2. Production of Charmonium

2.1. History

For the first decade after the discovery of charmonium, it was produced solely by e^+e^- annihilation. Although the masses resulting from such an experiment are very precise, the widths of the resonances are not. This is a result of the large energy spread in the electron beams and the radiative corrections that must be made. Furthermore , only states with quantum numbers $J^{PC}=1^{--}$ can be produced directly in large quantities, since these are the quantum numbers of the virtual photon from the e^+e^- annihilation.[22] Resonances without these quantum numbers do not couple to e^+e^- to first order, and must be studied in the decay from the 1^{--} states. The ability to see charmonium states at e^+e^- colliders depends greatly on the resolution of the detector in the experiment and the reconstruction of the final state.[23]

Due to the pioneering efforts of experiment R704 at the CERN Intersecting Storage Rings,[24] it became possible to study charmonium via $p\bar{p}$ annihilation. R704 implemented a two-arm non-magnetic spectrometer, consisting of an upstream section for tracking charged particles followed by a segmented electromagnetic calorimeter, to optimize the separation between neutral γ's and coalesced π^0's and between charged e^-'s and π's.[25] Despite the presence of a larger hadronic background, charmonium’s characteristic decays into a high mass e^+e^- pair allowed detection of these states. Stochastic cooling of an antiproton beam focused onto a hydrogen gas target and precise control of the energy of this beam in an antiproton storage ring permitted the measurement of masses and widths for these narrow resonances to great accuracy. Furthermore, one was no longer limited to studying only the 1^{--} channel: The full spectrum of charmonium could now be produced directly.

Experiment E760 at Fermilab improved the techniques of a $p\bar{p}$ annihilation experiment during the 1990-1991 Fixed Target Run. Among its most notable achievements are the discovery of the singlet P-wave[26] ($^1P_1$), examination of the triplet P-wave states (χ), and improvements on the mass and width of the $\eta_c(2980)$. E835's goals are to find the missing η_c', the radial excitation to the η_c, and to complete the spectrum below the threshold to open charm.[27]

2.2. Production and Storage of Antiprotons

The Fermilab Antiproton Accumulator (Figure 2.1) was designed to accumulate and cool antiprotons for use of the Tevatron colliding beam program. Protons with an energy of 120 GeV from the main ring collide with a tungsten target, and the resulting negatively charged particles are collected with a 15 cm X 1cm lithium lens.

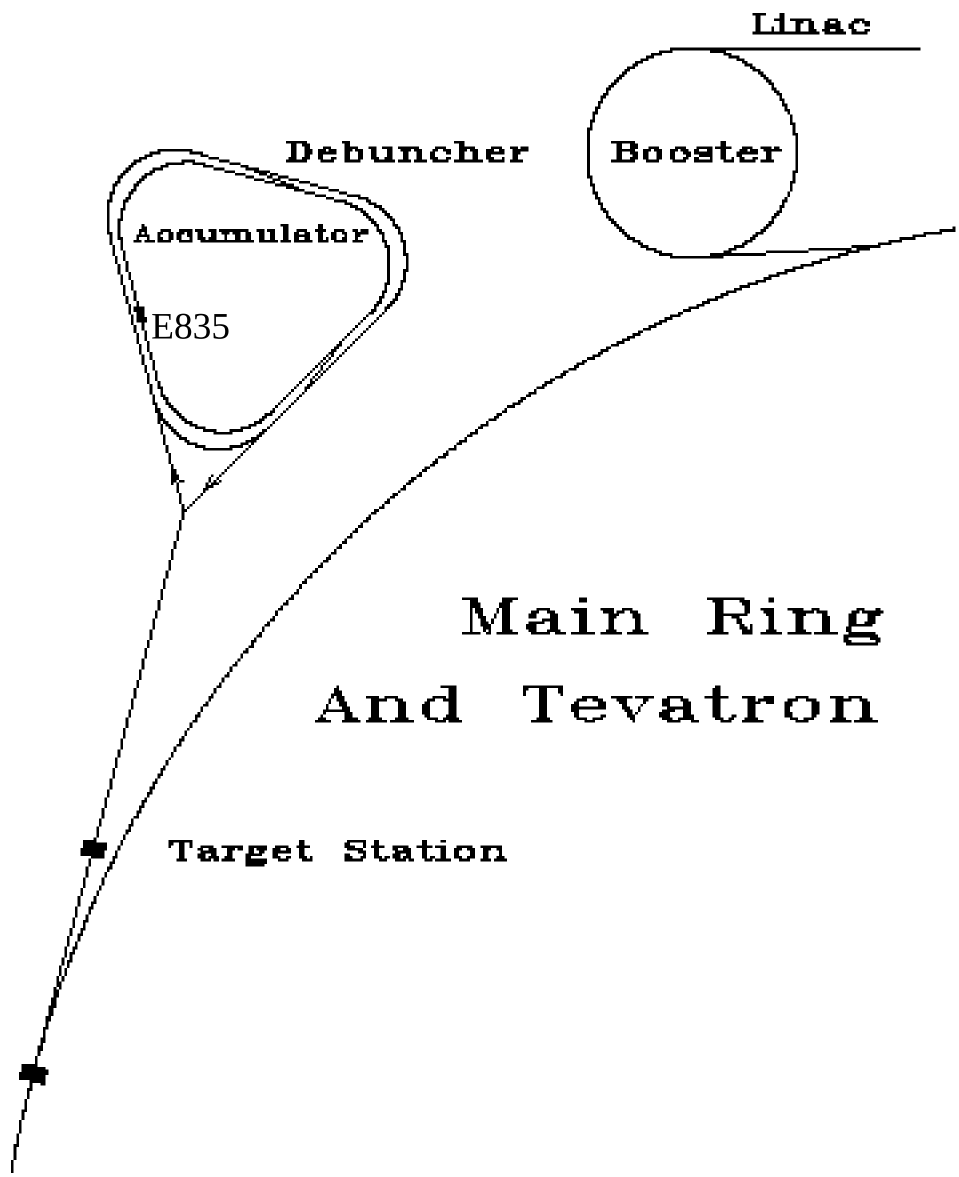

Figure 2.1 : The E835 Antiproton Accumulator.[28]

A debuncher ring then accepts this particle bunch with a momentum of 8.9 GeV/c and stochastically cools the antiprotons, or debunches the antiprotons, into a beam. Stochastic cooling is a process of moving antiprotons with a kicker magnet away from an unintended orbit to keep the beam transversely small and to keep the momentum spread small. The momentum spread $\Delta p/p$ drops from about 4 % to 0.2 % at this stage. During this transition any pions or muons have time to decay, and any electrons in the beam are lost due to synchroton radiation losses.[29,30]

Next, the antiproton beam travels to the Accumulator, where it is stochastically cooled again to a spread of $\Delta p/p$ of $2X10^{-4}$ by a series of of dipole and quadrupole magnets, and then decelerated to the desired momentum. Stochastic cooling is the primary reason why a $p\bar{p}$ annihilation experiment can be done. It counteracts the growth of beam emittance due to the many traversals through the hydrogen gas jet target and interactions with residual gas in the accumulator ring. As a result, the beam energy spread can be narrowed to about 0.5 MeV.

When the Accumulator is in the Fixed Target mode, antiprotons are collected until the beam current is anywhere from 50 to 100 mA. The beam is then decelerated until the center of mass energy of the antiproton-proton system reaches the mass of the desired resonance. The antiproton stack size decreases as it interacts with the hydrogen gas jet target. The energy of the beam is decelerated from above the desired value in small steps in order to scan the mass and width of the resonance. Even though the width of the resonance may be less than the width of the antiproton beam (~500 keV for the beam and ~100 keV for the J/Ψ), the total width for the resonance can be extracted if the ratio of the peak cross-section to the area under the curve is determined and the width of the beam is known.[22]

2.3. Beam Energy Measurement

The success of producing charmonium in $p\bar{p}$ annihilations depends in large part on the precise determination of the average beam energy and its width. We describe here the procedure to determine these quantities.[22,31]

The beam velocity is given by

$$c\beta = fL, \tag{2.1}$$

where f is the average revolution frequency of the antiprotons, and L is the orbit length. Usually L is defined with respect to some reference orbit length:

$$L = L_0 + \Delta L. \tag{2.2}$$

From equation (2.1) we can derive the following relation:

$$\frac{df}{f} = \frac{d\beta}{\beta} - \frac{dL}{L} . \tag{2.3}$$

The fractional momentum spread is defined via

$$\frac{d\beta}{\beta} = \frac{1}{\gamma^2} \frac{dp}{p} . \tag{2.4}$$

Furthermore, a transition gamma factor γ_t is given by

$$\frac{dL}{L} = \frac{1}{\gamma_t^2} \frac{dp}{p} . \tag{2.5}$$

Combining equations (2.3) , (2.4) , and (2.5) , the relation between the fractional momentum spread and the fractional frequency spread becomes:

$$\frac{dp}{p} = \frac{1}{\eta} \frac{df}{f} , \tag{2.6}$$

with the slip factor η defined as:

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} . \tag{2.7}$$

The transition gamma factor γ_t corresponds to the beam transition energy at which the slip factor η is zero and is completely determined by the nature of the accumulator lattice. Since antiprotons are charged particles, they interact with the other antiprotons in the beam and with the external magnetic fields that bend their path, resulting in both longitudinal oscillations and oscillations transverse to the beam. For beam energies above the transition energy ($\eta < 0$) a higher-energy particle takes a longer time to complete one orbit than a lower energy particle. For beam energies below this threshold ($\eta > 0$) a lower energy particle takes longer to complete one orbit.

Once η is known, the central frequency of the beam is found by analyzing the power spectrum within a given longitudinal Schottky noise band,

$$P(f)\Delta f \propto e^2 f_{ave}^2 \frac{dN}{df} \Delta f \ . \qquad (2.8)$$

The signal is detected by a coaxial quarter wavelength resonant pickup whose bandwidth is much greater than the beam frequency width, 79.323 MHz.

The energy of the beam can then be found from

$$E = \frac{m_p}{\sqrt{1 - (f\,L)^2}}. \qquad (2.9)$$

The error on the energy measurement is thus

$$\frac{\delta E}{E} = \beta^2 \gamma^3 \left(\frac{\delta L}{L} + \frac{\delta f}{f} \right). \qquad (2.10)$$

Because survey measurements of the central orbit are not accurate enough, the known value of the Ψ' mass is used to calculate the reference orbit length and its error. With the center of mass energy

$$s = 2\, m_p^{\,2} + 2\, m_p E \qquad (2.11)$$

and its respective error

$$\delta\sqrt{s} = \frac{m_p}{\sqrt{s}}\, \delta E \qquad (2.12)$$

expressed in terms of the beam energy, and noting that the fractional frequency error is very small, i.e. $\delta\, f/f \sim 10^{-7}$, the fractional error in the orbit length is:

$$\frac{\delta L}{L} = \frac{\sqrt{s}}{\gamma\beta^2 m_p^{\,2}}\,\delta\sqrt{s}\,. \qquad (2.13)$$

Using the best available measurement for the Ψ' mass,[32] 3686.00 ± 0.10 MeV, one attains a reference orbit length of 474.0457 m ± 0.67 mm. However, the quoted error of 0.67 mm is not the only error involved in the determination of the beam energy, since the beam cannot precisely be kept on the reference orbit at all energies. Normally the true orbit deviates from the reference orbit by ± 2 mm, as measured by 48 BPM's (Beam Position Monitors) distributed throughout the Accumulator. Furthermore, there was a random error in measuring the orbit length of ± 1mm. The final mass errors for the J/Ψ and the Ψ' were found to be 0.05 MeV/c^2 and 0.15 MeV/c^2 respectively in E760.[31]

2.4. Hydrogen Gas Jet

During the 1990-91 Fixed Target Run at Fermilab, E760 utilized a hydrogen gas jet (Figure 2.2) cooled down to 80 K with liquid nitrogen to form the target for the beam of antiprotons.[33] At low temperatures and high pressures, hydrogen gas may form clusters of large numbers of hydrogen molecules in an expansion process from a nozzle. Hence instead of trying to hit a single hydrogen molecule, the antiproton beam has a much larger target, and the probability of an interaction thus increases. This jet has been upgraded to increase the interaction rate with the antiproton beam for E835, whose intensity has also been increased. There are primarily three reasons why the upgrade on the gas jet was needed.

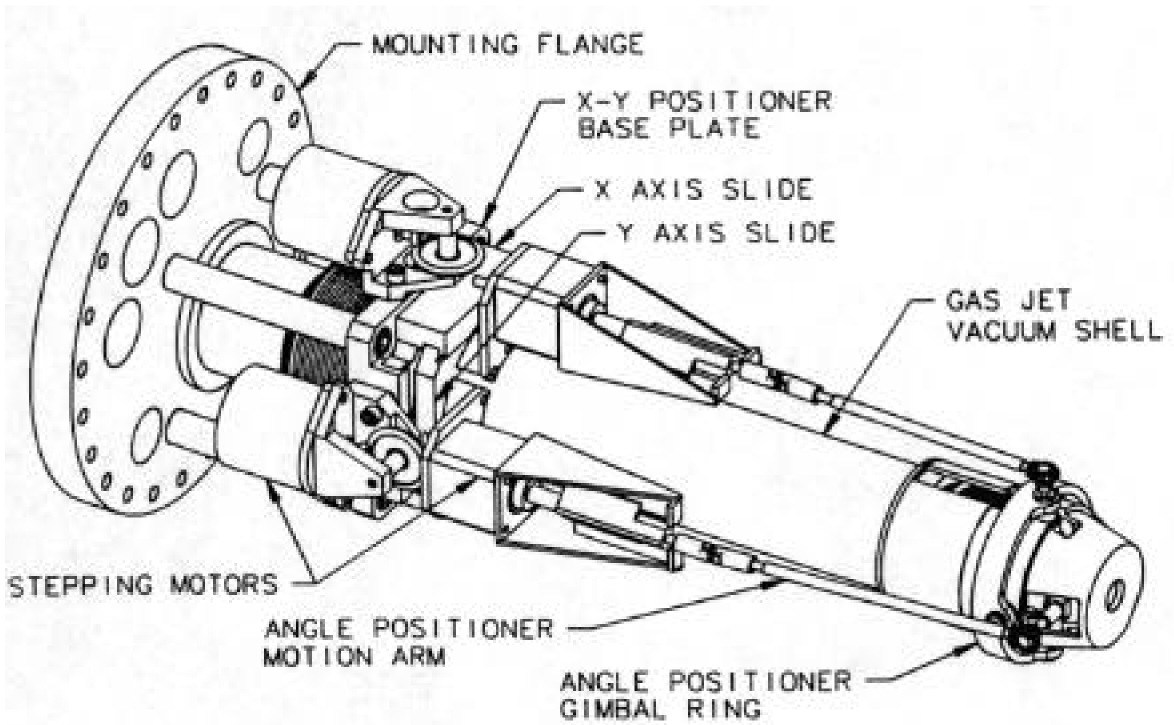

Figure 2.2 : The E835 Hydrogen Gas Jet.[33]

First, larger clusters yield a higher interaction rate with the antiproton beam. The temperature of the hydrogen gas jet has been decreased from 80K to 27K to enhance the clustering of the hydrogen gas, which happens as the gas expands from the nozzle, to at least 10^4 atoms per cluster. During testing it was shown that the cryocooler was capable of cooling the jet nozzle to at least 10K, and the density of the gas jet could be as much as 5 times as large as that in E760.

Second, less background gas escaping into the ring improves stochastic cooling and limits unwanted secondary interactions. The pumping speed for the vacuum chamber in which the gas jet sits has been improved. The chamber pressure can be maintained below 1 Pa, and this reduces the interaction of the background gas with the jet stream.

Third, adjusting the position of the jet nozzle can optimize the interaction rate with the antiproton beam. The nozzle may now be moved in the plane perpendicular to the gas stream produced by the nozzle, and the angular direction of the nozzle may be altered as well.

The end result is that an interaction rate of approximately 5 MHz yields a beam lifetime of about 30 hours for a 100 mA antiproton stack.[33]