Overview of Nuclear Structure with Electrons

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Abstract.
Following a broad summary of our view of nuclear structure in 1974, I will discuss the key elements we have learned in the past 25 years from the research at the M.I.T. Bates Linear Accelerator Center and its sister electron accelerator laboratories. Electron scattering has provided the essential measurements for most of our progress. The future is bright for nuclear structure research as our ability to realistically calculate nuclear structure observables has dramatically advanced and we are increasingly able to incorporate an understanding of quantum chromodynamics into our picture of the nucleus.

To grasp the scientific legacy of the M.I.T. Bates Linear Accelerator Center and its sister electron scattering laboratories in the development of our understanding of nuclear structure, we should look back to our world view of nuclear structure in the early 1970's, to the time when the Bates laboratory was first taking data. For me this is a personal look back to the time when I was a graduate student and first learning what nuclear physics was all about. The classic textbook by De Shalit and Feshbach [1] gives us a vivid picture of those times. After reviewing what we thought we understood, I will point out what were the important elements that were missing in 1974 and give a few examples of the types of experiments which made the difference. The talks which follow will provide much more complete explanations of the data and the physics. What I want to do is give you a sense of where we came from, how we got there, and where we should go into the future.

We begin considering closed shell nuclei which in 1974 were understood in terms of mean-field Hartree-Fock calculations. The nuclear ground state was a Slater determinant of single particle orbitals which interact in a self-consistent mean-field. The major success at the time was the demonstration that such calculations starting with realistic nucleon-nucleon interactions gave an excellent description of the then-measured charge distributions of nuclei. I remember very clearly a seminar by John Negele who asserted that this was now a solved problem. Indeed, while little reliable data on the much-harder-to-measure distributions of neutrons existed, John asserted that we should move on and use the calculated neutron

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distributions to extract other important nuclear structure information. We will return to the issue of neutron distributions later in this talk where parity violating electron scattering appears to offer a valuable new tool.

Nuclei with several valence nucleons outside a closed shell were the province of shell model calculations with residual interactions obtained from theory (e.g. Kuo-Brown [2]) or experiment (Schiffer-True [3]). Shell model calculations were being extended past the simplest configurations and many experimental phenomena could now be understood, but usually with effective operators that were substantially renormalized from the free nucleon values.

A telling characteristic of the time was that sum rules almost always added up to the full strength expected in simple shell model constructions. Much of the data came from nucleon transfer reactions. For example, everyone believed if one summed the single particle stripping and pickup reaction strengths over states within several MeV of the Fermi surface, one should get 2j+1, where j is the total angular momentum of the single particle orbital. The power of (e,e'p) reactions in examining the single particle strength was well understood [4] but only exploratory experiments had been done.

Hartree-Fock and random phase approximation techniques were the foundation of microscopic descriptions of the collective degrees of freedom and normal modes of the nucleus. The giant dipole resonance which is selectively excited by low energy electromagnetic probes was the only giant resonance which was well in hand, both experimentally and theoretically. Systematics on the giant monopole and quadrupole resonances as well as spin-flip resonances were soon to come. We did know about the importance of the interplay between shell and collective effects [5] in, for example, fission isomers. This last topic has been a central theme in high-spin gamma ray physics over the past two decades.

The most direct measure of bound nucleons in the nuclear medium came from quasifree electron scattering, and here we were all convinced by Moniz et al. [6] that the nucleus looked very much like a Fermi gas of independent nucleons. In the 1976 long range plan for Nuclear Physics, the Friedlander report suggested we just had to do these experiments on a few more nuclei to map out the Fermi momentum vs mass number and we might be done. As an important institutional note, this report, two years after the first beam at Bates, recommended significantly increased funding support for the M.I.T. Bates Laboratory and the doubling of the maximum electron energy.

Finally, we did know in 1974 about the importance of two-body currents in electromagnetic interactions with nuclei. The most striking example at high momentum transfer was in the threshold electrodisintegration of the deuteron, but meson exchange currents were also important at low momentum transfer in the $np \rightarrow d\gamma$ reaction. It has taken a long time for the understanding that almost every two-body nucleon-nucleon interaction requires two-body interaction currents to satisfy current conservation to sink in for many of us who dreamed we lived in a one-nucleon current world.

While much of the 1970's viewpoint remains at the center of our understanding of the nucleus today, it is easy to see five vital components of our present understanding of the nucleus that were missing in 1974:

- We had few measurements of radial distributions.
- We had little information on absolute normalizations in reactions.
- The role of short-range Nucleon-Nucleon correlations was considered a problem for theorists, not experimentalists.
- We had only begun to consider microscopic many-body forces.
- We had no consistent framework to deal with the impact of nucleon-substructure in nuclear structure.

In large part, it is these five issues which have substantively changed our view of the nucleus in the past two and a half decades.

The first two points, the lack of radial distributions and absolute normalizations are strongly coupled. I have already discussed that pickup and stripping nucleon transfer reaction sum rules generally added up to 2j+1. What one measures is the product of the squared radial wave function at the strong absorption radius and the normalization of the reaction. Since we always had optical model and reaction mechanism ambiguities we did excellent measurements relative to states near shell closures which we assumed had unit spectroscopic factors and we could build up an apparently self-consistent picture. What absolute matrix elements we measured with electro-weak interactions (beta and gamma decay lifetimes) gave us integral measurements which could only be fit in the shell model with effective charges, typically of 1.5-2.0 for the proton and 0.5-1.0 for the neutron for E2 transitions. This was a clear sign that significant structure effects were left out of our models, most notably, coupling of low-lying states to giant resonances.

Short range correlations were primarily a theorist's ball game. They were essential for handling the strong short range behavior of the nucleon-nucleon interaction in the nuclear medium. But once we had a suitable effective interaction, few seemed to care about the implications, and certainly very few experimentalists. Perhaps part of the problem was that the one place short range correlations were taken seriously was in nuclear matter calculations, and in the early 1970's there was a "crisis in nuclear matter". It had finally become evident that no realistic two-nucleon interaction would be able to simultaneously reproduce N-N phase shifts and the saturation binding energy and saturation density of nuclear matter. This problem along with the difficulties in reproducing the properties of the few-nucleon systems forced the community to consider microscopic three-body forces and the very complicated correlation structure of the nuclear ground state very seriously.

Finally, if we had found a smoking gun failure in our picture of nuclear structure, we had no clear path how to proceed because we did not have a theory of the structure of the nucleon. We could propose ad-hoc changes in the properties of the nucleon in the nuclear medium without any clear idea of how these changes would affect other nucleon properties. Today we believe quantum chromodynamics gives us the framework for a complete description of nucleon, and indeed, nuclear structure. While a realistic calculation of ^{16}O in a QCD basis still remains far in the future, we can now perhaps appreciate the right questions to ask.

From our historical perspective where we know what was missing, it is easy to understand in hindsight why electron scattering was so central to the progress in the past 25 years. Fundamentally, in electron scattering you know what you are measuring, providing the first two of the five links mentioned above that were missing in 1974, because the interaction, quantum electrodynamics, is well understood. Electromagnetic interactions are weak enough for perturbation theory to provide a quantitative tool for extracting the nuclear response. In the one-photon exchange approximation, where a virtual photon with energy ω and three momentum $\vec{q}$ ($Q^2 = |\vec{q}|^2 - \omega^2$) is exchanged the electron scattering cross section is given by

$$\frac{d^3\sigma}{d\Omega dE'} = \frac{4\pi\sigma_M}{M_t}\left\{(\frac{Q^4}{|\vec{q}|^4})W_L(q,\omega) + \left[(\frac{Q^2}{|\vec{q}|^2})/2 + \tan^2\frac{\theta}{2}\right]W_T(q,\omega)\right\} \quad (1)$$

where σ_M is the Mott cross section and M_t is the target mass. The separation between the response, W_L, to longitudinal photons which couple to the charge, and W_T, to transverse photons which couple to convection corrections and magnetic moments is very important. In many cases for longitudinal currents the two-body currents are weak and the virtual photon interacts with single nucleon currents, looking deep inside the nucleus at the single particle structure. For inelastic scattering of a fixed multipolarity λ between an initial state $|i\rangle$ and final state $\langle f|$ the response function W_L can simply be considered to be

$$W_L \propto \left[\langle f||a^\dagger_\alpha a_\beta||i\rangle \int \rho_{fi}(r)j_\lambda(qr)r^2dr\right]^2. \quad (2)$$

We directly measure the Fourier transform of the transition density $\rho_{fi}(r)$ and the magnitude of the particle-hole amplitude $\langle f||a^\dagger_\alpha a_\beta||i\rangle$. To invert the Fourier transform into a coordinate density requires data over a large range of momentum transfers extending out to 1/L fm^{-1} where L is less than $\sim$0.4 fm. It was the 1970's generation of electron accelerators: Bates, Saclay, and NIKHEF, that had the kinematic range, beam intensity, and experimental equipment to fully exploit this power.

Similarly in proton knockout $(e,e'p)$ reactions in the Plane Wave Impulse Approximation

$$\frac{d^6\sigma}{d\Omega dE' d^3\vec{p}} = \sigma^*_{ep} S(E_m, \vec{P}_i) \quad (3)$$

the cross section is simply proportional to the electron-nucleon cross section, σ^*_{ep} times the spectral function S which in the independant particle shell model is given by

$$S(E_m, \vec{P}_i) \propto \sum_i Z_i^2 \phi_i^2(\vec{P}_i)\delta(E_m - E_i). \quad (4)$$

where Z_i^2 is the spectroscopic factor and $\phi_i^2(\vec{P}_i)$ is the square of the single particle wave function. $\vec{P}_i$ is the initial proton momentum in the nucleus and E_m is the separation energy of the produced proton-hole state. Here one has to deal with the outgoing proton in the final state through the distorted wave impulse approximation. The dominant (but by no means sole) effect of the distortions is the attenuation of the outgoing protons while passing through the nucleus.

To do real experiments with the extended kinematic range of few hundred MeV electrons, the last essential requirement is experimental detection systems with the resolution and solid angle to make the measurements in a timely fashion. The Bates laboratory set the standard with a superb magnetic spectrometer, ELSSY [7], which led the community to dispersion-matched energy-loss spectrometers and achieved resolutions better than 10^{-4}. The vertical drift chamber detection system [8] was equally innovative. The technique of using a single chamber package to make multiple measurements on a track is now used in all large detector systems to provide the maximum track information with the minimum multiple scattering.

When all these elements came together, one could measure gorgeous experimental spectra, one example of which is shown in figure 1 [9] for electron inelastic scattering from ^{90}Zr. When I first saw such spectra, my eyes popped, even before I noted that they were presented on a logarithmic scale. In Fig. 2, the extracted radial transition densities are shown for the four states of the two-proton $g_{9/2}$ multiplet, $|[\pi g_{9/2}]^2 \otimes J = 2, 4, 6, 8\rangle$. The cross-hatched band is the range of uncertainty in the experimental transition densities and the solid (dashed) line is a calculation with (without) core polarization. One immediately sees that for the 2^+ state there are large core polarization corrections but that the theory has difficulty describing the transition density in the interior of the nucleus. As one goes to higher spin states the transition density looks much more like a single $g_{9/2}$ radial wave function and the calculated effects of core polarization are smaller.

Such inelastic scattering data indicated the simplicity of high-spin excitations and would reveal a significant reduction of the measured particle-hole strength from the mean-field expectation. These observations triggered a reexamination of the nuclear single particle strength near the Fermi surface. In the Hartree-Fock picture of a closed shell nucleus, the wave function was a Slater determinant of single particle orbitals which were occupied up to the Fermi surface and then empty above the Fermi surface. While it was recognized that long range correlations (from surface vibrations) and short-range correlations (from the N-N interaction) would dilute this abrupt transition, the perspective from the success of shell model calculations in the Pb region was that these were not large effects. The electron scattering data gave an overwhelming body of evidence that this was not true. The four types of data that played a key role were:

- Differences in elastic scattering yields for A and A-1 systems such as ^{206}Pb compared to ^{205}Th [10] and ^{208}Pb to ^{207}Pb [11].

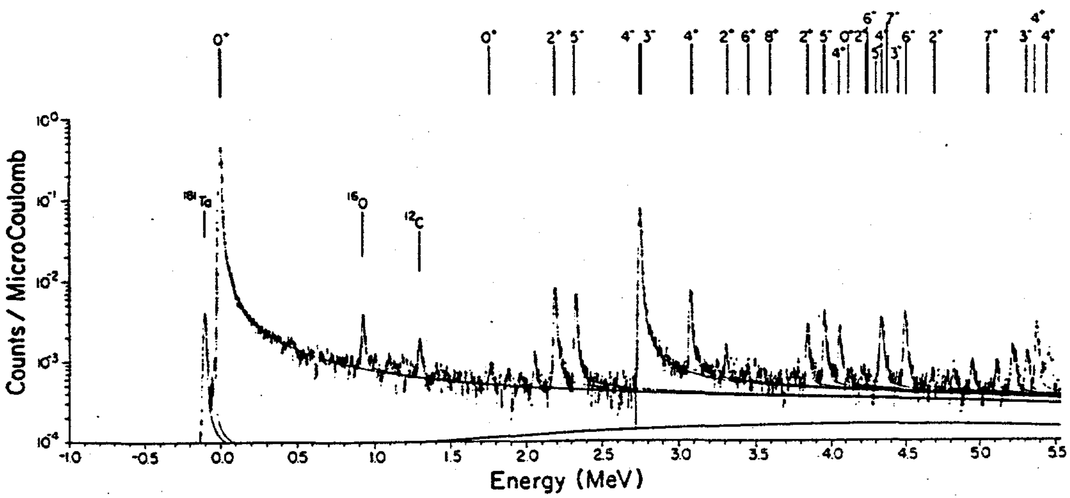

FIGURE 1. ELSSY spectrum of scattered electrons from ^{90}Zr measured at Bates with 150 MeV incident energy electrons [9].

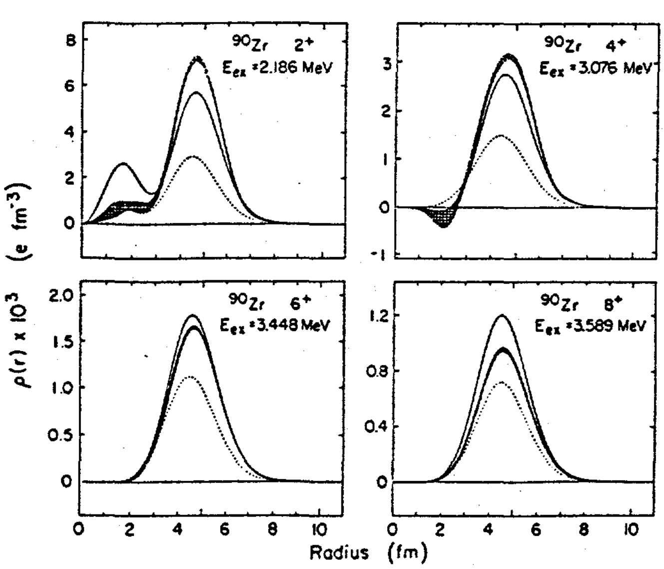

FIGURE 2. Transition charge densities for the 2^+, 4^+, 6^+ and 8^+ levels with dominant configuration $[\pi g_{9/2}]^2$. The cross hatched areas represent the error band on the experimental extraction. The solid (dotted) line is a calculation including (ignoring) core polarization effects [9].

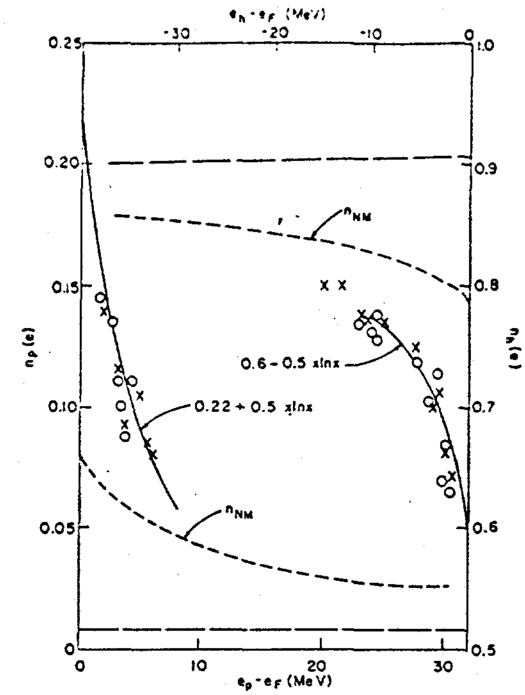

FIGURE 3. Calculated occupation numbers for single particle and hole states near the Fermi surface in Pb [14]. The dashed curve is a nuclear matter calculation including short-range correlations (long dashed) and long-range correlations and the points (crosses for proton states and circles for neutron states) include RPA correlations. The solid line is simply a parameterization of the points.

- Magnetic elastic scattering to high l orbitals [12].
- Inelastic Scattering to "relatively pure" particle-hole states [13].
- Spectroscopic factors for $(e, e'p)$ reactions.

These measurements were brought together in a coherent picture by Pandharipande, Papanicolas and Wambach [14] who showed that the combination of nuclear matter and random-phase approximation calculations shown in Fig. 3 could explain the occupation probabilities of single particle orbitals in the Pb region.

How do modern calculations stack up in describing the absolute normalization and radial transition densities measured in electron scattering? Today the state of the art is ab initio many-body calculations with realistic nucleon-nucleon forces and three-body interactions, free nucleon current operators and two-nucleon exchange currents. Such calculations are becoming a standard non-relativistic model of nuclear structure. The results show excellent detailed agreement with the data in ^{6}Li(e, e') inelastic scattering transitions (Fig. 4 [15]) and ^{7}Li$(e, e'p)$ proton knockout data (Fig. 5 [16]). The inelastic longitudinal response functions are dominated by the one-body currents while the transverse response functions show the need for significant contributions from exchange currents to fit the data at the larger momentum transfers. In the knockout reaction the calculation reproduces the $p_{3/2}$

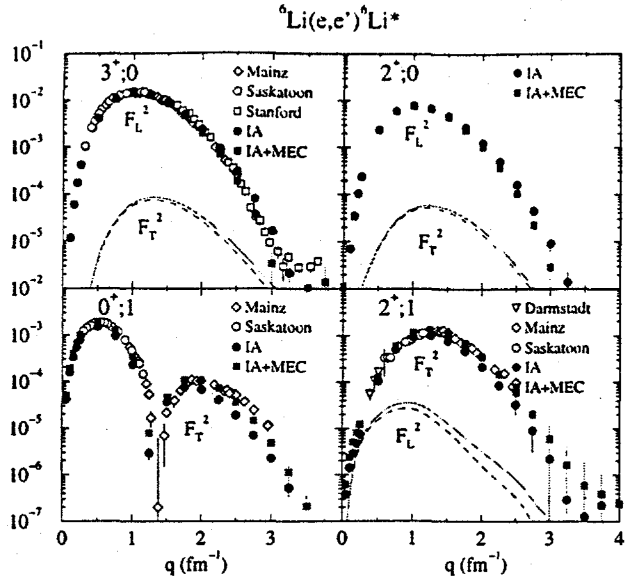

FIGURE 4. Electron inelastic scattering transition from factors in ^{6}Li. The calculations are variational Monte Carlo calculations with one-body (IA, filled circles) and two-body-meson-exchange (MEC, filled squares) transition operators [15].

spectroscopic factor of 0.42 that the data require. We have clearly come a long way from effective charges of 2.0 and a proton $p_{3/2}$ occupation probability of 1.0 in the lithium isotopes.

With the electron data in hand, we can now normalize our hadron inelastic scattering data and go on to extract new information about the isospin structure of nuclear excitations. A prime example is the case of negative parity 1 $\hbar\omega$ excitations. Bill Donnelly and his collaborators [17] pointed out in 1968 that at large momentum transfer the inelastic scattering spectra are dominated by so-called stretched particle-hole states involving the largest angular momentum particles and holes lying just above and below the Fermi surface. These are spin-flip excitations like $|[p_{3/2}^{-1} \otimes d_{5/2}]J = 4^-\rangle$ states in ^{12}C, $|[d_{5/2}^{-1} \otimes f_{7/2}]J = 6^-\rangle$ states in ^{28}Si, and $|[i_{13/2}^{-1} \otimes j_{15/2}]J = 14^-\rangle$ states in ^{208}Pb. Because they were easily observed, one could also study them with probes where such high resolution was not available, as I was doing with pion inelastic scattering at LAMPF or proton scattering at IUCF. The hadronic probes have differing isospin sensitivities and one can combine the electron and hadron data to extract the isoscalar and isovector, or neutron and proton transitions amplitudes for each state.

$$\begin{aligned} e: &\quad |M|^2 \propto (\mu_p Z_p + \mu_n Z_n)^2 \\ \pi^+: &\quad |M|^2 \propto (3Z_p + Z_n)^2 \\ \pi^-: &\quad |M|^2 \propto (Z_p + 3Z_n)^2 \end{aligned}$$

The electron scattering spin-flip matrix element is almost pure isovector—indeed,

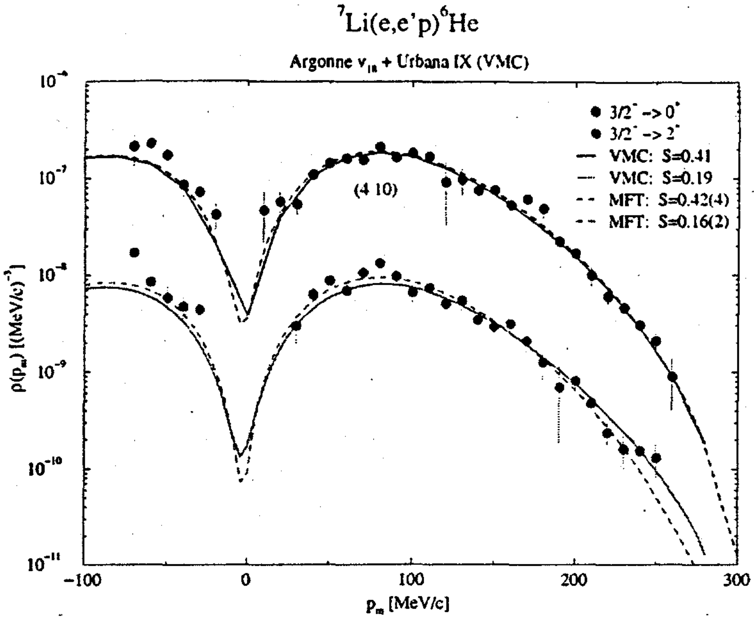

FIGURE 5. Momentum densities measured in proton knockout from ^{7}Li to the ground state 0^+ and first excited 2^+ states in ^{6}He. The calculations are variational Monte Carlo calculations (VMC) and mean field theory calculations (MFT) [16]. S is the spectroscopic factor.

magnetic-isoscalar transitions were extremely hard to see. However in the pion inelastic scattering case, isoscalar excitations are favored over isovector by a factor of 4. For these transitions the radial densities should be the same for each isospin combination so pure $\Delta T = 1$ transitions provide perfect normalizations for the pion reaction mechanism. Many groups contributed to this effort. A summary of the separated isovector and isoscalar yields is shown in Fig. 6. Typically 30-50% of the pure particle-hole isovector spin-flip strength is observed primarily due to the occupation of the single particle orbitals discussed above. But only about 15% of the isoscalar strength was observed, an additional quenching of a factor of 2. This can now be reproduced in large scale shell model calculations [19] but no simple explanation in terms of collective degrees of freedom of the nucleus has ever emerged.

Jim Kelly and his collaborators have made the most extensive use of this comparison of electron and hadron scattering to understand the nucleon-nucleon interaction in the nuclear medium. Kelly uses the detailed knowledge of the radial dependence of the transition densities from electron scattering to determine the density dependence of the N-N interaction by fitting proton elastic scattering, inelastic scattering and polarization observables [20]. This has given us powerful insight into the mechanisms of medium modifications and made proton scattering a better quantitative tool for nuclear structure information.

Let me now return to $(e, e'p)$ reactions. While in the one-body current approxi-

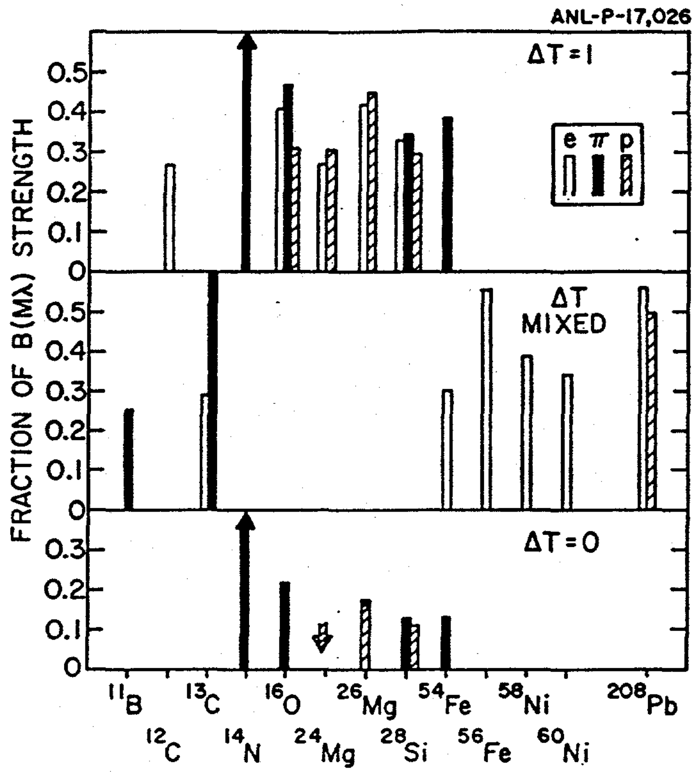

FIGURE 6. The fraction of the single-particle-hole strength contained in inelastic scattering to stretched $1\hbar\omega$ states from electron, proton and pion inelastic scattering is shown for a variety of nuclei. The upper panel corresponds to the summed $\Delta T = 1$ fractional strength and the lower panel to the summed $\Delta T = 0$ fractional strength. The middle panel corresponds to mixed isospin transitions where a $\Delta T = 1$ and $\Delta T = 0$ separation was not made.

mation the reaction measures the nuclear spectral function as in eq. 3, Bates studies at high energy loss showed significant strength that seemed to require multi-body mechanisms. The best way to study this is to separate the nuclear response to longitudinal and transverse photons. Since meson-exchange currents affect primarily the transverse response, the longitudinal coupling should give a better picture of the nuclear single particle structure. In the Bates work of Ulmer et al. [21] at $Q^2 = 0.15$ GeV^2, it was observed that for the p-shell proton knockout from ^{12}C the longitudinal and transverse strength were equal, but above two nucleon threshold there was a substantial excess of transverse strength. Everyone knows that L/T separation experiments are tough experiments, and one of the firsts things we did at Jefferson Lab was to repeat this L/T separation at two higher Q^2. In Fig. 7 I show the separated spectral function results from Dipangkar Dutta's thesis [22] on ^{12}C. As the lower panel illustrates, we definitely see an excess of transverse strength compared to longitudinal strength at $Q^2 = 0.6$ GeV^2. At the higher $Q^2 = 1.8$ GeV^2, the transverse strength is reduced. This return to a more purely single particle response is expected as the wavelength of the probe becomes shorter. In Fig. 8 it can be seen the both the longitudinal and transverse response we measured at Jefferson Lab at $Q^2 = 0.6$ GeV^2 are in agreement with the Ulmer et al. results. However in the new data one can see clearly that the longitudinal response extends to at least 80 MeV in missing energy. This long tail of the single particle response is the result of the spreading of the strength due to correlations.

In the 1980's several studies tried to look for evidence of medium modifications of nucleon structure by comparing the longitudinal and transverse strength. In Fig. 9 the ratio of the square root of the transverse to longitudinal response is displayed. If the nucleon electric and magnetic form factors had the same Q^2 dependence, this ratio would simply be the magnetic moment of the proton, 2.80. The Bates and Jefferson Lab results are consistent with this for the p shell knockout, and slightly below, but not inconsistent with, the NIKHEF and Saclay results. For the s shell region, the results are clearly above the free nucleon value at lower Q^2. The recent polarization transfer results [23] from Hall A at Jefferson Lab prove that the nucleon electric and magnetic form factors do not have the same momentum transfer dependence as indicated by the dashed curves in Fig. 9.

As a final example of the effect of correlations in nuclei I want to talk about attempts to directly measure the two-body density matrix or correlation function. With small acceptance spectrometers, this is very difficult to do directly. However it has long been known that by integrating over the longitudinal quasifree electron scattering response, one can use the Coulomb sum rule to extract the two body density. Doug Beck first analyzed the ^{3}He and ^{3}H data from Saclay and Bates to extract the two body density [24] and found significant disagreement with theoretical predictions. The later analysis of Schiavilla, Wiringa and Carlson [25] in Fig 10 showed that neutron contributions, relativistic corrections and meson exchange currents were all important in providing a complete description. The experimentalists will have to work even harder to truly nail down the two-body distributions. Indeed at this time, the largest discrepancies occur for ^{3}H, where the 2-proton

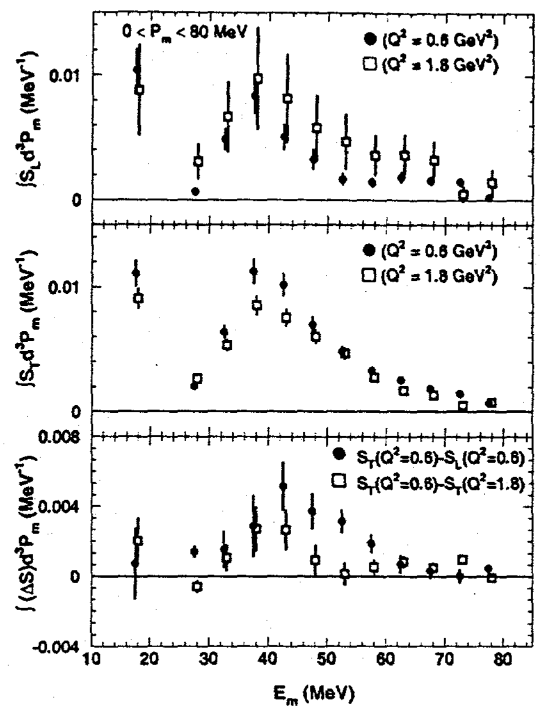

FIGURE 7. The integrals of S_L (top panel) and S_T (middle panel) from $0 < p_m < 80$ MeV are shown at Q^2 of 0.64 (circles) and 1.80 GeV^2 (squares). In the bottom panel the differences: $S_T - S_L$ at 0.64 GeV^2 (circles) and $S_T(Q^2{=}0.6)$-$S_T(Q^2{=}1.8)$ (open squares) are shown [22]. The errors are the sum in quadrature of the statistical and systematic uncertainties. The lowest E_m point is an average over 10< E_m <25 MeV. The response functions at 1.8 GeV^2 are corrected for differences in proton attenuation by factors of 1.075 for $E_m < 25$ MeV and 1.18 for $E_m > 25$ MeV.

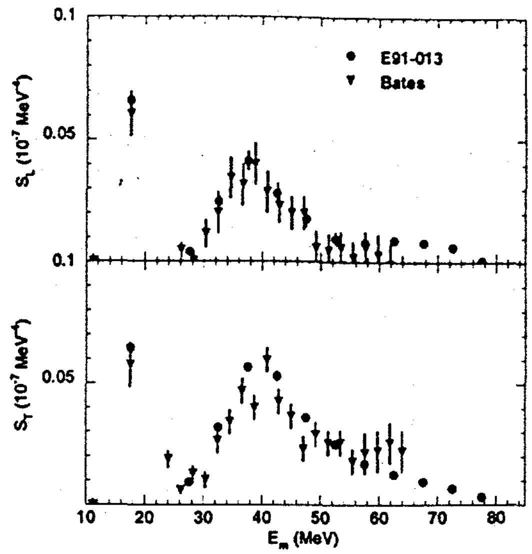

FIGURE 8. S_L (top panel) and S_T (bottom panel) at Q^2 of 0.64 GeV^2 (circles [22]) compared to the results of ref. [21] at Q^2 of 0.15 GeV^2 (triangles). The statistical uncertainties only have been shown. No attempt has been made to correct for different final state proton attenuation effects, but estimates suggest they are similar at the two proton energies.

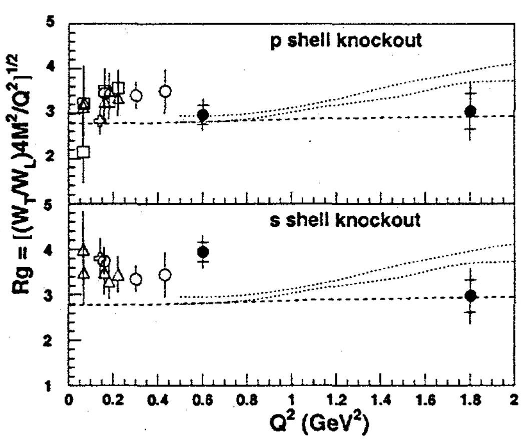

FIGURE 9. $R_G = \sqrt{W_T 4M_p^2 / W_L Q^2}$ for the $^{12}C(e, e'p)$ reaction (solid) from the measurements of Dutta et al. [22]. The top panel is for the p shell region and bottom panel is for the s shell region. The inner error bar represents the statistical error and the outer error bar includes the systematic error. Previous data from ^{6}Li (open squares from Nikhef) and ^{12}C (open triangles from NIKHEF, open circles from Saclay and open crosses from Bates [21]) at lower Q^2 are also shown. The dashed line is an older fit to R_G for the free proton while the dotted lines indicate the results of the new JLAB polarization transfer data [23].

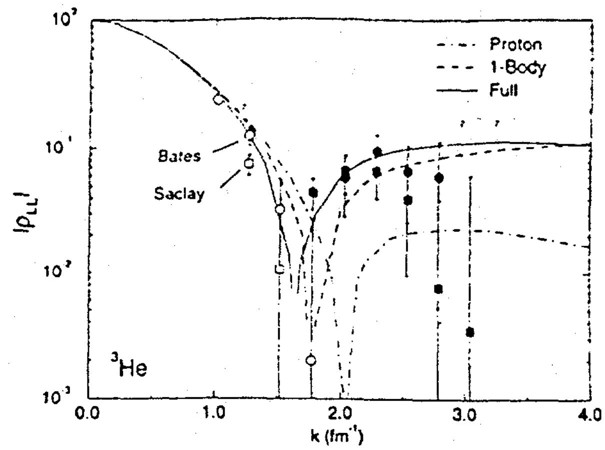

FIGURE 10. Experimental and theoretical longitudinal-longitudinal distribution functions in ^{3}He. The open (filled) symbols represent positive (negative) values of the data. The curves show the proton (dot-dashed), one-body (dashed) and the one-plus two-body contributions (solid) [25].

correlations are all due to two-body currents.

What I have tried to do in this talk is illustrate with a few key examples that 25 years of electron scattering results from Bates and her sister laboratories have profoundly changed our view of nuclear structure. I have concentrated on the effects of short range correlations which are, perhaps surprisingly, widespread. Have we reached the end? The Program Advisory Committee at Jefferson Lab examined the future of electron scattering in nuclear structure in a recent workshop and was convinced that there are many more exciting revelations to come [26]. We encouraged work in the following areas with nuclear targets

- Testing our standard model of the nuclear many body theory.
- Nuclear single particle structure, particularly at high excitation.
- A decisive measurement of neutron densities in parity violating electron elastic scattering.
- Explicit determination of nucleon correlation functions, possibly from large acceptance $(e, e'pp)$ and $(e, e'pn)$ measurements.
- A decisive measurement of the longitudinal and transverse quasifree response.
- Nuclei as a length scale or a source of nucleon targets for short-lived particles.
- Search for medium modifications of hadrons in nuclei.

and encouraged the users to present their own ideas.

As you listen to subsequent talks, reflect on how our field has changed in the past 25 years due to the work of electron scattering and where we should go in the future. In particular, how can we learn if the structure of the nucleon and quantum chromodynamics does affect nuclear structure, or do we now have a standard model of nuclear structure that will allow us to address all the relevant issues? You will hear that there are lots of exciting questions remaining, and lots more to be done.

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