Measurement of $\psi(3770)$ resonance parameters with KEDR detector at VEPP-4M

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KEDR collaboration
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**VEPP-4M collider**

- **Beam energy**: $1 \div 6$ GeV
- **Number of bunches**: $2 \times 2$
- **Beam current**, $E=1.8$ GeV: 2.0 mA
- **Luminosity**, $E=1.8$ GeV: $1.5 \cdot 10^{30} \frac{1}{cm^2 \cdot s}$

- **Resonant depolarization technique:**
  - Instant measurement accuracy $\approx 1 \times 10^{-6}$
  - Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ (10 $\div$ 30 keV)

- **Infra-red light Compton backscattering** (2005):
  - Statistical accuracy $\approx 5 \times 10^{-5} / 30$ minutes
  - Systematic uncertainty $\approx 3 \times 10^{-5}$ (50 $\div$ 70 keV)
KEDR detector

- 1. Vacuum chamber
- 2. Vertex detector
- 3. Drift chamber
- 4. Aerogel counters
- 5. ToF–counters
- 6. LKr–calorimeter
- 7. Superconducting coil
- 8. Magnet yoke
- 9. Muon tubes
- 10. CsI–calorimeter
- 11. Compensation solenoid
- 12. VEPP–4M quadrupole

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**ψ(2S) – ψ(3770) scans**

Left: Visible cross section $e^+e^- \rightarrow \text{hadrons}$ vs. CM energy for the three scans (detection efficiencies are different).

Right: Cross section $e^+e^- \rightarrow \text{hadrons}$ after light quark etc. background subtraction.

The lines are the result of a simultaneous fit. $\int \mathcal{L} \, dt \simeq 2.4 \text{ pb}^{-1}$
The lineshape for $\psi(3770)$

$$\sigma_{vis}^{fit}(W) = \epsilon_{D\bar{D}} \int \left( \left| BW_{\psi(3770)}^0 + A_{D^0\bar{D}^0} e^{i\phi} \right|^2 + \left| BW_{\psi(3770)}^+ + A_{D^+D^-} e^{i\phi} \right|^2 \right) \times F(x, W') G(W, W') dW' dx$$

$$+ \sigma_{D^*\bar{D}^*+\bar{D}^*D} + \sigma_{\psi(2S)}(W) + \epsilon_{\tau\tau} \sigma_{\tau\tau}(W) + \sigma_{\text{cont}}(W)$$

$$BW_{\psi(3770)}^+ = -\sqrt{12\pi} \Gamma_{ee} \frac{\Gamma_{D^+D^-}}{W^2-M^2+i\Gamma(W_f)M}, \quad |A_{D^+D^-}|^2 \sim Z(W) q_+^3 \left( \frac{m_{D^+}}{W} \right)^5 F(q_+, W)$$

$$BW_{\psi(3770)}^0 = -\sqrt{12\pi} \Gamma_{ee} \frac{\Gamma_{D^0\bar{D}^0}}{W^2-M^2+i\Gamma(W_f)M}, \quad |A_{D^0\bar{D}^0}|^2 \sim q_0^3 \left( \frac{m_{D^0}}{W} \right)^5 F(q_0, W)$$


$G(W, W')$ – Gaussian distribution of CM energy

$Z(W)$ – Coulomb interaction factor

$\sigma_{D^*\bar{D}^*+\bar{D}^*D} - D^*\bar{D}$ cross section above threshold

$F(q_0, W), F(q_+, W)$ – model form factor functions
Energy-dependent $\psi(3770)$ total width

$$\Gamma_{D^0\bar{D}^0}(W) = \Gamma_0 \frac{M}{W} \frac{\rho_0^3}{\rho_0^2+1} \frac{\rho_0^3}{\rho_0^2+1} + Z(M) \frac{\rho_{+r}^3}{\rho_{+r}^2+1}$$

$$\Gamma_{D^+D^-}(W) = \Gamma_0 \frac{M}{W} \frac{Z(W)\rho_+^3}{\rho_+^2+1} + Z(M) \frac{\rho_{+r}^3}{\rho_{+r}^2+1}$$

$\Gamma_0 = \Gamma(M)$ is nominal resonance width,

$m_{D^0}$ and $m_{D^+}$ are D meson masses,

$\rho_i = q_i R_0$, where $R_0$ is interaction radius and

$q_i (i = 0, +, 0r, +r)$ are the breakup momenta for $D\bar{D}$ pair

at the given $W$ and at the resonance peak:

$$q_0 = \sqrt{\frac{W^2}{4} - m_{D^0}^2}, \quad q_0r = \sqrt{\frac{M^2}{4} - m_{D^0}^2},$$

$$q_+ = \sqrt{\frac{W^2}{4} - m_{D^+}^2}, \quad q_+r = \sqrt{\frac{M^2}{4} - m_{D^+}^2}$$
The lineshape for $\psi(3770)$ (short review)

Description of the $\psi(3770)$ resonance lineshape in the experiments to study inclusive cross section:

- **MARK-I 1977, DELCO 1978, MARK-II 1980**
  - $\psi(3770)$ shape is non-relativistic p-wave Breit-Wigner with energy-dependent total width.
  - Nonresonant $D\bar{D}$ cross section $\sigma_{D\bar{D}} \propto q^3$
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- **BES2 2008b** – double resonance $\psi(3770)$ lineshape
Extended vector-dominance model and alternatives

Mahiko Suzuki, Walter W. Wada, Phys. Rev. 15, 3 1977

\[
\sigma_{\text{vis}}^{\text{fit}}(W) = \varepsilon_{D\bar{D}} \int \left( \left| BW_{\psi(3770)}^0 + BW_{\psi(2S)}^0 e^{i\phi} + A_{D^0\bar{D}^0} e^{i\phi} \right|^2 + \left| BW_{\psi(3770)}^+ + BW_{\psi(2S)}^+ e^{i\phi} + A_{D^+D^-} e^{i\phi} \right|^2 \right) \times F(x, W') G(W, W') dW' dx + \cdots
\]

Fit of BaBar and Belle data by Yuan-Jiang Zhang, Quiang Zhao arxiv:0911.5641
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+ \left| BW_{\Psi(3770)}^+ + BW_{\Psi(2S)}^+ e^{i\phi} + A_{D^+D^-} e^{i\phi} \right|^2 \right) \times \mathcal{F}(x, W') \ G(W, W') \ dW' \ dx + \cdots \]

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What are the alternatives?
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\]

\[ + \left| BW_{\psi(3770)} + BW_{\psi(2S)} e^{i\phi} + A_{D^+D^-} e^{i\phi} \right|^2 \right) \]

\[ \times \mathcal{F}(x, W') \ G(W, W') dW' dx + \cdots \]

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What are the alternatives?

We checked a few possible form factor dependences on \( q \) and \( W \):

\[ e^{-\frac{q^2}{a^2}} \ ; \ e^{-\frac{q^2}{a^2}} e^{ib(W-2m_{D^0, +})} \ ; \ \frac{1}{1+aq^b} \ ; \ \frac{e^{ib(W-2m_{D^0, +})}}{1+aq^4} \ ; \ \frac{1}{1+aq^2+bq^4} \]

\[ \frac{1}{1+a(W-M_{\psi(2S)})+b(W-M_{\psi(2S)})^2} \ ; \ \frac{1}{(W-M_{\psi(2S)})^a} \ ; \ \frac{e^{ib(W-2m_{D^0, +})}}{(W-M_{\psi(2S)})^a} \]
<table>
<thead>
<tr>
<th>Model, $F(q)$</th>
<th>$M_\Psi(3770)$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
<th>$\Gamma_{ee}$ [eV]</th>
<th>$\sigma^{bg}_{DD}(M)$ [nb]</th>
<th>C.L. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDM</td>
<td>3779.9 ± 1.6</td>
<td>24.0 ± 3.6</td>
<td>166 ± 69</td>
<td>0.21 ± 0.21</td>
<td>91.1</td>
</tr>
<tr>
<td>No Interf.</td>
<td>3772.8 ± 0.5</td>
<td>23.3 ± 2.2</td>
<td>324 ± 28</td>
<td>0.23 ± 0.10</td>
<td>12.2</td>
</tr>
<tr>
<td>$e^{-\frac{q^2}{a^2}}$</td>
<td>3780.5 ± 2.1</td>
<td>27.9 ± 3.6</td>
<td>258 ± 81</td>
<td>3.67 ± 1.69</td>
<td>86.2</td>
</tr>
<tr>
<td>$\frac{1}{1+aq^b}$</td>
<td>3779.4 ± 1.5</td>
<td>24.0 ± 3.6</td>
<td>168 ± 62</td>
<td>3.38 ± 0.85</td>
<td>90.5</td>
</tr>
<tr>
<td>$\frac{1}{1+aq^2+bq^4}$</td>
<td>3779.5 ± 1.5</td>
<td>24.8 ± 3.3</td>
<td>184 ± 61</td>
<td>3.29 ± 0.39</td>
<td>90.3</td>
</tr>
<tr>
<td>$\frac{e^{ib(W-2m_{D^0, +})}}{1+aq^4}$</td>
<td>3778.7 ± 1.7</td>
<td>25.3 ± 3.3</td>
<td>477 ± 236</td>
<td>2.81 ± 0.94</td>
<td>91.2</td>
</tr>
<tr>
<td>$\frac{1}{(W-M_\Psi(2S))^a}$</td>
<td>3780.4 ± 1.7</td>
<td>25.3 ± 3.8</td>
<td>185 ± 75</td>
<td>3.99 ± 1.25</td>
<td>89.8</td>
</tr>
<tr>
<td>$\frac{e^{ib(W-2m_{D^0, +})}}{(W-M_\Psi(2S))^a}$</td>
<td>3780.1 ± 1.5</td>
<td>25.1 ± 3.8</td>
<td>322 ± 246</td>
<td>3.52 ± 1.10</td>
<td>90.0</td>
</tr>
</tbody>
</table>
Comparison of different experiments

Measurement of $\psi(3770)$ resonance parameters with KEDR detector at VEPP-4M
Fits curves for different models

\[ F(q) \sim \frac{1}{1+aq^b} \]

\[ F(q) \sim \exp\left(-\frac{q^2}{a^2}\right) \]

No Interference

\( \sigma \text{ [nb]} \)

\( W \text{ [MeV]} \)

Kornely Todyshev
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Conclusions

- The parameters of $\psi(3770)$ are measured using the data collected by KEDR detector at VEPP-4M collider in 2004 and 2006.

- Model errors were underestimated at all previous works where total cross section was fitted.

- Correct resonance description should include interference and form factor.

- We did not observe two resonances near $\psi(3770)$ energy region.

\[
M_{\psi(3770)} = 3779.9 \pm 1.6^{+0.6}_{-1.3} \text{ MeV} \\
\Gamma_{\psi(3770)} = 24.0 \pm 3.6^{+1.3}_{-0.7} \text{ MeV}
\]
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Parametrization of $\psi(2S)$

$$\sigma_{\psi(2S)}(W) = \frac{12\pi}{W^2} \frac{\Gamma_{ee,\psi(2S)} \Gamma_{h,\psi(2S)}}{\Gamma_{\psi(2S)} M_{\psi(2S)}} \left[ \left( 1 + \delta_{sf} \right) \text{Im } f ight.$$

$$\left. - \left( 1 + \frac{11}{12} \beta \right) \frac{2\alpha\sqrt{R} \Gamma_{\psi(2S)} M_{\psi(2S)}}{3W \sqrt{\Gamma_{ee,\psi(2S)} \Gamma_{h,\psi(2S)}}} \lambda \text{ Re } f + \cdots \right],$$

Here $\alpha$ is the fine structure constant, $R = \sigma^{(h)}/\sigma^{(\mu\mu)}$, $\lambda = 0.023 \pm 0.009$

$$\delta_{sf} = \frac{3}{4} \beta + \frac{\alpha}{\pi} \left( \frac{\pi^2}{3} - \frac{1}{2} \right) + \beta^2 \left( \frac{37}{96} - \frac{\pi^2}{12} - \frac{1}{36} \ln \frac{W}{m_e} \right)$$

$$\beta = \frac{4\alpha}{\pi} \left( \ln \frac{W}{m_e} - \frac{1}{2} \right)$$

$$f = \frac{\pi \beta}{\sin\pi \beta} \left( \frac{M_{\psi(2S)}^2}{W^2} - 1 - i \frac{\Gamma_{\psi(2S)} M_{\psi(2S)}}{W^2} \right)^{\beta-1}$$

$$\sigma_{\psi(2S)}^{\text{fit}}(W) = \epsilon_{\psi(2S)} \int \sigma_{\psi(2S)}(W') G(W, W') \, dW'$$
Event selection

2004

1. $\geq 3$ charged tracks
2. $\geq 2$ charged tracks from IP
3. Sphericity more than 0.05

Selection efficiency is about 66%

2006

1. $\geq 3$ charged tracks
2. $\geq 1$ charged tracks from IP and $\geq 5$ clusters
   OR
   $\geq 2$ charged tracks from IP and $\geq 4$ clusters
   OR
   $\geq 3$ charged tracks from IP and $\geq 3$ clusters
3. An energy deposited in calorimeter $\geq 0.25$ energy beam

Selection efficiency is about 78%
### ψ(3770) mass systematic errors

<table>
<thead>
<tr>
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<th>Error [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-resonant cross section form</td>
<td>+0.5, −1.2</td>
</tr>
<tr>
<td>Fitting form ($R_0$ variations)</td>
<td>0.3</td>
</tr>
<tr>
<td>Luminosity measurement</td>
<td>0.2</td>
</tr>
<tr>
<td>Detection efficiency instability</td>
<td>0.1</td>
</tr>
<tr>
<td>Event selection</td>
<td>0.1</td>
</tr>
<tr>
<td>Absolute energy determination</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Sum in quadrature**

$$\approx +0.6, -1.3 \text{ MeV}$$

*Table:* The main systematic uncertainties in ψ(3770) mass (MeV)
### Table: The main systematic uncertainties in $\psi(3770)$ width (MeV)

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<td>Non-resonant cross section form</td>
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$\approx^{+1.3}_{-0.7}$ MeV