Precision measurement of the $\psi(2S)$ width in antiproton-proton annihilations

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Experimental technique
Resonance parameters from energy scan

\[ \bar{p} p \rightarrow e^+ e^- X \] events

antiproton beam energy distributions
Model: observed cross section is resonant cross section smeared by beam energy distribution

\[ \sigma_i = \frac{N_i}{\varepsilon_i L_i} = \int \sigma(w) \cdot B_i(w) \, dw \]

Resonance mass, width, peak cross section from maximum-likelihood fit to the data

With stochastically-cooled antiprotons, beam FWHM (0.4-0.5 MeV) is comparable with resonance width \( \Gamma \) (0.3 MeV)
Recent measurements of $\psi(2S)$ width

- E760 (1993): $306 \pm 36 \pm 16$
- BES (2002): $264 \pm 27$
- BES (2006): $331 \pm 58 \pm 2$
Event selection
Experiment E835 at the Fermilab Antiproton Accumulator

Two psi(2S) resonance scans during the 2000 data taking:
0.75 pb\(^{-1}\) (stack 1) and 0.89 pb\(^{-1}\) (stack 29)

Detector designed to tag inclusive e\(^{+}\)e\(^{-}\) pairs with high invariant mass

Same selection used for psi(2S) branching ratios

Low background contamination from hadronic processes (mainly photon conversions and Dalitz decays from pions)
\[ \bar{p} p \rightarrow \psi(2S) \rightarrow J/\psi + X \rightarrow e^+ e^- + X \]

invariant mass of e+e- candidates
Beam-energy measurement
After deceleration, beam is slightly bunched for stability and for detection with beam-position monitors (BPMs)

Usually, energy of antiprotons in rf bucket is calculated from their velocity

- revolution frequency is $f_{\text{rf}}$

- orbit length $L = L_0 + dL$ from comparison with reference orbit
  - external calibration from BPMs + lattice model

- velocity $v_{\text{rf}} = f_{\text{rf}} \times L \implies$ c.m. energy $w_{\text{rf}}$
Uncertainties

\[
\frac{\delta w}{w} = \gamma p^2 \left( \frac{\delta f}{f} + \frac{\delta L}{L} \right)
\]

(0.05 Hz) \quad (0.05 mm)
(0.6 MHz) \quad (474 m)

At the psi(2S)

\[
\frac{dw}{df} = 113 \text{ keV/Hz}
\]
\[
\frac{dw}{dL} = 149 \text{ keV/mm}
\]

uncertainty on \( L_0 \)
irrelevant for width

from \( dL \)
Beam energy distribution from Schottky frequency distribution

\[ \frac{p - p_{\text{rf}}}{p_{\text{rf}}} = -\frac{1}{\eta} \cdot \frac{f - f_{\text{rf}}}{f_{\text{rf}}} \quad \text{(constant B field)} \]

and machine slip factor \( \eta \)
Width determination
- Beam width is inversely proportional to slip factor $\eta$
- Positive correlation between slip factor and resonance width
- Slip factor can be measured from synchrotron frequency; uncertainty is 10%
- Corresponding systematic uncertainty on resonance width is 16% (E835/2000 stack 1 “constant orbit”)
$\psi(2S)$ Scan: Stack 1 (Jan 2000), $\eta = 0.02164$

<table>
<thead>
<tr>
<th>CENTER−OF−MASS ENERGY (MeV)</th>
<th>EVENTS / LUMINOSITY (nb)</th>
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<td>3684</td>
<td>3685</td>
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$\Gamma = (288 + 39 - 36) \text{ keV}$

$M = (3686.111 + 0.013 - 0.013) \text{ MeV}$

$\sigma_p = (6.09 + 0.7 - 0.59) \text{ nb}$

$\sigma_b = (65 + 34 - 32) \text{ pb}$

$\chi^2 / \text{ d.o.f.} = 33.2 / 12$

Stack 1

“constant orbit”
Need better accuracy on eta

E760 achieved 6% at psi(2S) with double-scan technique

In E835/2000

- combine scan at constant orbit with scan at constant B
- higher luminosity
- accurate beam spectra
At constant $B$, energy differences between energy points are obtained from frequency differences and $\eta$:

$$\frac{p_{\text{run}} - p_0}{p_0} = \frac{1}{\eta} \cdot \frac{f_{\text{run}} - f_0}{f_0}$$

In this case, larger $\eta$ implies smaller resonance width. A 10% increase in $\eta$ translates into a -10% variation in width.
\( \psi(2S) \) SCAN: STACK 29 (Jun 2000), \( \eta = 0.02164 \)

Center-of-Mass Energy (MeV)

Events / Luminosity (nb)

\( \Gamma = (317 + 39 - 35) \) keV

\( M = (3686.111 + 0.009 - 0.009) \) MeV

\( \sigma_p = (6.94 + 0.61 - 0.53) \) nb

\( \sigma_b = (103 + 33 - 31) \) pb

\( \chi^2 / \text{d.o.f.} = 6.2/9 \)
By combining the two stacks, resonance width and slip factor can be determined simultaneously.
E835 $\psi(2S)$ SCANS: STACKS 1 (Jan 2000) and 29 (Jun 2000)

\[ \Gamma = (300 + 26 - 25) \text{ keV} \]
\[ M = (3686.11 + 0.009 - 0.009) \text{ MeV} \]
\[ \sigma_p = (7.2 + 0.62 - 0.54) \text{ nb} \]
\[ \sigma_b = (95 + 25 - 24) \text{ pb} \]
\[ \chi^2 / \text{d.o.f.} = 39.1 / 23 \]

\[ \eta = (0.0218 + 0.0014 - 0.0012) \]
\[ \epsilon_1 / \epsilon_{29} = (0.804 + 0.046 - 0.044) \]
Conclusions

- Width of narrow resonances can be measured precisely in antiproton-proton annihilations.
- Mainly based on frequency measurements; almost uncorrelated to machine parameters.
- For E835/2000 at the FNAL Accumulator, uncertainty mainly due to event statistics.
- Technique can be relevant to PANDA at GSI.

Thanks for your attention!