Deuteron Electro-Disintegration At Very High Missing Momenta

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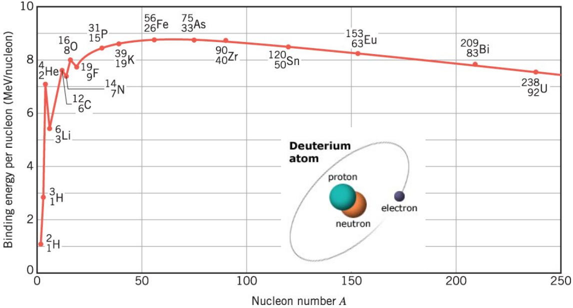
What is the Deuteron?

- Discovered in 1931 by H. Urey
- Starting point for studying NN interaction
- Weakly bound state (2.22 MeV/pair)



- Experiment: Deuteron has + spatial parity $\Longrightarrow$ L=0,2,4,...
- Experiment: Total Angular Momentum $J = 1\hbar$

$$\Longrightarrow S = s_p + s_n = \tfrac{1}{2} \otimes \tfrac{1}{2} = \boxed{1} \oplus 0$$

- $|\psi_D\rangle = a\,|^3S_1(L=0)\rangle + b\,|^3D_1(L=2)\rangle$
- No observed nn or pp bound states (Pauli exclusion, only S=0 singlet state possible for identical fermions)
- NN interaction is spin dependent

Evidence of Deuteron D-state Admixture

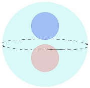
- Magnetic Dipole Moment $\mu_d = \mu_p^{(\text{orbital})} + \mu_p^{(\text{spin})} + \mu_n^{(\text{spin})}$

  $\mu_d^{tht}(^3S_1(L=0)) = \mu_p + \mu_n = 0.879805\mu_N \quad \mu_d^{tht}(^3D_1(L=2)) = 0.310\mu_N$

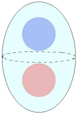
  $\mu_d^{exp} = 0.85741 \pm 0.00002\mu_N$

- Electric Quadrupole Moment
  - I.I. Rabi measured electric quadrupole moment in D (1939)
  - Multipole Expansion: $\phi(\mathbf{r}) = \phi_m(\mathbf{r}) + \phi_d(\mathbf{r}) + \phi_q(\mathbf{r}) + \cdots$

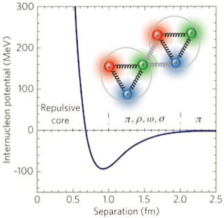
$$\phi(\mathbf{r}) = \sum_L \sum_{M=-L}^{L} C_L^M Y_L^M(\theta,\phi) = C_0^0 Y_0^0 + C_2^M Y_2^M(\theta,\phi)$$



$L = 0$



$L = 2$



$V_{int} = V_{central} \quad + \quad V_{non-central} \implies$ tensor force

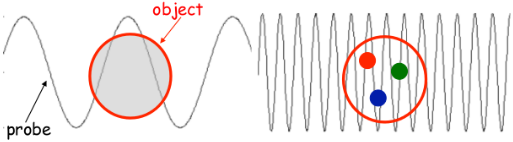
Motivation

- Study Deuteron at short ranges ($\lesssim$ 1fm).

  High momentum transfers (Q^2) $\Longrightarrow$ probe the Deuteron at smaller distances. Smaller internucleon distances enables one to access the high momentum components of nucleons

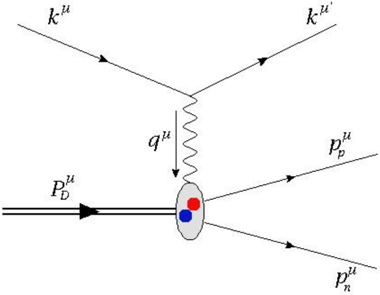
- Extract momentum distributions(not an observable) from cross sections

- Study transition from hadronic to quark-gluon degrees of freedom



Theoretical Framework of D(e,e'p)n

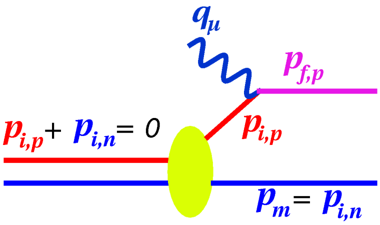
- E.M. Interaction ($\alpha \sim \frac{1}{137}$)
- One Photon-Exchange Approximation is valid
- virtual photon interacts with Deuteron through a variety of processes
- preferably, proton absorbs photon and is ejected while neutron recoils without further interaction (missing neutron momenta is same as internal momenta)

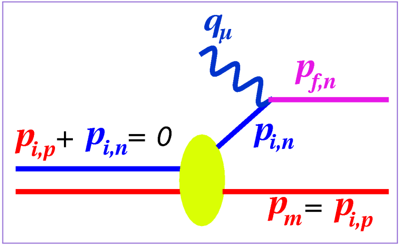


$$k^{\mu} = (E, \mathbf{k}) \qquad k^{\mu'} = (E', \mathbf{k}')$$
$$q^{\mu} = (\omega, \mathbf{q})$$
$$\omega = E' - E, \mathbf{q} = \mathbf{k}' - \mathbf{k}$$
$$P_D^{\mu} = (M_D, \mathbf{P_D})$$
$$\mathbf{P_D} = \mathbf{p_{i,p}} + \mathbf{p_{i,n}} = 0$$
$$Q^2 \equiv -q_{\mu}q^{\mu} = 4EE' \sin^2\left(\frac{\theta_e}{2}\right)$$

Plane Wave Impulse Approximation (PWIA)

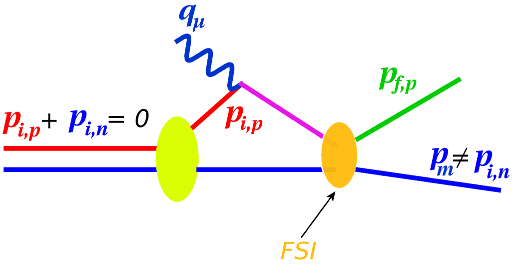
- virtual photon is completely absorbed by one of the nucleons
- the other nucleon is a spectator
- final state particles treated as plane waves (free particles)
- process in which neutron absorbs photon (+PWBA) is suppressed only for proton momenta significantly higher than missing momenta.





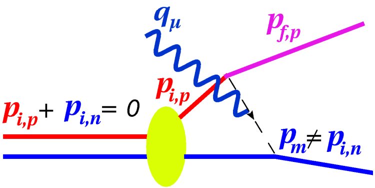
Final State Interactions (FSI)

- in final state, the nucleons are at short enough distances ($\sim$ 2 fm) and continue to interact
- eikonal approximation: infinite NN interactions are represented by an effective NN interaction amplitude obtained from NN scattering experiments
- nucleons re-scatter after interacting



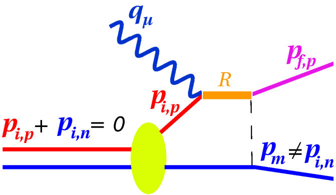
Meson Exchange Currents (MEC)

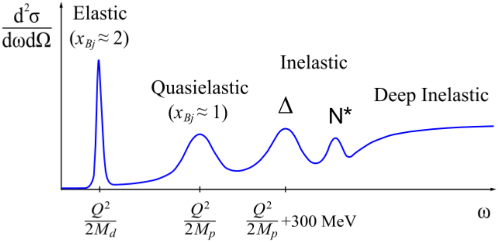
- virtual photon couples with exchange meson between nucleons
- virtual meson may become real after photon absorption
- meson exchange propagator is proportional to $(1 + \frac{Q^2}{m_{meson}^2})^{-1}$
  $\Longrightarrow$ MEC suppressed for $Q^2 \gg m_{meson}^2$



Isobar Configuration Currents (IC)

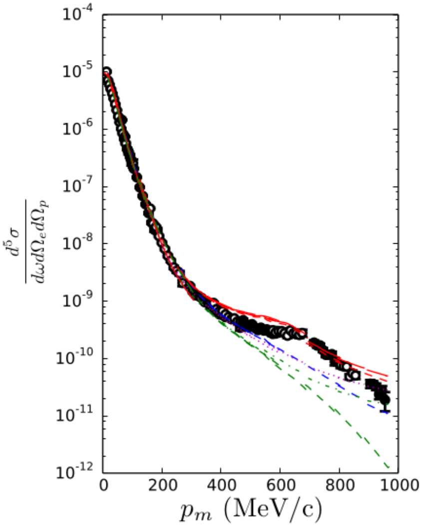
- virtual photon excites nucleon into resonance
- resonance de-excites through meson exchange with spectator nucleon
- for high Q^2, and $x_{B_j} > 1$ ($x_{Bj} \equiv \frac{Q^2}{2M_p\omega}$) one is able to probe the lower ω region of the quasi-elastic peak to suppress Δ or N^* resonance production





● Data
Arenhövel (FSI+MEC+IC)
PWIA+FSI+MEC+IC+R
PWIA+FSI+MEC
PWIA + PWBA
PWIA+FSI
PWIA

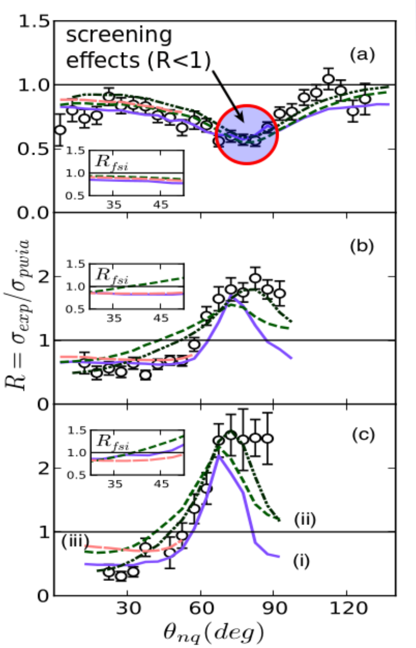
MAMI $Q^2 = 0.33$ (GeV/c)^2
Blomqvist et al. PLB 424 (1998) 33



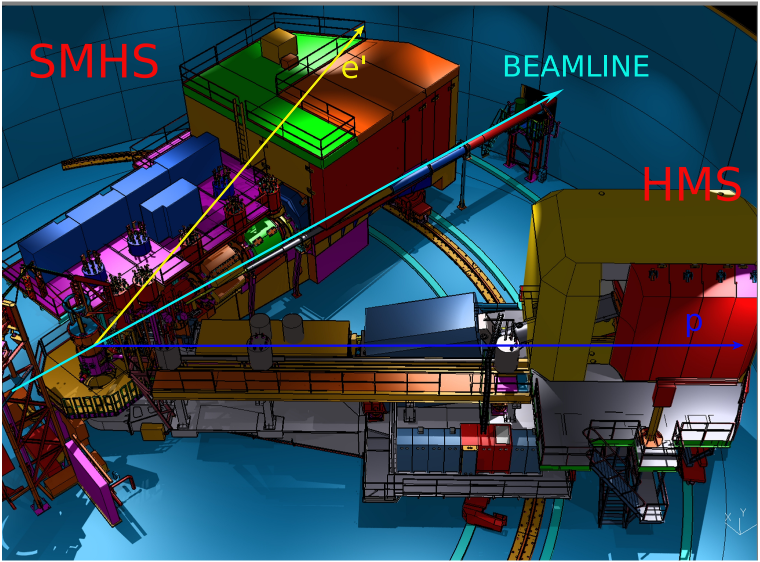
○ Data (JLAB HallA)
-·-·-·- JML (FSI+MEC+IC)
- - - - - JML (FSI)
——— MS using CD-Bonn potential
- - - - - JVO

$Q^2 = 3.5$ (GeV/c)^2
(a)p_m=0.2 GeV/c
(b)p_m=0.4 GeV/c
(c)p_m=0.5 GeV/c

W.U. Boeglin et. al
PRL 107(2011) 262501



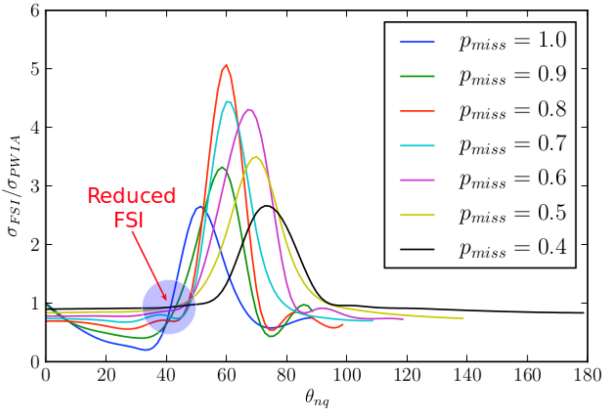
Hall C 12 GeV Upgrade and D(e,e'p)n



D(e,e'p)n Kinematics

$E_e = 11$ GeV
$Q^2 = 4.25$ (GeV/c)^2
$x_{B_j} = 1.35$
$p_m = 0.5 - 1.0$ GeV/c
$\theta_{nq} = 35^\circ - 40^\circ$

W.U. Boeglin et. al
Int.J.Mod.Phys. E24
(2015) no.03, 1530003



Conclusion and Future Outlook

- *np* bound state serves as starting point to study the strong nuclear force
- Investigate NN interaction at sub-fermi distances by using high energy e^- probe
- Previous experiments have shown that final state processes may be minimized in certain kinematic regions
- There are theoretical expectations that at high Q^2 and $x_{Bj} > 1$, soft two-body processes such as MEC and IC may be suppressed
- With the 12 GeV Upgrade at HallC, the D(e,e'p)n experiment seeks to explore new kinematic regions (backed by experimental and theoretical support) that will enhance PWIA over other processes

Acknowledgments

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Thank You!