Electromagnetic Nuclear Interactions at GeV Energies

Can electron scattering data contribute to an understanding of the backgrounds?

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“Cosmic ray muons produce neutrons through several different mechanisms...”

1. Negative muon capture on nuclei.
2. Electromagnetic showers generated by muons.
3. Muon interactions with nuclei via the exchange of virtual photons $$\Rightarrow$$ muon nuclear interactions and photoneutron production.

These energetic neutrons (100's of MeV) are produced thru quasielastic and inelastic processes from moving nucleons in the nucleus.
Nuclear Response Function

\[ Q^2 = \bar{q}^2 - \nu^2 \]

\[ \nu = (E - E') \quad (\nu \equiv \omega) \]
What studies motivate inclusive inelastic electron scattering from nuclei?
A variety of topics

- Momentum distributions and the spectral function $S(k, E)$.
- Short Range Correlations and Multi-Nucleon Correlations
- Scaling $(x, y, \varphi', \xi)$ - tests and the violation of ‘laws’
- Medium Modifications -- effects of the nuclear environment (EMC, exotic quark states)
- Duality - The strongly $Q^2$ dependent resonance structure function averages to DIS scaling - access to pdfs at very high $x$

The inclusive nature of these studies make disentangling all the different pieces a challenge but we have a couple of knobs....
Inclusive Electron Scattering from Nuclei

Two distinct processes

Quasielastic from the nucleons in the nucleus

$$M_A M^*_{A-1}, -\mathbf{k}$$

$$\mathbf{k} + \mathbf{q}, W^2 = M^2$$

Inelastic (resonance production) and DIS from the quark constituents of the nucleon.

$$W^2 \geq (M_n + m_\pi)^2$$

Inclusive final state means no separation of two dominant processes

$$x = Q^2/(2mu)$$

$$u, \omega = \text{energy loss}$$
There is a rich, if complicated, blend of nuclear and fundamental QCD interactions available for study from these types of experiments.

The two processes share the same initial state

**QES in IA**

\[
\frac{d^2\sigma}{dQ^2 dp} \propto \int dk \int dE \sigma_{ei} S_i(k, E) \delta() \]

**DIS**

\[
\frac{d^2\sigma}{dQ^2 dp} \propto \int dk \int dE W_{1,2}^{(p,n)} S_i(k, E) \]

However they have very different \(Q^2\) dependencies

\[\sigma_{ei} \propto \text{elastic (form factor)}^2\]

\[W_{1,2} \text{ scale with } \ln Q^2 \text{ dependence}\]

Exploit this dissimilar \(Q^2\) dependence
Spectral Function

Helium – 3

\( ^9\text{Be}(e,e'p)^8\text{Li} \)

Fig. 10. Proton separation energy spectra for the \( ^9\text{Be}(e,e'p) \) reaction, within different recoil momentum bins. The energy resolution of ~ 0.9 MeV renders visible some different excited states of \( ^8\text{Li} \) at low separation energy. Data have been corrected for radiative effects, but the overall absolute scale is arbitrary.

Saclay, J. Mougey
The nucleon spectral function at high values of both $k$ and $E$ should be governed by ground-state configurations in which the high-momentum $k^1$ of a nucleon is almost entirely balanced by the momentum $k^2$ of another nucleon, with the remaining $(A^2)$ nucleons acting as a spectator with momentum $k^A$. When the momentum and the intrinsic excitation energy of the $(A^2)$ system are totally disregarded, the energy conservation would require that

$$E_{A}^{\ast} \equiv E_{A}^{R} = \frac{k^2}{2(A^2)} M,$$

where $E_{A}^{R}$ is the recoil energy of the $(A^2)$-nucleon system; thus the intrinsic excitation of the $(A^2)$ system would be

$$E_{A}^{\ast} = A^2 E_{A}^{R}.$$

Within such a picture, the nucleon spectral function $P_1(k, E)$ has the following form:

$$P_1(k, E) = \int_0^{\infty} S(k, E) dE.$$

Configurations corresponding to high values of $k^A$ should be ascribed to three-nucleon correlations; indeed, high values of $k^A$ can be due to ground-state configurations with a third "hard" nucleon, whose momentum balances the CM one of particles 1 and 2.
Independent Particle Shell model: describes basic properties like spin, parity, magic numbers ...

But there is a problem!

Spectroscopic factor \[ Z_\alpha = 4\pi \int_{k_f}^\infty \frac{dE dk k^2 S(k, E)}{k^2} \] ≠ number of nucleons in shell

NIKHEF results
Short Range Correlations (SRCs)

Mean field contributions: $k < k_F$  Well understood, SF Factors $\approx 0.65$

High momentum tails: $k > k_F$

- Calculable for few-body nuclei, nuclear matter
- Dominated by two-nucleon short range correlations
- Poorly understood part of nuclear structure
- Sign. fraction have $k > k_F$

\[ n(p) \approx \frac{1}{k^3} \]

Similar shapes for $k > k_F$

- $k > 250 \text{ MeV/c}$
  - 15% of nucleons
  - 60% of KE

- $k < 250 \text{ MeV/c}$
  - 85% of nucleons
  - 40% of KE

\[ n(p) \approx \frac{1}{k^3} \]

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This strength must be accounted for when trying to predict the cross sections
CS Ratios and SRC

In the region where correlations should dominate, large $x$,

$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A) \sigma_j(x, Q^2)$$

$$= A \frac{1}{2} a_2(A) \sigma_2(x, Q^2) + A \frac{1}{3} a_3(A) \sigma_3(x, Q^2) + \cdots$$

$a_j(A)$ are proportional to finding a nucleon in a $j$-nucleon correlation. It should fall rapidly with $j$ as nuclei are dilute.

$$\sigma_2(x, Q^2) = \sigma_{eD}(x, Q^2) \quad \text{and} \quad \sigma_j(x, Q^2) = 0 \quad \text{for} \quad x > j.$$
Ratios and SRC

\[
\frac{2 \sigma_A}{A \sigma_D} = a_2(A); \ (1.4 < x < 2.0)
\]


\( a_j(A) \) is proportional to probability of finding a \( j \)-nucleon correlation
Early 1970's Quasielastic Data

\[ \mathbf{q} \approx 500 \text{MeV}/c \]

\[ \frac{d\sigma}{d\Omega}/A \quad \text{[nb/sr/GeV]} \]

\[ \nu \quad \text{[GeV]} \]

\[
\begin{array}{|c|c|c|}
\hline
\text{Nucleus} & k_F & \bar{\sigma} \\
\hline
^{6}\text{Li} & 169 & 17 \\
^{12}\text{C} & 221 & 25 \\
^{24}\text{Mg} & 235 & 32 \\
^{40}\text{Ca} & 251 & 28 \\
\text{nat Ni} & 260 & 36 \\
^{89}\text{Y} & 254 & 39 \\
\text{nat Sn} & 260 & 42 \\
^{181}\text{Ta} & 265 & 42 \\
^{208}\text{Pb} & 265 & 44 \\
\hline
\end{array}
\]
The shape of the low $\nu$ cross section is determined by the momentum distribution of the nucleons.

- As $Q^2 \gg$ inelastic scattering from the nucleons begins to dominate
- We can use $x$ and $Q^2$ as knobs to dial the relative contribution of QES and DIS.

The quasielastic contribution dominates the cross section at low energy loss ($\nu$) even at moderate to high $Q^2$.
A dependence: higher internal momenta broadens the peak

Also note while broadening the qep it also sweeps strength from the inelastic regions.
Scaling

• Scaling refers to the dependence of a cross section, in certain kinematic regions, on a single variable.
  • Scaling validates the assumptions about the underlying physics
  • Scale-breaking provides information about conditions that go beyond the assumptions.

• At moderate $Q^2$ inclusive data from nuclei has been well described in terms $y$-scaling, one that arises from the assumption that the electron scatters from quasi-free nucleons.

• We expect that as $Q^2$ increases we should see for evidence ($x$-scaling) which could be interpreted as scattering from the more fundamental constituents – quarks.
**y-scaling in inclusive electron scattering from $^3$He**

Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus. $y$ is the momentum of the struck nucleon parallel to the momentum transfer:

$$y = y(q, \omega) \simeq \sqrt{\omega(2m_n + \omega) - q}$$
Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus. $y$ is the momentum of the struck nucleon parallel to the momentum transfer.

$$y = y(q, \omega) \approx \sqrt{\omega(2m_n + \omega)} - q$$

### Deuteron $F(y)$ and calculations based on NN potentials

$$F(y) = \frac{\sigma^{\text{exp}}}{(Z\sigma_p + N\sigma_n)} \cdot K$$

$$n(k) = -\frac{1}{2\pi y} \frac{dF(y)}{dy}$$

**SRC region, nucleons with $k \approx 500$ MeV/c**

**Independent of $q$**
Presented in this way $F(y)$ demonstrates an independence of $q$. Independent of $q$. 

Thursday, April 14, 2011
Scaling of a second kind independent of $A$

\[ k_A = \sqrt{\langle k^2 \rangle_A} = k_f \]

\[ f(q, y) \equiv k_A \cdot F(q, y) \]

\[ \psi \simeq y/k_A \]

Super Scaling - independent of $A$ and $q$

There exists only one universal (QE) scaling function, $f^{QE}_L$ longitudinal response, which contains the nuclear physics information of the process.

Beyond the QE-Peak: Delta Region

Inclusive electron scattering from $^{12}\text{C}$ and $^{16}\text{O}$ in the $\Delta$ regions -- energies extending from 300 MeV to 4 GeV and scattering angles from 12 to 145 degrees, Amaro et al, PRC 71, 015501(2005)
Inelastic contribution increases with $Q^2$

DIS begins to contribute at $x > 1$
Convolution model

We expect that as $Q^2$ increases to see evidence ($x$-scaling) that we are scattering from a quark at $x > 1$
x and $\xi$ scaling

Remarkably when the data is presented in terms of the nuclear inelastic structure functions evidence of scaling emerges.

\[ x = \frac{Q^2}{2M\nu} \]

\[ \xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}} \rightarrow x \]
Especially for the heavier nuclei

\( \xi \) (fraction of nucleon light cone momentum \( p^+ \)) is proper variable in which logarithmic violations of scaling in DIS should be studied.

Local duality (averaging over finite range in \( x \)) should also be valid for elastic peak at \( x = 1 \) if analyzed in \( \xi \)

\[
F_2^A(\xi) = \int_\xi^{A} dz F(z) F_n^2(\xi/z)
\]

Evidently the inelastic and quasielastic contributions cooperate to produce \( \xi \) scaling. Is this local duality?

Can we extract nuclear pdfs in this region?
A connection to quark distributions at $x > 1$

Two measurements (very high $Q^2$) exist so far:

CCFR ($\nu$-C): $F_2(x) \propto e^{-sx}$, $s = 8$

BCDMS ($\mu$-Fe): $F_2(x) \propto e^{-sx}$, $s = 16$

Poor resolution, limited x range

Low statistics

CCFR results suggested large contribution from SRC or other exotic effects

We can, but first we must account for the fact that none of these measurements are at the asymptotic limit.
Application of ‘target mass corrections’

E02-019 carbon
SLAC deuterium
BCDMS carbon
× CCFR projection
(ξ=0.75,0.85,0.95,1.05)

In any effort at prediction you must have the e/m FF right and there have been surprises

\[
\frac{d\sigma}{d\Omega} = \sigma_{NS} \left[ \frac{G_E^2}{1 + \tau} + 2\tau G_M^2 \tan^2(\theta/2) \right],
\]

At a \( Q^2 = 6 \text{ GeV}/c^2 \) you would make about a 6% error ignoring the electric form factor of the neutron.
Muon mean energy  Neutron spectrum

What this suggests to me.
There is a significant body of experimental and theoretical work on inclusive electron scattering which has direct application to muon scattering.

The e/m community is contributing to experimental studies of neutrino oscillations at GeV energies MiniBooNE and K2K/T2K experiments. These involve neutrino energies of several GeV.

Lots of things to worry about - correct nucleon FF, medium modifications, SRC, FSI .. but it appears that scaling holds over a very large range of $Q^2$ and $x$ which should allow reliable predictions of the cross sections.

I can not offer much on the fate of the neutron - there transport codes that are proving useful to the neutrino community for just this problem - GIBUU.

Any reliable calculation for muon scattering must be tested against electron scattering data.

Inclusive quasi-elastic electron-nucleus scattering.
O. Benhar, DD, I Sick, Rev. Mod. Phys. 80 (2008) 189-224
Welcome to Quasielastic Electron Nucleus Scattering Archive

In connection with a review article (Quasielastic Electron-Nucleus Scattering, by O. Benhar, D. Day and I. Sick) to be submitted to Reviews of Modern Physics, we have collected here an extensive set of quasielastic electron scattering data in order to preserve and make available these data to the nuclear physics community.

We have chosen to provide the cross section only and not the separated response functions. Unless explicitly indicated the data do not include Coulomb corrections.

Our criteria for inclusion into the data base is the following:

2. Radiative corrections applied to data.
3. No known or acknowledged pathologies

At present there are about 600 different combinations of targets, energies and angles consisting of some 19,000 data points.

In the infrequent event that corrections were made to the data after the original publications, we included the latest data set, adding an additional reference, usually a private communication.

As additional data become known to us, we will add to the data sets.

If you wish to be alerted to changes in the archive or to the inclusion of new data, send an email to me. Send any comments or corrections you might have as well.