Photoproduction of Eta Meson in Nuclear Target


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1 Introduction

Reactions with Lepton: Probes Electron Scattering & Photo Reaction

Purpose: Information of Nuclear Current $\langle \overline{\psi} \Gamma_\mu \psi \rangle$

photon absorption process

Information

Inclusive Reaction  □  Pure but Insufficient Amount

Exclusive Reaction  □  Large Amount but Impure

→ Final State Interaction

Collisional Processes of Observed Particles

Semi-Classical Numerical Simulation

BUU, QMD
Quantum Molecular Dynamics (QMD)

1) Single Events Semi-Classical Numerical Simulations

2) Classical Motions of Particles

3) Two Boson Collisions ← Experimental Data
   Inelastic Collisions: $N + N \rightarrow N + \Delta (N^*)$
   Particle Decays: $\Delta (N^*) \rightarrow N + \pi$

4) Describing Multi-Step Processes

5) Possible to Give Coincident Observables (p, \pi)

6) Applicable to various Kinds of Reaction

Photoreactions
   starting simulations at gamma-ray absorbed
Photoreaction

Total photoabsorption on nuclei

Total Photoabsorption Cross-Section

- N* - Resonance Peaks disappear

Medium Properties for N* Resonance?

Widths of D13(1520) and F15(1680) are broadened?

How about other S11(1535)?

Total photoabsorption cross section per nucleon (D, Be, C, U)
Chiral symmetry with spontaneous breakdown: Important concept in the hadron dynamics

$S_{11}(1535)$:
- A candidate of a chiral partner of nucleon

Partially restoration of chiral symmetry in nuclear medium
- Mass, coupling, width and so on


Properties of $S_{11}$ in Nuclei?
- Chiral structure of nucleon and nuclear resonance

Large branching ratio to $N$-$\pi$ (35 ~ 55 %)
Most of the $\pi$ photoproduction occur via $S_{11}$ resonance up to 1 GeV

16/Feb. 2006 Hadron-nuclear physics probed by photon
2 QM D Model

\[ Q M D = A \text{-Body Classical Motion} + 2\text{-Body Collisions} \]

1) Wave Function

\[ \Phi(\bar{x}_1, \ldots, \bar{x}_A) = \prod_i \phi_i(\bar{x}_i), \quad \phi_i(\bar{x}) = \frac{1}{(2\pi L^2)^{3/2}} e^{-\frac{1}{2} \frac{1}{L^2}(\bar{x} - \bar{r}_i)^2 + i\bar{p}_i \bar{x}} \]

2) Classical Motion Parts (Mean-Field Parts)

\[ \frac{d\bar{r}_i}{dt} = \frac{\partial H_{QMD}}{\partial \bar{p}_i}, \quad \frac{d\bar{p}_i}{dt} = -\frac{\partial H_{QMD}}{\partial \bar{r}_i}, \quad H_{QMD}(r_1, \ldots r_A; p_1, \ldots p_A) = \langle \Phi | H | \Phi \rangle \]

3) 2-Body Collisions + Pauli Blocking

\[ \text{Elastic Collisions: } N+N \rightarrow N+N \]
\[ \text{Inelastic Collisions: } N+N \rightarrow N+R \text{ (R+R)} \]

4) Statistical Decay
A nucleon absorbs photon
\[ \gamma + N \rightarrow \Delta, N^* \]

2 Body Col & Isobar Decay
Elastic Collisions
\[ N + N \leftrightarrow N+R, R+R \]
\[ R \leftrightarrow N + \pi(\eta) \]

Classical Motions by mean-field

Statistical Decay

Final Distribution
QMD (Quantum Molecular Dynamics)
Excite one nucleon

$\gamma N \rightarrow S_{11}$ (initial channel)

$\sigma_{\gamma p \rightarrow \eta p} = A \left( \frac{k_0}{k} \right)^2 \frac{s \Gamma_\gamma \Gamma_\eta}{(s - M_{S_{11}})^2 + s \Gamma_{\text{tot}}^2}$

$\Gamma_\gamma = b_\gamma \left( \frac{k}{k_0} \right) \Gamma_0$

$\Gamma_\pi = b_\pi \pi \Gamma_0$, $\Gamma_\eta = b_\eta \eta \eta \Gamma_0$

$\Gamma_{\text{tot}} = \Gamma_\pi + \Gamma_\eta = (b_\pi \pi + b_\eta \eta) \Gamma_0$

$x_{\pi(\eta)} = \frac{q_{\pi(\eta)}}{q_{R,\pi(\eta)}} \frac{e^2 + q_{R,\pi(\eta)}^2}{e^2 + q_{\pi(\eta)}^2}$

$\sigma_{\gamma n} = 0.67 \sigma_{\gamma p}$

Recent result of $(e,e'p)\eta$ at Jlab $\sim 154$ MeV

Analysis of QMD for $^{12}\text{C}$

![Graph showing $\sigma$ vs $E$ with various curves and data points]

- $\Gamma_0 = 212$ MeV, $b_\eta = 0.45$
- $\sigma_p \times (6 + 6 \times 0.67)$: elementary process
- + Fermi Motion & Pauli Blocking
- + $\eta$ absorption
- + $\Gamma_{\text{NR} \rightarrow \text{NN}}$

3 RMF approach

RMF approach: two kinds of Dirac Mean-Fields
\[ U_s : \text{attractive Scalar Fields} \]
\[ U_\mu : \text{repulsive Vector Fields} \]

In-medium Properties for Nucleon are quite different from that in vacuum

If in-medium corrections for N* are not so big, .... ?

\[ N^* (\text{vacuum}) \rightarrow N (\text{medium}) : \text{big medium effects are seen ?} \]

unbound \hspace{1cm} bound

\[ N^* \text{- mean-fields} \hspace{1cm} U_\alpha (N^*) = c_\alpha U_\alpha (N) \hspace{1cm} (\alpha = s, 0) \]
\[ \gamma + ^{12}\text{C} \rightarrow S_{11} \rightarrow \eta^+ \ X \]

**N*-width in Medium : Function of Phase Space**

\[ k_i^2 \rightarrow \langle k_i^2 \rangle = \frac{\sqrt{S_{\text{eff}}}}{2 p_R} \int_{p_-}^{p_+} \frac{p}{E_p} (1 - n(p)) \]

\[ S_{\text{eff}} = (p^* + q)^2 \]
BUU calculations

non-rela. calculation with Momentum-Dependent Potential

N* (high p, weak pot.) N (low p, deep pot.)

FIG. 1. Momentum dependence of the potential $V$ with parameter set $\mathcal{M}$ given in Table I for different densities.
\[
\sqrt{s_{\text{eff}}} = \sqrt{s} - U_N
\]

\[\text{N}^*(\text{unbound}) \rightarrow \text{N} (\text{bound})\]

Peak shift
Jaegle et al., Proc. of NSTAR05

Exp. : \( \gamma + D \rightarrow \pi\eta \)

a new production process
in high energy photon
Comparison with QMD

Potential change

\[ C(\gamma, \eta) \]

\[ \alpha = 0.0 \]

\[ \alpha = 1.0 \]

\[ \alpha = 0.8 \]

\[ U(N^*) = \alpha U(N) \]

Mass modification

\[ C(\gamma, \eta) \]

\[ M_{S_{11}}: 1541 \rightarrow 1491 \text{ MeV} \]
5 Summary

Numerical Simulation Approaches for Nuclear Reaction (BUU, QMD) are useful for study of Photoreaction Analyzing Final State Interaction

\[ \gamma + C, \text{Cu} \rightarrow \eta + X \quad \text{No dramatic results} \]

Elementary Process \[ \gamma + N \rightarrow \eta + X, \quad \gamma + N \rightarrow \pi \eta + X \]

Future

\[ \eta + \text{Nucleus Bound State} \]

Applying QMD to neutrino Reaction

In-Medium Form Factor

Neutrino Reaction \( \nu_\mu (500\text{MeV}) + C \rightarrow \nu_\mu \)

Neutrino Current Contribution

Exp: MiniNOONE

$\nu (500 \text{ MeV}) + ^{56}\text{Fe} \rightarrow p + X$

$\theta_p = 10^\circ$

$\theta_p = 30^\circ$

$\theta_p = 60^\circ$

$\theta_p = 90^\circ$

$10^3 \frac{d^2}{d^2E_p}\cdot [\text{cm}^2/\text{sr} \cdot \text{GeV}]$

$E_p [\text{MeV}]$

- full
- 1st.
- 2nd.
- higher step
- SD

\[
\Gamma(\text{In-Med.}) = \Gamma(\text{vac}) + \Gamma_{\text{coll}} \quad N^* + N \rightarrow N + N
\]

\[\Delta\Gamma = 75 \text{ MeV}\]

\[\Delta\Gamma = 315 \text{ MeV}\]

\[\Delta\Gamma = 320 \text{ MeV}\]

\[\Delta\Gamma = 315 \text{ MeV} \implies \sigma_{NN^*} = 180 \text{ mb}\]

cf. \[\sigma_{NN^*} = 90 \text{ mb} \] (from the inverse reaction)
Pion photoproduction and N*

Cooperative effect of collision broadening, π distortion and interference of 2π production

\[ \gamma p \rightarrow \pi^+ \pi^0 n \]

Single pion production
(Δ, N* dominant)

Double pion production
(Δ-KR etc.)

It is important to investigate the properties of each N* exclusively in this energy region.
Widths of $D_{13}(1520)$ and $F_{15}(1680)$ are broadened?

How about other $N^*$ Isobars?

$D_{13}(1520)$ and $F_{15}(1680)$ Decay Processes are too Complicated

\[
N^* \rightarrow N + \pi \\
\rightarrow N + \pi + \pi \\
\rightarrow N + \eta
\]

$S_{11}(1535)$ Decay Process is Simple

\[
N^* \rightarrow N + \pi \\
\rightarrow N + \eta
\]

KEK-Tanashi Experiments: $\gamma + A \rightarrow \eta + X$

Information of $S_{11}$ Isobar Resonances

QMD Analysis (Yorita et al.)

Theory \* Ecperiment

Width $\Gamma(S_{11}) = 150\text{MeV}$ Not Good

Elementary $\Gamma(S_{11}) = 150\text{MeV}$

Width $\Gamma(S_{11}) = 212\text{MeV}$ Good