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 $\psi(2S)$ 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 $\bar{p}$ 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 $\psi(2S)$ 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.

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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 μ_i in a decay channel is given by the Breit-Wigner cross section σ_{BW} and the center-of-mass energy distribution, B_i, as follows:

$$\mu_i = \mathscr{L}_i \left[\varepsilon_i \int \sigma_{\mathrm{BW}}(w)\, B_i(w)\, dw + \sigma_{\mathrm{bkg}} \right], \qquad (1)$$

where w is the center-of-mass energy, ε_i is the detector efficiency, $\mathscr{L}_i$ 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 $\bar{p}p$ annihilations is

$$\sigma_{\mathrm{BW}}(w) = \frac{(2J+1)}{(2S+1)^2}\,\frac{16\pi}{w^2-4m^2}\,\frac{(\Gamma_{\mathrm{in}}\Gamma_{\mathrm{out}}/\Gamma)\cdot\Gamma}{\Gamma^2+4(w-M)^2}; \qquad (2)$$

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

The resonance mass M, width Γ, 'area' $(\Gamma_{\mathrm{in}}\Gamma_{\mathrm{out}}/\Gamma)$ and the background cross section σ_{bkg} are left as free parameters in the maximization of the log-likelihood function $\log(\Lambda) = \sum_i \log P(\mu_i, N_i)$, where $P(\mu, N)$ 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 $f^{\mathrm{cav}} \sim 1.25$ MHz, the second harmonic ($h = 2$) of the

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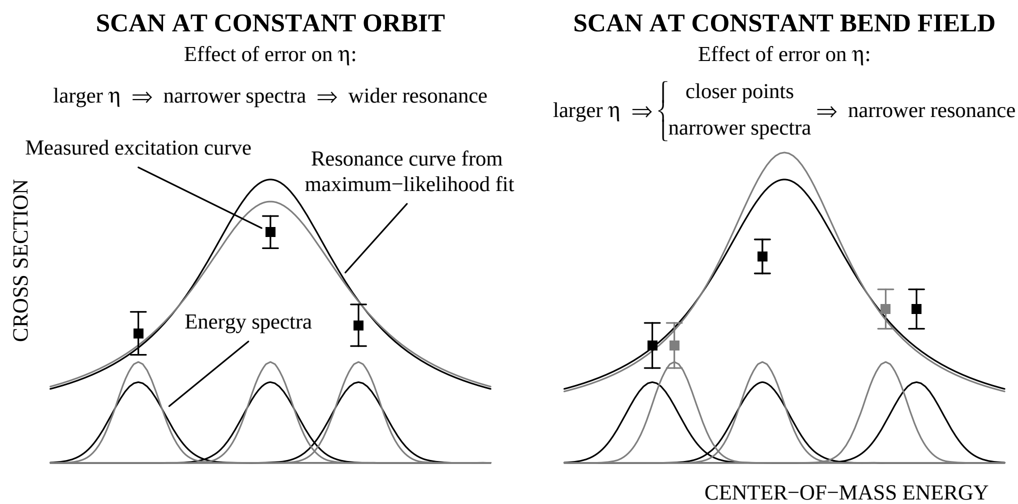

Figure 1: Schematic representation of the complementary-scan technique.

revolution frequency. The beam is bunched both for stability (ion clearing) and for making the beam position monitors (BPMs) sensitive to a portion of the beam. Therefore, recorded orbits refer to particles bunched by the rf system, and their revolution frequency is $f^{\rm rf} = f^{\rm cav}/h$. The bunched-beam revolution frequency $f^{\rm rf}$ is usually close to the average revolution frequency of the beam. Each orbit consists of 48 horizontal and 42 vertical readings. As a result of hardware and software improvements, these readings are much less noisy than E760's [1].

From the BPM readings and the Accumulator lattice model, we can accurately calculate differences ΔL in the length of one orbit and another. The main systematic uncertainties come from BPM calibrations, from bend-field drifts, and from neglecting second-order terms in the orbit length. They are estimated to be 0.05 mm out of 474 m for the runs at the $\psi(2S)$.

The absolute length L of an orbit can be calculated from a reference orbit of length L_0: $L = L_0 + \Delta L$. The calibration of L_0 is done by scanning a charmonium resonance (the $\psi(2S)$ itself in this analysis) the mass of which is precisely known from the resonant-depolarization method in e^+e^- experiments [4]. For particles in the bunched portion of the beam (rf bucket), the relativistic parameters $\beta^{\rm rf}$ and $\gamma^{\rm rf}$ are calculated from their velocity $v^{\rm rf} = f^{\rm rf} \cdot L$, from which the center-of-mass energy w of the $\bar{p}p$ system is calculated: $w^{\rm rf} = w(f^{\rm rf}, L) \equiv m\sqrt{2(1+\gamma^{\rm rf})}$. (The superscript rf is omitted from orbit lengths because they always refer to particles in the rf bucket.)

For width and area determinations, energy differences are crucial, and they must be determined precisely. In our standard experiments, where we keep the beam near the central orbit of the Accumulator, a particular run is chosen as the reference (subscript 0). Energy differences between the reference run and other runs in the scan (subscript i), for particles in the rf bucket, are simply

$$w_i^{\rm rf} - w_0^{\rm rf} = w(f_i^{\rm rf}, L_0 + \Delta L_i) - w(f_0^{\rm rf}, L_0). \tag{3}$$

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 ΔL are considered.

Once the energy $w_i^{\rm rf}$ 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:

$$\frac{\Delta p}{p} = -\frac{1}{\eta}\frac{\Delta f}{f}, \tag{4}$$

where η 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,

$$w - w_i^{\rm rf} = -\frac{1}{\eta}\frac{(\beta_i^{\rm rf})^2(\gamma_i^{\rm rf})m^2}{w_i^{\rm rf}}\frac{f - f_i^{\rm rf}}{f_i^{\rm rf}}. \tag{5}$$

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 η. Usually, the resonance width and area are *positively correlated* with the phase-slip factor (Fig. 1). A larger η 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 η 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 η, or both. In E760, the 'double scan' technique was used [1, 2, 3]. It yielded η 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 η 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 ΔL, 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:

$$w_i^{\mathrm{rf}} - w_p^{\mathrm{rf}} = -\frac{1}{\eta}\frac{(\beta_p^{\mathrm{rf}})^2(\gamma_p^{\mathrm{rf}})m^2}{w_p^{\mathrm{rf}}}\frac{f_i^{\mathrm{rf}} - f_p^{\mathrm{rf}}}{f_p^{\mathrm{rf}}}. \qquad (6)$$

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 η (Fig. 1). The increasing width with increasing η is still present, as it is in scans at nearly constant orbit. But the dominant effect is that a larger η brings the energy points in the excitation curve closer to the pivot point, making the width smaller. In our case, a 10% increase in η 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 η 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 η 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 $\bar{p}p \to e^+e^-$ and $\bar{p}p \to J/\psi + X \to e^+e^- + X$ 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: $\Gamma = 290 \pm 25(\mathrm{sta}) \pm 4(\mathrm{sys})$ keV, $\Gamma_{e^+e^-}\Gamma_{\bar{p}p}/\Gamma = 579 \pm 38(\mathrm{sta}) \pm 36(\mathrm{sys})$ 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.

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