Measurement of the in-medium $\Phi$-meson width in proton-nucleus collisions

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Scope of the talk

- Physics motivation
- Experiment at ANKE
- Data analysis
- Results and discussion
Φ in free space

- Meson spectral function:

\[ S(m) = \frac{1}{\pi} \frac{\Gamma_0/2}{(m - m_0)^2 + (\Gamma_0/2)^2}, \]

where:
- \( m_0 \) – pole mass
- \( \Gamma_0 \) – meson width

\( m_0 = 1.0195 \) GeV (PDG 2008)
\( \Gamma_0 = 4.26 \) MeV

- \( \Phi \) is a long-lived meson:

\[ \lambda_{\text{dec}} = \frac{\hbar c}{\Gamma_0} = 44 \text{ fm} \gg R(\text{Au}) \]
Φ in nuclear matter

- **Meson spectral function:**
  
  \[ S^*(m) = \frac{1}{\pi} \frac{\left( \Gamma_0 - 2\text{Im} U_{\text{opt}} \right)/2}{\left( m - (m_0 + \text{Re} U_{\text{opt}}) \right)^2 + \left( \left( \Gamma_0 - 2\text{Im} U_{\text{opt}} \right)/2 \right)^2}, \]

- **A general picture of numerous studies in different approaches, e.g. effective Lagrangians and QCD sum rules:**
  - mass modification is small
  - main medium effect on the Φ is significant increase of its width up to an order of magnitude
Methods of $\Phi$ in-medium width measurement I

- Study of the meson spectral function – measurement of low momentum $\Phi$'s:
  - $\Phi \rightarrow e^+e^- \ (BR = 3 \cdot 10^{-4})$
  - $\Phi \rightarrow K^+K^- \ (BR = 0.49, K^- FSI, hadronic potential)$

- Experiments:

**KEK-PS-E325:**
- Reaction: $pA \rightarrow \Phi X$, $\Phi \rightarrow e^+e^-$
- p-Energy: 12 GeV
- Targets: C, Cu
- Result: $\Gamma*/\Gamma_0 = 3.6$,
  - $\Gamma* \approx 11$ MeV for $<p_\Phi> = 1$ GeV/c
  - $\Delta m/m_0 = -3.4\%$
  - at $\rho=\rho_0$

R. Muto et al.,
PRL 98 (2007) 042501
Methods of Φ in-medium width measurement II

- Attenuation measurement of the Φ flux – analysis of the target mass dependence for the Φ production cross section

The Φ survival probability $D$ in the nucleus matter rest frame:

$$D = \exp \left( -\int_{z}^{\infty} dl \frac{\Gamma^* (p_{\Phi}, \rho(r)) m_0}{p_{\Phi}} \right), \quad \rho(r) - \text{local nuclear density.}$$

- Experiments:

**Spring-8/LEPS:**
- Reaction: $\gamma A \rightarrow \Phi X$, $\Phi \rightarrow K^+K^-$
- $\gamma$-Energy: 1.5 - 2.4 GeV
- Targets: Li, C, Al, Cu
- Result: $\sigma^*_{\Phi N} = 35^{+17}_{-11}$ mb
- $\Gamma^* \approx 100$ MeV
- for $<p_{\Phi}> = 1.8$ GeV/c

**JLab/CLAS:**
- Reaction: $\gamma A \rightarrow \Phi X$, $\Phi \rightarrow e^+e^-$
- $\gamma$-Energy: up to 4 GeV
- Targets: $^2$H, C, Ti-Fe, Pb
- Result: $\sigma^*_{\Phi N} = 16$-70 mb

**COSY/ANKE:**
- Reaction: $pA \rightarrow \Phi X$, $\Phi \rightarrow K^+K^-$
- $p$-Energy: 2.83 GeV ($\varepsilon_{NN} \approx 76$ MeV)
- Targets: C, Cu, Ag, Au
- Result: $\Gamma^* = 33$-50 MeV
- for $<p_{\Phi}> = 1.1$ GeV/c

T. Ishikawa et al., PLB 608 (2005) 215
M.H. Wood et al., PRL 105 (2010) 112301
A.Polyanskiy et al., PLB 695 (2011) 74

In low density approximation:

$$\Gamma^*_{lab}(\rho_0) = \frac{p_{\Phi}}{E} \sigma^*_{\Phi N} \rho_0$$
ANKE – forward angle magnetic spectrometer at internal target position of COSY

Pd – positive detector system
Nd – negative detector system
Fd – forward detector system

$\Phi$ momentum $(0.6 - 1.6)$ GeV/c,
and angular range: $0^\circ \leq \Theta_{\Phi} \leq 8^\circ$
Analysis: $K^+$ selection

- Delayed Veto Technique
- TOF Stop-Start

![Graphs showing the analysis of $K^+$ selection with and without delayed veto.](image)
Analysis: $\Phi/K^+K^-$ pairs identification

7000-10000 $\Phi$'s for each target (C, Cu, Ag Au)
A-dependence of $\Phi$ production cross section

- A-dependence in the form:

$$R = \frac{T_A}{T_C} = \frac{12}{A} \frac{\sigma^A_\Phi}{\sigma^C_\Phi} \quad T_A = \frac{\sigma^A_\Phi}{A \sigma^N_\Phi} \quad T_A \text{ – nuclear transparency ratio}$$

- Absolute and relative normalization of the $\Phi$ production cross section – use of the know pion data:

  relative normalization:

$$\frac{\sigma^A_\Phi}{\sigma^C_\Phi} = \frac{N^A_\Phi}{N^C_\Phi} \frac{N^A_\pi}{N^C_\pi} \frac{\sigma^A_\pi}{\sigma^C_\pi} \quad \frac{\sigma^A_\pi}{\sigma^C_\pi} = \left( \frac{A}{12} \right)^{\alpha_\pi}$$

  $\pi^+: p = 0.5 \text{ GeV} / c, \theta \sim 0^0$

  $\alpha_\pi = 0.38 \pm 0.02$

J. Papp et al., Phys. Rev. Lett. 34 (1975) 601;
V. V. Abaev et al., J. Phys. G 14 (1988) 903;
Yu. T. Kiselev et al., Preprint ITEP 56-96,
Moscow (1996).
Transparency ratio: experiment

ANKE (preliminary)

![Graph showing the transparency ratio experiment results]

- $R = (12/A)(\sigma^A/\sigma^C)$
- Data points for different materials (Cu/C, Ag/C, Au/C) are plotted against $p$ [GeV/c].

Note: The graph illustrates the experimental results for the transparency ratio across different values of $p$ for Cu/C, Ag/C, and Au/C materials.
Transparency ratio: experiment and models

ANKE (preliminary)

Valencia/E. Oset et al.
MC & Chiral Unitary Approach

Prediction: 28 MeV for Φ at rest for ρ=ρ₀

V. Magas et al., PRC 71 (2005) 065202; L. Roca (private communication)
Transparency ratio: experiment and models

**ANKE (preliminary)**

- **Cu/C**
- **Ag/C**
- **Au/C**

**Valencia/E. Oset et al.**
MC & Chiral Unitary Approach

**MOSCOW/E. Paryev**
Nuclear Spectral Function Approach

- V. Magas et al., PRC 71 (2005) 065202; L. Roca (private communication)
- E. Paryev, J. Phys. G 36 (2009) 015103
Transparency ratio: experiment and models

**ANKE (preliminary)**

- **Valencia/E. Oset et al.**
  - MC & Chiral Unitary Approach

- **Moscow/E. Paryev**
  - Nuclear Spectral Function Approach

- **Rossendorf/B. Kämpfer et al.**
  - BUU

**Graphs**

1. **R_{12A}(1)A_l^2 (GeV)** vs **p [GeV/c]**
   - **Cu/C**
   - **Ag/C**
   - **Au/C**

2. **R_{12A}(1)A_l^2 (GeV)** vs **p [GeV/c]**
   - Model 1
   - Model 2
   - Model 3

3. **R_{12A}(1)A_l^2 (GeV)** vs **p [GeV/c]**
   - Ag/C
   - Au/C

4. **R_{12A}(1)A_l^2 (GeV)** vs **p [GeV/c]**

**References**

- V. Magas et al., PRC 71 (2005) 065202; L. Roca (private communication)
- E. Paryev, J. Phys. G 36 (2009) 015103
- H. Schade, B. Kämpfer (private communication); cf. PRC 81 (2010) 034902
Transparency ratio: experiment and models

ANKE (preliminary)

Valencia/E. Oset et al.
MC & Chiral Unitary Approach

Moscow/E. Paryev
Nuclear Spectral Function Approach

Rossendorf/B. Kämpfer et al.
BUU

Relevant features for models:
• forward acceptance
• two-step production processes
• $\sigma_{pn \rightarrow pn\Phi}/\sigma_{pp \rightarrow pp\Phi} \approx 4$

V. Magas et al., PRC 71 (2005) 065202; L. Roca (private communication)

E. Paryev, J. Phys. G 36 (2009) 015103

H. Schade, B. Kämpfer (private communication); cf. PRC 81 (2010) 034902.
In-medium width $\Gamma_\Phi$ and $\sigma^*_{\Phi N}$ cross section (preliminary)

$$\text{LDA: } \Gamma^{\text{lab}}_\Phi (\rho_0) = \frac{p_\Phi}{E} \sigma^*_{\Phi N} \rho_0$$

$\Gamma^{\text{lab}}_\Phi \approx 33-50$ MeV ($\langle p_\Phi \rangle = 1.1$ GeV/c, $\rho_0 = 0.16$ fm$^{-3}$)

A.Polyanskiy et al., PLB 695 (2011) 74
Double differential cross section of $\Phi$ production (preliminary)

Excess in low momentum part

+ common systematics ~ 20 %
In-medium width $\Gamma_\Phi$ and $\sigma^{*}_{\Phi N}$ cross section (preliminary)

for $p_\Phi > 1.1$ GeV/c \( \Gamma_{\Phi}^{lab} \approx 45 \text{ MeV} \) and/or \( \sigma^{*}_{\Phi N} \approx 17 \text{ mb} \)
Summary

Momentum dependence of the $\Phi$-meson production under the forward angles has been studied at ANKE:

- Large in-medium $\Phi$ width is extracted from high momentum part of spectrum

- Preliminary differential cross sections are not completely reproduced by current model calculations in low momentum part
Thank You!
Extra Slides
Invariant mass spectra for 6 momentum bins
Comparison with three model calculations → \( \Phi \) in-medium width, and ...

Relevant features:

- two-step production
-\( \frac{\sigma_{pn \rightarrow pn \Phi}}{\sigma_{pp \rightarrow pp \Phi}} \approx 4 \)
- forward acceptance

A) V. Magas et al., PRC 71, 065202 (2005): MC & Chiral unitary approach
B) E. Paryev, J. Phys. G. 36 (2009) 015103: Nuclear spectral function
C) H. Schade, B. Kaempfer (private communication)
   (cf. PRC 81 (2010) 034902): BUU-Rossendorf

\[ \Gamma_{\Phi}^{\text{lab}} \approx 33-50 \text{ MeV} \quad (\langle p_{\Phi} \rangle = 1.1 \text{ GeV}/c, \rho_0 = 0.16 \text{ fm}^{-3}) \]

A. Polyanskiy et al., PLB 695 (2011) 74
BUU-Rossendorf (preliminary)

B. Kaempfer & H. Schade
BUU-Rossendorf (preliminary)
... its momentum dependence (preliminary)

**BUU/Rossendorf (preliminary):**
- including secondary production processes
- only primary production