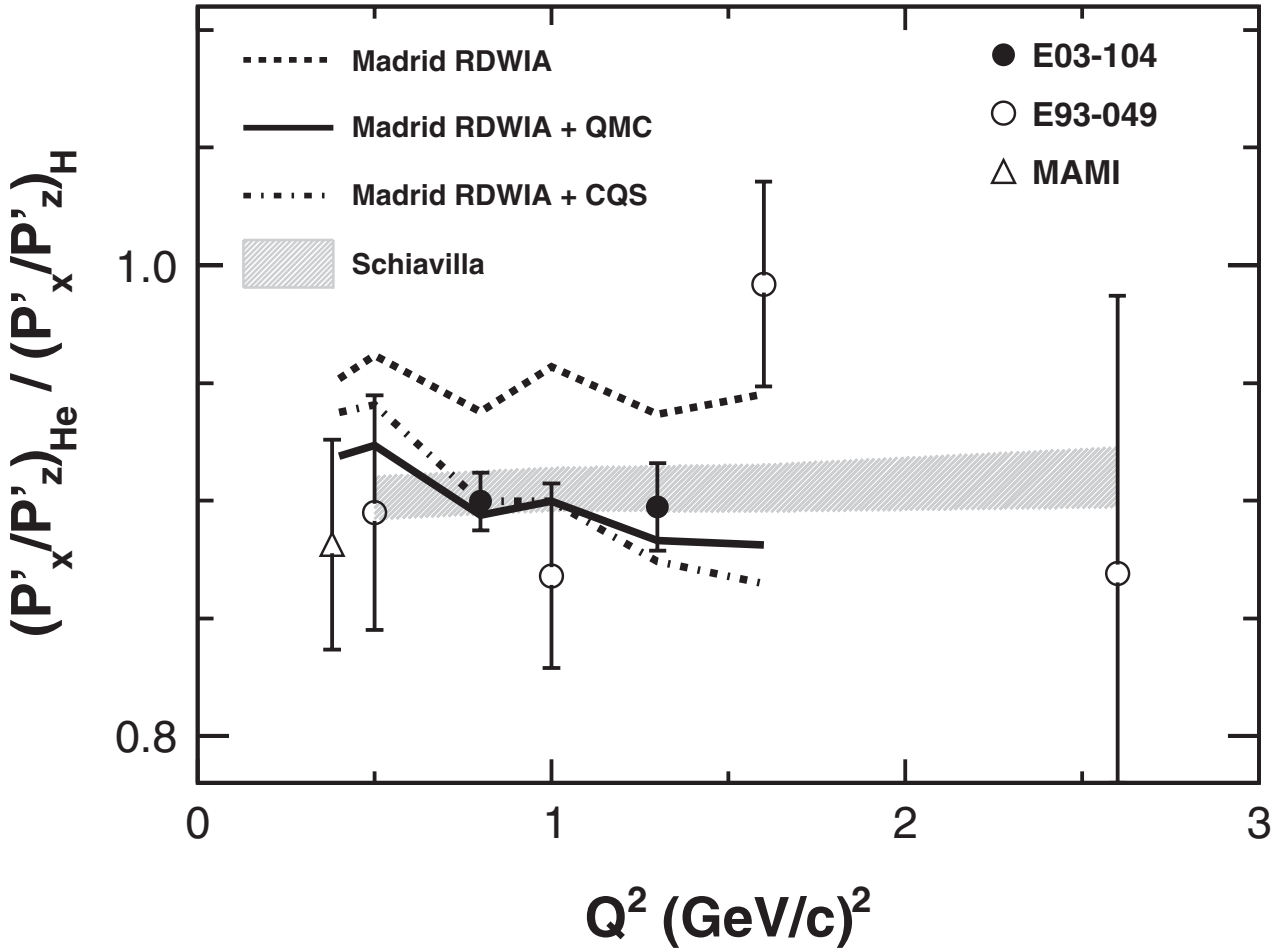




- The detection of back-to-back outgoing protons is a clearcut signature of nucleon-nucleon correlations

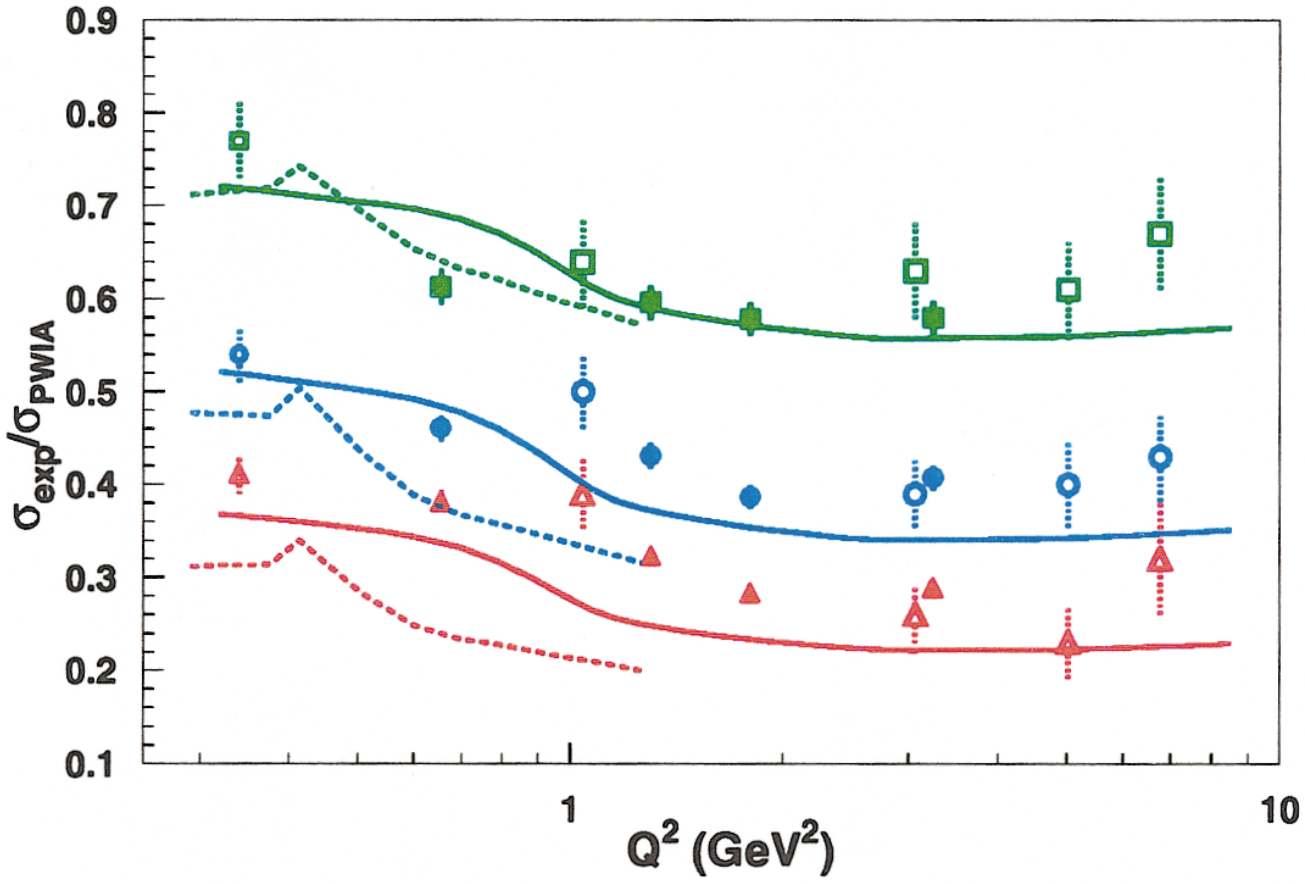
Exploiting Polarisation Degrees of Freedom: ^{4}He$(\vec{e}, \vec{e}\,' p)$

- Looking for possible medium modifications of the proton electromagnetic structure



$(e, e'p)$ AND THE QUEST FOR COLOR TRANSPARENCY

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



Jefferson Lab Experiment E12-14-012

- Mesaurement of the spectral function of ^{40}Ar through the $(e, e'p)$ reaction
- Collaboration of 31 physicists, from 8 institutions, based in the US, Europe and Japan
- Approved by the Jefferson Lab Program Advisory Committed in July 2014, for the full amount of requested beamtime
- Scientific grade A-

PR12-14-012

Scientific Rating: A-

Recommendation: Approve

Title: **Measurement of the Spectral Function of ^{40}Ar through the (e,e′p) reaction**

Spokespersons: O. Benhar, C. Mariani, C.-M. Jen, D.B. Day, D. Higinbotham

Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in ^{40}Ar. The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the (e,e′p) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.

This experiment has significant support from the neutrino community. Letters of support for this proposal were received from the Fermilab management, and spokespeople from LBNE, ArgoNeuT, Captain, LArIAT, and MicroBooNE. The analysis and simulation groups of these experiments will use these data.

Measurement and Feasibility: The experimenters propose a measurement of the (e, e′p) cross section on argon. Kinematics will be chosen to scan the missing energy domain extending from $E_m \sim 8$ MeV to $E_m \sim 60$ MeV, using the Hall A HRS spectrometers. Similar (e,e'p) experiments have been performed at JLAB and hence this measurement should be straightforward. Kinematical conditions corresponding to interactions with protons moving parallel to the incoming electron beam will be selected to minimize the final state interactions. To test the final-state interaction corrections, and inform such corrections needed for neutrino interactions, the experimenters also propose to measure two days in anti-parallel kinematics where final state interactions should be largest.

Issues: The proposal did not describe how the precision of the proposed experiment would translate into a precision in neutrino oscillation experiments. Given the uncertainty in correction for final-state interactions, it is likely that the systematic errors will be larger than the quoted 3%. However we anticipate that larger errors are likely to be acceptable. The energy resolution will also be larger than the quoted value, but again this appears to be acceptable. The PAC also noted that for anti-neutrino experiments the spectral functions of the neutrons are also important, but this experiment will only determine the proton spectral functions. An appropriate model will be needed to infer neutron spectral functions from the proton data taken in this experiment.

Recommendation: **Approve** for the requested 9 days of beam time.

22

Closing

- For over thirty years, Jean Mougey's has been one of the leading figures in the field of Electro-Nuclear Physics, to which he gave a number of outstanding and lasting contributions.

- As stated in the Obituary posted in The Jefferson Lab News on November 12, 2015

  He will be remebred as a passionate physicist, a spectrometer designer, a warm and sensitive person to work with