Cold nuclear matter experiments

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Outline
• motivation
• experimental approaches for studying in-medium properties of mesons
• in-medium properties of $\rho$, $\omega$, and $\Phi$ meson
• summary and outlook

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Electromagnetic probes of strongly interacting matter
ECT* Trento, Italy
May 20-24, 2013
hadrons = excitations of the QCD vacuum
QCD vacuum: complicated structure characterized by condensates
in the nuclear medium: condensates are changed

\[ m \approx \langle \bar{q}q \rangle_0 \approx 0.8(\rho \approx \rho_0) \]

\[ \frac{m^*}{m} \approx \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle_0} \approx 0.8(\rho \approx \rho_0) \]

\[ \frac{m^*_V}{m_V} = \left(1 - \alpha \frac{\rho}{\rho_0}\right); \alpha \approx 0.18 \]

widespread theoretical and experimental activities to search for in-medium modifications of hadrons
QCD sum rule approach: drop of $\rho, \omega$ mass by about 10% at average nuclear density of 0.6 $\rho$

spectral function for $\omega$ meson at rest: splitting into $\omega$-like and $N^*N^{-1}$ mode due to coupling to $S_{11}$ resonance; almost no mass shift; strong in-medium broadening
model predictions for spectral function of the $\rho$ meson

- structure in $\rho$ spectral function due to coupling to baryon resonances
- strong momentum dependence
- modifications most pronounced at small momenta

M. Post et al, NPA 741 (2004) 81
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**experimental task:** search for \{ mass shift ? broadening ? structures ? \} of hadronic spectral function

ensure acceptance for low meson momenta !!
- **heavy-ion collisions:**
  - CERN SPS: HELIOS-3, CERES, NA60, $\sqrt{s} = 17$ GeV;
  - BNL RHIC: PHENIX, STAR, $\sqrt{s} = 200$ GeV;
  - GSI SIS18: HADES, $\sqrt{s} \approx 3$ GeV
  - probes: $e^+e^-, \mu^+\mu^-$, acceptance for $p_t > 0$ MeV/c

- **proton induced reactions:**
  - KEK: 12 GeV p;
    - probes: $e^+e^-, K^+K^-$; acceptance for meson momenta $> 800$ MeV/c
  - COSY ANKE: p 1.0 - 3.5 GeV/c;
    - probes: $K^+K^-$; acceptance for meson momenta 0.6-1.6 GeV/c
  - GSI SIS18: HADES, $\sqrt{s} \approx 3$ GeV
    - probes: $e^+e^-, K^+K^-$; acceptance for meson momenta $> 50$ MeV/c

- **photon induced reactions:**
  - LEPS@SPRING8: 1.4-2.5 GeV
    - probes $K^+K^-$; acceptance for meson momenta $> 1.2$ GeV/c
  - JLab CLAS: 0.6-3.5 GeV
    - probes: $e^+e^-$; acceptance for meson momenta $> 0.8$ GeV/c
  - CBELSA/TAPS: 0.8-3.1 GeV
    - probes: photons; acceptance for meson momenta $> 0$ MeV/c
  - CB/TAPS@MAMI: 0.9-1.4 GeV
    - probes: photons; acceptance for meson momenta $> 0$ MeV/c
From theoretical predictions to experimental observables
calculations of meson spectral functions assume:
- infinitely extended nuclear matter in equilibrium at $\rho, T = \text{const.}$;
- meson at rest in nuclear medium
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- meson at rest in nuclear medium

transport calculations (GiBUU, HSD, UrQMD, MCMC...)
are needed for comparison with experiment !!!

- initial state effects: absorption of incoming beam particles
- non equilibrium effects: varying density and temperature
- absorption and regeneration of mesons
- fraction of decays outside of the nuclear environment
- final state interactions: distortion of momenta of decay products
experimental approaches for studying in-medium effects of mesons in photon- and proton- induced reactions

meson-nucleus optical potential:

\[ U(r) = V(r) + iW(r) \]
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\[ V(r) = \Delta m_0 \cdot \frac{\rho(r)}{\rho_0} \]
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\[ V(r) = \Delta m_0 \cdot \frac{\rho(r)}{\rho_0} \]

**meson absorption**

\[ W(r) = -\frac{\Gamma_0}{2} \cdot \frac{\rho}{\rho_0} \]

\[ = -\frac{1}{2} \cdot \hbar c \cdot \rho(r) \cdot \beta \cdot \sigma_{inel} \]
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- **Lineshape analysis**
  \[
  M \rightarrow X_1 + X_2
  \]
  \[
  m_M(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}
  \]

- **Analysis of meson momentum distribution**

- **Meson-nucleus bound states**
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- transparency ratio
  \[ T_A = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}} \]
measurement of the transparency ratio

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transparency ratio measurement

attenuation measurement of meson flux:
(D. Cabrera et al., NPA 733 (2004) 130)

\[ T_A = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}} \]

production probability per nucleon within the nucleus compared to production probability on the free nucleon;

inelastic channels: \( \pi / \eta \)
transparency ratio measurement

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production probability per nucleon within the nucleus compared to production probability on the free nucleon;

inelastic reactions remove mesons, e.g. \( \omega, N \rightarrow \pi N, \eta N \)
shortening of \( \omega \) lifetime in the medium \( \Rightarrow \) increase in width

low density approximation:
\[ \Gamma(\rho) = -\frac{Im\Pi(\rho)}{E} = \hbar c \cdot \rho \cdot \beta \cdot \sigma_{inel}; \quad \Gamma(\rho) = \frac{\Gamma(\rho_0)}{\rho_0} \frac{\rho}{\rho_0} \]

information on imaginary part of meson-nucleus potential

width = property of the meson-quasi-particle in the medium, reflecting the interaction with the nuclear environment
transparency ratio measurement

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information on imaginary part of meson-nucleus potential

width = property of the meson-quasi-particle in the medium, reflecting the interaction with the nuclear environment

applicable to any meson lifetime !!

information on in-medium properties of mesons from measurement of their decay outside of the nucleus
systematic uncertainties in measurement and interpretation of the transparency ratio

1.) secondary production in multi-step processes

\[ \gamma \, N_1 \rightarrow \pi \, N_1 \]
\[ \pi \, N_2 \rightarrow \omega \, N_2 \]

second generation particles have on average lower momenta
⇒ apparent increase of transparency ratio at low meson momenta
⇒ \textit{momentum dependence} of transparency ratio
systematic uncertainties in measurement and interpretation of the transparency ratio

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2.) photon shadowing:
due to hadronic fluctuations photons do not reach all nucleons
⇒ apparent reduction of transparency ratio

\[ A \Rightarrow A_{\text{eff}} \text{ (below 2 GeV < 10\% effect)} \]
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3.) two-body absorption processes:
absorption processs involving 2 nucleons distort \( \Gamma \rightarrow \sigma_{\text{inel}} \) conversion

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\[ \text{e.g. } \gamma N_1 \rightarrow \pi N_1 \]
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\Rightarrow \text{apparent increase of transparency ratio at low meson momenta}
\Rightarrow \text{momentum dependence of transparency ratio}

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3.) two-body absorption processes:
absorption processs involving 2 nucleons distort \[ \Gamma \rightarrow \sigma_{\text{inel}} \text{ conversion} \]
distortions can be reduced by taking light nucleus like C as reference:
\[
T_A^C = \frac{11.4 \times \sigma_{\gamma A \rightarrow \omega X}}{A_{\text{eff}} \times \sigma_{\gamma C \rightarrow \omega X}}
\]
photoproduction of $\omega$ off $p$, $d$, $C$, $Ca$, $Nb$, $Pb$

CB/TAPS@ELSA  $\omega \rightarrow \pi^0 \gamma \rightarrow 3\gamma$

M. Kotulla et al, PRL 100 (2008) 192302

$E_\gamma = 1200 - 2200$ MeV

$\omega$ photoproduction on the proton and deuteron;
F. Dietz et al.

- free proton
- bound proton
- bound neutron

$E_\gamma = 1.9-2.0$ GeV
$\gamma d \rightarrow \omega n(p)$
$\gamma d \rightarrow \omega p(n)$

bound neutron
bound proton

incident beam energy $E_\gamma$ [GeV]
transparency ratio normalized to carbon: \( T_A^C = \frac{11.4 \times \sigma_{\gamma A \rightarrow \omega X}}{A_{\text{eff}} \times \sigma_{\gamma C \rightarrow \omega X}} \)

comparison to calculations: Mühlich and Mosel; Ramos and Oset

M. Kotulla et al.,
PRL 100 (2008) 192302

low density approximation:
\[ \Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{\text{inel}} \]
\[ \sigma_{\omega N} \approx 60 \text{ mb} \]
transparency ratio normalized to carbon: 

\[ T^C_A = \frac{11.4 \times \sigma_{\gamma A \rightarrow \omega X}}{A_{eff} \times \sigma_{\gamma C \rightarrow \omega X}} \]

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low density approximation:

\[ \Gamma(\rho_0) = \frac{\hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}^{inel}}{\sigma_{\omega N}^{inel}} \approx 60 \text{ mb} \]

no strong variation of transparency ratio with meson momentum;
\[ \Rightarrow \text{no evidence for two-step processes} \]
comparison to CLAS measurement of $\omega$ transparency ratio

M.H. Wood et al., PRL 105 (2010) 112301

long standing puzzle:
much stronger $\omega$ absorption observed by CLAS than by CBELSA/TAPS (when normalized to carbon)
comparison to CLAS measurement of $\omega$ transparency ratio

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long standing puzzle: much stronger $\omega$ absorption observed by CLAS than by CBELSA/TAPS (when normalized to carbon)

$$T_A \Gamma_{12}^C$$

$$T_A^D = \frac{\sigma_{\gamma A \rightarrow \omega X}}{Z_{eff} \sigma_{\gamma p^{bound}} + N_{eff} \sigma_{\gamma n^{bound}}}$$

$T_C$ normalized to $^2\text{H}$

CLAS: $0.9\pm0.2$

CBELSA/TAPS: $0.46\pm0.05$

CLAS $T_A$-values for $A>50$ consistent with CBELSA/TAPS data when normalized to $^2\text{H}$

⇒ normalization problem ??
momentum dependence in transparency ratio: dilepton production


\[ \pi^0, \eta \rightarrow \gamma e^+ e^-; \omega \rightarrow \pi^0 e^+ e^-; \]
\[ \Delta, N^* \rightarrow N e^+ e^-; \rho, \omega \rightarrow e^+ e^- \]
momentum dependence in transparency ratio: dilepton production


$\pi^0, \eta \rightarrow \gamma e^+e^-; \omega \rightarrow \pi^0 e^+e^-;
\Delta, N^* \rightarrow N^e e^-; \rho, \omega \rightarrow e^+e^-$

$R_{pA} = \frac{d\sigma / dp^p}{d\sigma / dp^p_{part}} \cdot \frac{A_{pp}^{pN_b}}{A_{pp}^{pN_b}_{part}} \cdot \frac{\sigma_{pp}^{reaction}}{\sigma_{pN_b}^{reaction}}$

momentum dependence of dilepton spectra; $\Rightarrow$ two-step production processes
the higher the $e^+e^-$ invariant mass the stronger the momentum dependence;
no momentum dependence for transparency ratio of identified $\omega$
extraction of in-medium width and inelastic cross section for $\phi$

**LEPS@SPring-8**

$\gamma A \rightarrow \phi + X \rightarrow K^+ K^- + X; \ E_\gamma = 1.5 - 2.4 \text{ GeV}$

T. Ishikawa et al., PLB 608 (2005) 215


$\sigma_{\phi N} = 27 \text{ mb}$

$\Gamma(\rho_0) = \hbar c \cdot \rho_0 \cdot \beta \cdot \sigma_{\text{inel}} \approx 80 \text{ MeV}$

T. Ishikawa et al., PLB 608 (2005) 215

$\sigma_{\phi N}^A = 35^{+17}_{-11} \text{ mb} \gg \sigma_{\phi N}^{\text{free}} = 7.7 - 8.7 \text{ mb}$

$\Gamma(\rho_0) = \hbar c \cdot \rho_0 \cdot \beta \cdot \sigma_{\text{inel}} \approx 100 \text{ MeV \ for \ } \langle p_{\phi} \rangle = 1.8 \text{ GeV/c; \ } \langle \beta_{\phi} \rangle = 0.87$
momentum dependence of $\Phi$ meson transparency ratio

**ANEK@COSY:** $p\ (2.83\ \text{GeV}) \rightarrow C, Cu, Ag, Au$

$\Phi \rightarrow K^+ K^-$

A. Polyanski et al., PLB 695 (2011) 74
M. Hartmann, et al., PRC 85 (2012) 935206

transparency ratio momentum dependent:
$\Rightarrow$ two-step production processes important
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transparency ratio momentum dependent:
$\Rightarrow$ two-step production processes important

evidence for increase of $\Phi$ meson width with momentum,
consistent with earlier Spring8 and JLab measurements

$\Gamma_\Phi \approx 30 - 60$ MeV
$\sigma_{\Phi N} \approx 14 - 21$ mb
for $p_\Phi \approx 0.6 - 1.6$ GeV/c
what have we learned from transparency ratio measurements?

- Transparency ratio measurements provide information on absorption of mesons in nuclei \( \Rightarrow \) imaginary part \( W(\rho=\rho_0) \) of meson-nucleus potential; applicable for any meson lifetime

- \( \omega, \eta', \Phi \) mesons show broadening in nuclei; lifetime shortened (width increased) by inelastic processes

<table>
<thead>
<tr>
<th>Particle</th>
<th>( \Gamma(\rho_0) ) [MeV]</th>
<th>( \langle p \rangle ) [GeV/c]</th>
<th>( W(\rho=\rho_0) ) [MeV]</th>
<th>( \sigma_{\text{inel}} ) [mb]</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega )</td>
<td>130-150</td>
<td>1,1</td>
<td>65-75</td>
<td>( \approx ) 60</td>
<td>CBELSA/TAPS</td>
</tr>
<tr>
<td>( \eta' )</td>
<td>15-25</td>
<td>1,1</td>
<td>7.5-12.5</td>
<td>3-10</td>
<td>CBELSA/TAPS</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>30-60</td>
<td>0.6-1.4</td>
<td>15-30</td>
<td>14-21</td>
<td>ANKE@COSY</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>100(^{+50}_{-30})</td>
<td>1.8</td>
<td>50(^{+25}_{-15})</td>
<td>35(^{+17}_{-11})</td>
<td>LEPS@SPring-8</td>
</tr>
</tbody>
</table>
determination of the real part of the meson-nucleus potential: line shape analysis

\[ M \rightarrow X_1 + X_2; \quad m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2} \]

sensitive to nuclear density at decay point

1.) ensure sizable fraction of decays in the nuclear medium: ⇒ select short lived mesons or cut on recoil momentum

2.) avoid distortion of 4-momentum vectors by final state interactions ⇒ dilepton spectroscopy: \( \rho, \omega, \Phi \rightarrow e^+e^- \)

disadvantage: small branching ratio \( \approx 10^{-4} - 10^{-5} \)

\( \omega \rightarrow \pi^0\gamma \rightarrow 3\gamma; \) br=8.3% ; disadvantage: \( \pi^0 \)-FSI

3.) measured mass distribution = convolution of spectral function with branching ratio into final state:

\[ \frac{d\sigma}{dm} \sim A(m, p) \cdot \frac{\Gamma_{M\rightarrow X_1+X_2}}{\Gamma_{tot}} \]

e\textsuperscript{+}e\textsuperscript{-} spectra from photon and proton induced reactions

**JLAB-CLAS:** \( \gamma A \rightarrow e^+e^-X; \)  
\( E_\gamma = 0.6-3.8 \) GeV  
R. Nasseripour et al., PRL 99 (2007) 262302

**KEK-E325:** \( p(12 \text{ GeV}) A \rightarrow e^+e^-X; \)  
M. Naruki et al., PRL 96 (2006) 092301

\[ m_\rho(\rho) = m_0 \cdot (1 - 0.092 \frac{\rho}{\rho_0}) \]

\( \rho \) slightly broadened; no mass shift

\( \rho \) shifted in mass; no broadening!!

(b) Cu

with mass modification
e^+e^- spectra from photon and proton induced reactions

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no consistent picture !! needs further experimental clarification !! ⇒ JPARC-E16
dilepton invariant mass spectra

HADES@GSI  
p + p, Nb 3.5 GeV


$p_{ee} > 800$ MeV/c

shape of $m_{ee}$ spectrum in $p+Nb$ identical to reference spectrum in $p+p$
dilepton invariant mass spectra

HADES@GSI  p + p, Nb 3.5 GeV


- $p_{ee} > 800$ MeV/c
- $p_{ee} < 800$ MeV/c

- Strong $e^+e^-$ excess yield below $\omega$ peak attributed to $\rho$-like channels;
- No hint for change in $\omega$ line shape;
- Strong $\omega$ absorption confirmed

Shape of $m_{ee}$ spectrum in $p+\text{Nb}$ identical to reference spectrum in $p+p$
comparison to Gi BUU simulations


comparison to different in-medium modification scenarios

HADES data


\( p + Nb \) at 3.5 GeV

\[ m_{e^+e^-} \text{ [GeV]} \]

- difficult to distinguish between different in-medium scenarios:
- difficult to disentangle \( \rho, \omega \) contributions and to extract individual in-medium properties
only small differences between the scenarios: “no medium effects” and “collisional broadening”
(treatment of bremsstrahlung using extrapolation of OBE approximation to such high energies questionable)
in \( \rho \) mass region collisional broadening scenario somewhat closer to data
$E_\gamma = 0.9 - 1.3$ GeV

$\omega \rightarrow \pi^0 \gamma$ lineshape analysis

M. Thiel
$\omega \rightarrow \pi^0 \gamma$ lineshape analysis

comparison with reference measurement on LH$_2$

no significant structure in spectral function; signal on Nb slightly broader than on C, LH$_2$
$\omega \rightarrow \pi^0 \gamma$ lineshape analysis

M. Thiel

CB@MAMI

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comparison with reference measurement on LH$_2$

comparison with GiBUU calculations for different in-medium scenarios (J. Weil, U. Mosel)

no significant structure in spectral function; signal on Nb slightly broader than on C, LH$_2$

data consistent with collisional broadening; mass shift scenario less likely

PRELIMINARY
Why is the line shape measurement so insensitive to in-medium modifications of the $\omega$ meson??

- only 20-30% of the $\omega \rightarrow \pi^0 \gamma$ decays occur within the nuclear medium;
  $\tau_\omega = 22$ fm/c; $<p_\omega> \approx 600$ MeV/c; $<\beta_\gamma>\omega \approx 0.77$; $<d> = \beta_\gamma c \tau \approx 17$ fm
Why is the line shape measurement so insensitive to in-medium modifications of the $\omega$ meson??

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- a possible density dependent mass shift is smeared out due to the in-medium collisional broadening of the $\omega$-signal: $\Gamma(\rho_0) \approx 130 - 150$ MeV

- due to $\pi^0$ absorption ($\pi^0$-FSI) $\omega \rightarrow \pi^0 \gamma$ decays in the center of the nucleus are not registered; only $\omega \rightarrow \pi^0 \gamma$ decays in the surface region can be reconstructed.
Φ meson in the nuclear medium

KEK-E325 $p(12 \text{ GeV}) A \rightarrow \Phi + X; \quad \Phi \rightarrow e^+e^-; \quad cT = 46 \text{ fm}$

R. Muto et al., PRL 98 (2007) 042501

$\beta \cdot \gamma \leq 1.25$ (slow) \quad 1.25 \leq \beta \cdot \gamma \leq 1.75$

mass shift of Φ meson in Cu for low Φ recoil momenta:

$m_\phi(\rho) = m_0 (1 - 0.034 \frac{\rho}{\rho_0})$

increase in width by factor 3.6 $\Rightarrow \Gamma_\Phi \approx 15 \text{ MeV}$
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increase in width by factor 3.6 ⇒ \[ \Gamma_\Phi \approx 15 \text{ MeV} \]

to be confirmed in JPARC-E16, S. Yokkaichi et al.
mesons with lowered in-medium mass have to leave the nucleus with on-shell mass; mass has to be generated at the expense of the kinetic energy of the meson

⇒ shift of meson momentum distributions towards smaller momenta

GiBUU calculations (J. Weil et al., PLB (2013)) in comparison to CB@MAMI data (M. Thiel et al.) for $^{12}$C, $^{92}$Nb ($\gamma$,ω); $E_\gamma = 900 - 1300$ MeV

scenarios with large (-16%) mass shift not supported by data
Search for meson-nucleus bound states
Population of $\omega$-mesic states in photo induced reactions

Forward going proton takes up momentum of incoming photon, leaving meson at rest; 
⇒ captured by nucleus in case of an attractive interaction

E. Marco and W. Weise, PLB 502 (2001) 59

Two ways of measuring excitation energy of mesic nucleus:
1.) missing mass spectrometry: measure spectrum of forward going proton
2.) measure kinetic energy of decay products of mesic state
theoretical predictions for $\gamma^{12}\text{C} \rightarrow \omega \otimes^{11}\text{B} + p$


formation cross section

no structures due to large $\omega$ in-medium width
peak in kinetic energy distribution correlated with depth of real potential
formation cross section

no structures due to large \( \omega \) in-medium width

peak in kinetic energy distribution correlated with depth of real potential

\( \omega \) absorption and \( \pi^0 \gamma \) decay + escape probability from GiBUU
theoretical predictions for $\gamma^{12}\text{C}\to\omega\otimes^{11}\text{B} + p$


formation cross section

no structures due to large $\omega$ in-medium width
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expected $\pi^0\gamma$ cross section

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peak in kinetic energy distribution for different potential depth

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π̄γ decay
S. Friedrich, CBELSA/TAPS collaboration
photo production of $\omega$ mesons on LH$_2$, C
in coincidence with forward going proton
$E_\gamma = 1250 - 3100$ MeV

kinetic energy distributions
of $\pi^0 \gamma$ pairs
peak at almost the same energy
for free proton and carbon:
$E_{\text{peak}} \approx 60$ MeV
⇒ $\omega$-nucleus potential
neither strongly attractive
nor strongly repulsive
S. Friedrich, CBELSA/TAPS collaboration
photo production of $\omega$ mesons on LH$_2$, C
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$E_Y = 1250 - 3100$ MeV

$\omega$-nucleus potential
neither strongly attractive
nor strongly repulsive

comparison with experiment
data consistent with shallow or even zero potential

V$_0 \approx$ -35$\pm$35 MeV

peak at 61$\pm$3 MeV
formation cross sections: GiBUU ↔ Nagahiro et al.

good agreement between quantum mechanical and transport calculation

within model dependencies:

\[ V_0 \approx (-35 \pm 35) \text{ MeV} \]
• observables for extracting in-medium properties of mesons: determination of real and imaginary part of the meson-nucleus potential
Summary

- observables for extracting in-medium properties of mesons: determination of real and imaginary part of the meson-nucleus potential

- imaginary potential:
  transparency ratio: (CBELSA/TAPS, ANKE, CLAS, LEPS)
  in-medium broadening of $\omega$, $\eta'$, $\Phi$ mesons;

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Observables for extracting in-medium properties of mesons: determination of real and imaginary part of the meson-nucleus potential

**Imaginary potential:**
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Meson spectral functions do change in the nuclear environment!!