A NEW COMPLEMENTARY-SCAN TECHNIQUE FOR PRECISE MEASUREMENTS OF RESONANCE PARAMETERS IN ANTIPROTON-PROTON ANNIHILATIONS

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Abstract

A new technique for precision measurements of resonance widths in antiproton-proton annihilations is presented. It is based on the analysis of excitation curves obtained by scanning the resonance twice, at constant orbit and at constant magnetic bend field, in an antiproton storage ring. The technique relies on precise revolution-frequency and orbit-length measurements, while making the results almost independent of the machine’s phase-slip factor. The uncertainty is dominated by event statistics. The technique was recently applied by Fermilab experiment E835 at the Antiproton Accumulator to obtain the most precise measurements to date of the total and partial widths of the ψ(2S) charmonium meson.

INTRODUCTION

A precise measurement of the excitation curve of narrow charmonium resonances depends both on the detection technique (event statistics, detector efficiency) and on the properties of the beam-energy spectrum. In p̄p annihilations on a hydrogen target, one can take advantage of stochastically cooled antiproton beams, corresponding to FWHM energy spreads of 0.4–0.5 MeV in the center-of-mass frame. A large source of uncertainty is the machine’s phase-slip factor η, which is necessary to translate the measured revolution-frequency spectra of the beam into energy distributions. Fermilab experiment E760 measured the widths of the J/ψ and ψ(2S) mesons [1]. The ‘double-scan’ technique was used to drastically reduce the impact of the phase-slip factor on the width measurement [2, 3]. The uncertainty was dominated by event statistics and statistical fluctuations in the beam position measurements. A sizeable systematic uncertainty was due to the measurement of the beam-energy spectrum. In this paper, we present a new ‘complementary-scan’ technique and its application to the year-2000 run of Fermilab experiment E835. The new scanning technique, together with higher event statistics, improvements in the beam position measurement and momentum-spread analysis, allow us to reach the highest precision to date.

EXPERIMENTAL TECHNIQUE

Let us consider a coasting beam of antiprotons colliding with an internal gas-jet hydrogen target. The detector selects and counts events tagged as charmonium decays. The resonance is scanned by decelerating the antiproton beam in small steps.

The resonance parameters are determined from a maximum-likelihood fit to the excitation curve (Fig. 1). For each data-taking run (subscript i), one assumes that the average number of observed events μi in a decay channel is given by the Breit-Wigner cross section σBW and the center-of-mass energy distribution, Bi, as follows:

\[ μ_i = \mathcal{L}_i \int \sigma_{BW}(w) B_i(w) dw + σ_{bkg}, \]

where \( w \) is the center-of-mass energy, \( ε_i \) is the detector efficiency, \( \mathcal{L}_i \) is the integrated luminosity, and \( σ_{bkg} \) is a constant background cross section. The integral is extended over the energy acceptance of the machine. The spin-averaged Breit-Wigner cross section for a spin-J resonance of mass \( M \) and width \( Γ \) formed in \( p̄p \) annihilations is

\[ σ_{BW}(w) = \frac{(2J+1) \cdot 16\pi}{(2S+1)^2 \cdot w^2 - 4m^2 \cdot Γ^2 + 4(w-M)^2}, \]

where \( m \) and \( S \) are the (anti)proton mass and spin, while \( Γ_{in} \) and \( Γ_{out} \) are the partial resonance widths for the entrance \( pp \) in our case) and exit channels.

The resonance mass \( M \), width \( Γ \), ‘area’ \( (Γ_{in}Γ_{out}/Γ) \) and the background cross section \( σ_{bkg} \) are left as free parameters in the maximization of the log-likelihood function

\[ \log(Λ) = \sum_i \log P(μ_i, N_i), \]

where \( P(μ, N) \) are Poisson probabilities of observing \( N \) events when the mean is \( μ \).

BEAM ENERGY MEASUREMENTS

The center-of-mass energy distribution \( B_i(w) \) is critical for width and area measurements. Here we describe how it is obtained.

The beam-frequency distribution is accurately measured by detecting the Schottky noise signal generated by the coasting beam. The signal is sensed by a 79-MHz longitudinal Schottky pickup and recorded on a spectrum analyzer. An accuracy of 0.05 Hz is achieved on a revolution frequency of 0.63 MHz, over a wide dynamic range in intensity (60 dBm).

The beam is slightly bunched by an rf cavity operating at \( f_{cav} \sim 1.25 \text{ MHz} \), the second harmonic \( (h = 2) \) of the...
**SCAN AT CONSTANT ORBIT**

Effect of error on $\eta$:

- Larger $\eta$ ⇒ narrower spectra ⇒ wider resonance

**Energy spectra**

Resonance curve from maximum-likelihood fit

**Measured excitation curve**

$w_i^\text{rf} - w_0^\text{rf} = w(f_i^\text{rf}, L_0 + \Delta L_i) - w(f_0^\text{rf}, L_0)$.  

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**SCAN AT CONSTANT BEND FIELD**

Effect of error on $\eta$:

- Larger $\eta$ ⇒ closer points ⇒ narrower spectra ⇒ narrower resonance

**CENTER-OF-MASS ENERGY**

Figure 1: Schematic representation of the complementary-scan technique.

Within the energy range of a resonance scan, these differences are largely independent of the choice of $L_0$. For this reason, the absolute energy calibration is irrelevant for width and area measurements. Only uncertainties coming from $\Delta L$ are considered.

Once the energy $w_i^\text{rf}$ for particles in the rf bucket is known, the complete energy distribution is obtained from the Schottky spectrum using the relation between frequency differences and momentum differences at constant magnetic field:

$$\frac{\Delta p}{p} = -\frac{1}{\eta} \frac{\Delta f}{f},$$  

(4)

where $\eta$ is the energy-dependent phase-slip factor of the machine, which is one of the parameters governing synchrotron oscillations. In terms of the center-of-mass energy,

$$w - w_i^\text{rf} = -\frac{1}{\eta} \frac{(\beta_i^\text{rf})^2(\gamma_i^\text{rf})m^2}{w_i^\text{rf}} f - f_i^\text{rf}. $$  

(5)

Within a run, rf frequencies, beam-frequency spectra, and BPM readings are updated every few minutes. Frequency spectra are then translated into center-of-mass energy through Eq. 5, weighted by luminosity and summed, to obtain the luminosity-weighted normalized energy spectra $B_i(w)$ for each data-taking run.

The phase-slip factor is usually determined from the synchrotron frequency. In our case, this determination has a 10% uncertainty coming from the bolometric rf voltage measurement [5]. At the $\psi(2S)$, the synchrotron-frequency method yields a phase-slip factor $\eta = 0.0216 \pm 0.0022$.

The resonance width and area are affected by a systematic error due to the uncertainty in $\eta$. Usually, the resonance width and area are positively correlated with the phase-slip factor (Fig. 1). A larger $\eta$ implies a narrower energy spectrum, as described in Eq. 5. As a consequence, the fitted resonance will more closely resemble the measured excitation curve, yielding a larger resonance width.
For our scan at the central orbit, the 10% uncertainty in $\eta$ translates into a systematic uncertainty of about 18% in the width and 2% in the area.

**COMPLEMENTARY SCANS**

For precision measurements, one needs a better estimate of the phase-slip factor or determinations that are independent of $\eta$, or both. In E760, the ‘double scan’ technique was used [1, 2, 3]. It yielded $\eta$ with an uncertainty of 6% at the $\psi(2S)$ and width determinations largely independent of the phase-slip factor, but it had the disadvantage of being operationally complex.

Here we describe a new method of ‘complementary scans’ to achieve a similar precision on $\eta$ and arbitrarily small correlations between resonance parameters and phase-slip factor; the technique is also operationally simpler. The resonance is scanned once on the central orbit, as described above. A second scan is then performed at constant magnetic bend field. The energy of the beam is changed by moving the longitudinal stochastic-cooling pickups. The beam moves away from the central orbit, and the range of energies is limited but appropriate for narrow resonances.

Since the magnetic field is constant, beam-energy differences can be calculated independently of $\Delta L$, directly from the revolution-frequency spectra and the phase-slip factor, according to Eq. 5. A pivot run is chosen (subscript $p$). The rf frequency of this run is used as a reference to calculate the energy for particles in the rf bucket in other runs. These particles have revolution frequency $f^i_{rf}$ and the energy is calculated as follows:

$$w^i_{rf} - w^p_{rf} = -\eta \frac{(\beta^i_{p})^2 (f_p^i)^2 m^2 (f^i_{rf} - f^p_{rf})}{w^p_{rf}}.$$

For the scan at constant magnetic field, this relation is used instead of Eq. 3. Once the energy for particles at $f^i_{rf}$ is known, the full energy spectrum within each run is obtained from Eq. 5, as usual.

Using this alternative energy measurement, the width and area determined from scans at constant magnetic field are negatively correlated with $\eta$ (Fig. 1). The increasing width with increasing $\eta$ is still present, as it is in scans at nearly constant orbit. But the dominant effect is that a larger $\eta$ brings the energy points in the excitation curve closer to the pivot point, making the width smaller. In our case, a 10% increase in $\eta$ implies a ~10% variation in both width and area.

The constant-orbit and the constant-field scan can be combined. The resulting width has a dependence on $\eta$ that is intermediate between the two. An appropriate luminosity distribution can make the width practically independent of the phase-slip factor. Moreover, thanks to this complementary behavior, the width, area and phase-slip factor can be determined in a maximum-likelihood fit where $\eta$ is also a free parameter. Errors and correlations are then obtained directly from the fit.

**RESULTS**

The complementary-scan technique was recently applied to the E835 data-taking [6]. The E835 detector is a non-magnetic spectrometer designed to extract, from a large hadronic background, electron-positron pairs of high invariant mass as a signature of charmonium formation [5]. The processes $\bar{p}p \rightarrow e^+ e^-$ and $\bar{p}p \rightarrow J/\psi + X \rightarrow e^+ e^- + X$ are selected with an overall efficiency of about 40%, while background contamination is only 0.1% for the $e^+ e^-$ channel and 1% for the inclusive channel [7]. Two scans of the $\psi(2S)$ resonance were performed, in January 2000 and in June 2000. Both channels in both scans are fitted simultaneously, leaving the phase-slip factor as a free parameter. The final results are the following: $\Gamma = 290 \pm 25$ (sta) $\pm 4$ (sys) keV, $\Gamma_{e^+ e^-} \Gamma_{\bar{p}p}/\Gamma = 579 \pm 38$ (sta) $\pm 36$ (sys) meV, and $\eta = 0.0216 \pm 0.0013$. The width measurement is the most precise to date. It is consistent with those reported by E760 [1] and by the BES Collaboration at BEPC [8, 9].

Our measurement of $(\Gamma_{e^+ e^-} \Gamma_{\bar{p}p}/\Gamma)$ is also compatible, but much more precise, than that reported by the BABAR at PEP-II [10].

This method of complementary scans can be applied to future experiments for the direct determination of narrow resonance widths in antiproton-proton annihilations, such as PANDA at the future FAIR facility in Darmstadt. If one performs a scan at constant orbit and a scan at constant magnetic field in conditions similar to those in the Antiproton Accumulator, the uncertainty is mainly statistical. Moreover, by appropriately choosing the relative luminosities and energies of the two scans, one can make the width almost uncorrelated with the phase-slip factor, as in the E835 case discussed in this paper.

**REFERENCES**


