Electromagnetic probes – from nuclei to flux tubes

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Lecture outline

- Generating intense photon beams
- Current facilities: Tagged polarised photon beams
- Future facilities: “Quasi-real” tagged polarised photon beam at JLAB

Two selected physics topics

The equation of state for neutron rich matter

Direct probe of the nature of light quark confinement
High intensity electron beams

**Microtron technique**
(MAMI, Jefferson Lab)
- $e^-$ beam accelerated by rf cavities
- Tune magnetic field to ensure path through magnets multiple of $\lambda$ of accelerating field.
- $e^-$ arrive back in phase → "Continuous" beam (high d.f.)

**Strecher ring technique**
(Spring8, Bonn, Frascati, GRAAL)
- $e^-$ beams fed in from linac
- Accelerated and stored in ring. - Useable beam bled off slowly
- Many built for synchrotron radiation – can exploit !!
- Tend to have poorer duty factors beam properties and less stable operation than microtrons
High intensity electron beams

From JLAB at 6 GeV to JLAB at 12 GeV

ADD magnets and power supplies

Upgrade Hall D (and beam line)

Upgrade magnets and power supplies

Enhance equipment in existing halls

Beam Power: 1MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV
Real photon beams from electron beams

**Laser back-scattering**
(LEGS, FRASCATI, DUKE, Spring8)
$E_γ$ smaller than beam energy
Facilities up to 4 GeV

**Tagged Bremsstrahlung**
(MAMI, Bonn, Lund, Jlab)
$E_γ$ up to ~beam energy
Facilities up to 6 GeV (9GeV ~ Yr 2012)

Both techniques can produce *polarised* $γ$ beams

- **Transverse polarisation**
  (Electric field vector oscillates in a plane)

- **Circular polarisation**
  (Electric field rotates Clockwise or anticlockwise)
Quasi-real photon tagging

★ Electron scattering kinematics

\[ -Q^2 = E^2 - |P|^2 \]
\[ Q^2 = 4 E_e E_{e'} \sin^2 \left( \frac{\theta_e}{2} \right) \]

\( Q^2 \approx 0 \) if electron scatters in very forward direction
Virtual photon \sim same properties as “real” photon
Termed “Quasi-real”

★ Photon tagged by detecting the scattered electron at low \( \theta_e < 4^\circ \)
High energy photons eg. upgraded JLAB: \( 7 < E_\gamma < 10.5 \) GeV

★ Quasi-real photons are linearly polarized
Analytic function of \( \theta_e, Q^2 \) and \( (E_e - E_{e'}) \)

★ High Luminosity (can even use thin gas target!)
Equivalent photon flux \( N_\gamma \approx 5 \times 10^7 \gamma \text{ sec}^{-1} \)
## Photon beam facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>$E_{\gamma}^{\text{max}}$ (GeV)</th>
<th>$I_{\gamma}^{\text{max}}$ (s$^{-1}$MeV$^{-1}$)</th>
<th>$\Delta E_{\gamma}$ (FWHM) (MeV)</th>
<th>Pol$_{\gamma}^\text{lin}$ (%)</th>
<th>Pol$_{\gamma}^\text{circ}$ (%)</th>
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<td>ELSA</td>
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<td>80</td>
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<td>30</td>
<td>100</td>
<td>100</td>
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Two selected physics topics

The equation of state for neutron rich matter

Coherent pion photoproduction to measure matter form factor

Transition matter FF’s

Probing confinement in the light quark sector

The hunt for hybrids
Our knowledge of the shape of stable nuclei is presently incomplete.

- Neutron skin

\[ r_n - r_p \]

- Relativistic mean field
- Skyrme HF

\[ 208 \text{Pb} \]

RMS charge radius accuracy < 0.001 fm
RMS neutron radius accuracy ~0.2 fm !!

Horowitz et al. PRC63 025501 (2001)
Piekarewicz et al. NPA 778 (2006)
Neutron skin and the equation of state

\[ E(n, \alpha) = E(n, 0) + S_2(n)\alpha^2 + S_4(n)\alpha^4 + \cdots \]

\[ S_2(n) = a_\text{sym} + \frac{p_0}{n_0^2} (n - n_0) + \frac{\Delta K_0}{18n_0^2} (n - n_0)^2 + \cdots \]

\[ n = \text{density (fm}^{-3}\text{)} \]
\[ \alpha = \frac{(N-Z)}{A} \]
\[ n_0 = \text{nuclear density} \]
Neutron stars
Thick neutron skin
→ Low transition density in neutron star
New data from X-Ray telescopes → mass, radii, temp of neutron stars!

Rutel et al, PRL 95 122501 (2005)
Horowitz, PRL 86 5647 (2001)
Horowitz, PRC 062802 (2001)

Direct URCA Cooling
\[ n \rightarrow p + e^- + \bar{\nu} \]
\[ e^- + p \rightarrow n + \nu \]

Constrains gravitational wave emission from neutron stars – Frequency and damping modes!!
**Coherent pion photoproduction**

Photon probe✓
Interaction well understood

π⁰ meson – produced with ~equal probability on protons AND neutrons.
Select reactions which leave nucleus in ground state

Reconstruct π⁰ from π⁰→2γ decay

Angular distribution of π⁰ → PWIA contains the matter form factor

\[
d\sigma/d\Omega(PWIA) = (s/m_N^2) A^2 (q_{\pi}/2k_\gamma) F_2(E_{\gamma*},\theta_{\pi*})^2 |F_m(q)|^2 \sin^2\theta_{\pi*}
\]

π⁰ final state interactions - use latest complex optical potentials tuned to π-A scattering data. Corrections modest at low pion momenta
Crystal Ball at MAMI

Crystal Ball
672 NaI crystals

TAPS
528 BaF$_2$ crystals

$\Delta E_\gamma \sim 2$ MeV
$10^8 \gamma$ sec$^{-1}$

Upstream view into the ball
Theoretical calculations: Unitary isobar model with complex $\pi^0\cdot A$ interaction

- $^{208}$Pb Coherent pion photoproduction – total $\sigma$

- $E_\gamma$ from threshold to $\sim$190 MeV is the “window” to get best access to FF
208Pb Coherent pion photoproduction – analysis for neutron skin

- Red line – Coh pi model plus detector resolution (Geant 4)
- Skin extraction - Linear interpolation between predicted distributions for different skin thicknesses – $\chi^2$ minimising fit to the data
- 2 parameter Fermi Fn. → Charge radii = $e^-$ scattering; ntn radii interval 0 - 0.5 fm
Neutron skins extracted from fit

Further work in progress – interpolated fit between Skyrme model predictions (Alex Brown)

Preliminary results rule out direct URCA cooling in neutron stars!
Transition matter form factors

→ Detect nuclear decay photon *in the same detector* as the $\pi^0$ decay photons

$\gamma$, $E_x$, $q$

$12\text{C}(\gamma,\pi^0)^{12}\text{C}(4.4\text{ MeV})$

$E_r=220-240\text{ MeV}$

$\sin^2(2\alpha)$  $\cos^2(2\alpha)$

Counts [arb. Units]

Alpha (deg)

Transition matter form factor with an EM probe!

CM Tarbert, DP Watts et. al.
$E_\gamma$ dependence of spin dependent / independent in medium

$E_\gamma = (170-180)\text{MeV}$

$^{12}\text{C}(\gamma,\pi^0)^{12}\text{C}(4.4\text{MeV})$

$E_\gamma = 175 \pm 5 \text{ MeV}$

$E_\gamma = (300-320)\text{MeV}$

$^{12}\text{C}(\gamma,\pi^0)^{12}\text{C}(4.4\text{MeV})$

$E_\gamma = 310 \pm 10 \text{ MeV}$

$E_\gamma = (400-440)\text{MeV}$

$^{12}\text{C}(\gamma,\pi^0)^{12}\text{C}(4.4\text{MeV})$

$E_\gamma = 420 \pm 20 \text{ MeV}$
Confinement – the process creating the nucleus

One of the outstanding issues in modern physics - full understanding of Quantum Chromodynamics

QCD → underpins understanding of mass and binding of the atomic nucleus, neutron stars, QGPs ...

Ability to calculate phenomena at the nucleonic and nuclear distance does not yet exist.
Need to test and understand the confinement process

Major advances in quality of experimental data and theory
In the coming decade (lattice, holographic dual)
Beyond the quark model: hybrids and exotica

Quarks are confined inside colourless hadrons
Combine to 'neutralize' the colour force

Other quark-gluon configuration can give colorless objects

QCD does not prohibit such states but not yet unambiguously observed
“Normal” mesons

★ **No** excitation of the gluonic field (or flux tube)

![Diagram of angular momentum](image)

S = S₁ + S₂

J = L + S

P = (-1)^(L+1)

C = (-1)^(L+S)

If the quark spins align then it is known as a **“vector” meson**

If anti aligned known as a **“scalar” meson**

**Normal meson:**

flux tube in ground state
m = 0 (no ang momentum in flux tube)

CP = (-1)^{S+1}

“C-parity” symmetry

Under operation of changing quarks to antiquarks

|q, q> = |qq> C=+1

|q, q> = - |qq> C=-1

Can define an intrinsic parity for the meson
(extra “+1” factor as parity q opposite to q)
### "Normal" Meson quantum numbers

<table>
<thead>
<tr>
<th>Meson(Mass)</th>
<th>S</th>
<th>J</th>
<th>P</th>
<th>C</th>
<th>CP</th>
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<tr>
<td>$\pi^0(135)$</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$\eta (547)$</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>$\Phi(1020)$</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

**Normal meson:**
- Flux tube in ground state
- $CP = (-1)^{S+1}$
**What if we excite the flux tube ??**

- Extra degree of freedom in the meson.
- Extra possibilities in relation between the quantum numbers

**Normal meson:**
- flux tube in ground state
  - \( m = 0 \)
  - \( CP = (-1)^{S+1} \)

**Hybrid meson:**
- flux tube in excited state
  - \( m = 1 \)
  - \( CP = (-1)^{S} \)

```
\[ q \quad \overline{q} \]
```

```
\[ m=1 \text{ flux tube alone has } J^{PC} 1^{++} \text{ or } 1^{+} \]
```

Combine excited flux tube quantum number with those of the quarks

→ “Exotic” Quantum Nos

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the meson!!

```
\[ J^{PC} = 1^{-} \text{ or } 1^{++} \]
```

```
\[ \tilde{L} = 0, \tilde{S} = 0 \]
```

```
\[ J^{PC} = 0^{-}, 1^{++}, 2^{++} \]
exotic
```

```
\[ \tilde{L} = 0, \tilde{S} = 1 \]
```
Lattice QCD indicates they should be there!

Dudek et. al.
PRL 103 262001 (2009)
Why photoproduction?

★ Only get exotic quantum numbers if excite a vector meson (S=1)

★ Cannot get a beam of vector mesons 😞. However high energy photons interact dominantly from fluctuations into a qq pair (Vector meson dominance)

Most attempts to date used pion beams.
S=0  →  exotics produced with low rate

★ Photoproduction rate for exotics is expected to be comparable to regular mesons !!
Quasi-real photon tagger for CLAS at JLAB

Calorimeter + tracking device + veto

Electron energy/momentum
- Photon energy ($\nu = E - E'$)
- Polarization $\varepsilon^{-1} = 1 + \nu^2/2EE'$

Electron angles
- $Q^2 = 4EE' \sin^2 \vartheta/2$
- $\varphi$ polarization plane

Veto for photons

Rates in the forward tagger

Inelastic electro-production Signal
- $R \sim 10\text{kHz}$

Elastic radiative tail
- $L_e \sim 10^{35} \text{ cm}^{-2} \text{s}^{-1}$
- $(N_\gamma \sim 0.5 \times 10^8 \gamma/\text{s})$

Moeller scattering Background
- $R \sim 100\text{kHz}$
- $R \sim 10\text{MHz}$

Veto for photons
Forward tagger in CLAS detector at JLab
The forward tagger in CLAS
Veto design

Will be placed in front of forward tagger crystals

Requirements - high rate capability, readout in high magnetic field (1-5 T)

- Newly developed, high gain SiPMs will be tested with fibre readout
- EU (FP7) seed funding for Edinburgh to lead development of the device + JLAB funding
CLAS12 in more detail

Hermetic charged/neutral particle detector

Forward Detector

★ TORUS Magnet
★ Forward SVT tracker
★ HT Cerenkov Counter
★ LT Cerenkov Counter
★ Forward TOF System
★ Preshower calorimeter
★ E.M. Calorimeter

Central Detector

★ SOLENOID magnet
★ Barrel silicon tracker
★ Central TOF

Proposed updates

★ Micromegas (CD)
★ Neutron detector (CD)
★ Forward Tagger
Statistical errors in the data used for the PWA extraction will become negligible with the new generation of experiments.

Key to establishing the feasibility of (and analysing) the next generation experimental data is assessing and controlling systematic errors.

Edinburgh has key role:
→ Shown that PWA with necessary accuracy to unambiguously isolate exotic partial waves is achievable using CLAS(12) and forward tagger.

Simulation studies (D. Glazier) form basis of first forward tagger proposal to PAC.
Partial wave analysis

Edinburgh-IU- INFN-JLab

Benchmark channel:
\[ \gamma p \rightarrow n \pi^+ \pi^+ \pi^- \]

- The process is described as sum of 8 isobar channels:
  - \( a_2 \rightarrow \rho \pi \) (D-wave)
  - \( a_1 \rightarrow \rho \pi \) (S-wave)
  - \( a_2 \rightarrow \rho \pi \) (D-wave)
  - \( \pi_2 \rightarrow \rho \pi \) (P-wave)
  - \( \pi_2 \rightarrow n \pi \) (F-wave)
  - \( \pi_2 \rightarrow f_2 \pi \) (S-wave)
  - \( \pi_2 \rightarrow f_2 \pi \) (D-wave)
  - \( \pi_1 \rightarrow \rho \pi \) (P-wave) (exotic)

- Amplitudes calculated by Szczepaniak (indiana)

- CLAS12 acceptance projected and fitted

Can isolate exotic with 1% contribution with a few weeks of beamtime!!
Detailed systematic studies are crucial ...

Possible evidence of exotic meson $\pi_1(1600)$ in $\pi^+p \rightarrow p \pi^-\pi^+$ (E852-Brookhaven)

Not confirmed in a re-analysis of a higher statistic sample
Our group leads new initiative to exploit production from nuclei in hybrid searches.

Momentum exchange in t-channel well suited to the nuclear wavefunction.

Nuclear production **kills** nucleon resonance production which complicates PWA.

Wide range of spin/isospin filters available!! Tag with low energy nuclear gamma.

Measure isoscalar and isovector in same measurement?
Incoherent count rates

Rate $\sim 15k$ day$^{-1}$

Count rate estimates assume modest decay gamma array at backward angle (120-150 deg) With 50% efficiency

Rate $\sim 1.2k$ day$^{-1}$

First calculations collaboration between Sandy Donnachie and Helmy Sherif
**Possible crystals to detect the nuclear decay photons**

- Phoswich design - good timing properties of LaBr to be combined with high stopping power, lower cost scintillators

- Planned for Spiral – set up collaboration to share costs of crystals/readout for use at JLAB
Other aspects of forward tagger programme

- Edinburgh co-spokesperson on $\Omega$ photoproduction proposal using forward tagger

- Cascades: Doubly strange nucleons – expect correspondence with excited states of nucleon (but .. much narrower states than in light quark sector, different dependences on dynamical processes)
Summary

- New generation of experiments with electromagnetic probes give clean information on strongly interacting matter from the scale of large nuclei down to the interactions between the light quarks of the nucleus.

- There is an exciting decade ahead of us in terms of understanding the strong interaction!