$\bar{P}P$ SYSTEMS AT ISABELLE

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I. Introduction

As was stated by Lee Pondrom,[1] it is to be expected that pp interactions will be studied at CERN and at Fermilab several years before they will be studied at ISABELLE. Further, pp interactions will be studied at ISABELLE with far higher luminosities than $\bar{p}p$. In the light of such observations, a pp program at BNL can only be justified if: 1) the luminosity is higher than at CERN/Fermilab; and 2) the luminosity is high enough for detailed comparison of pp and $\bar{p}p$ interactions. These requirements would seem to suggest a minimum acceptable luminosity of 10^{31}.

I will consider three schemes, or stages, with steadily increasing cost and complexity only the last of which really meets the above requirement. The step by step presentation enables one to study what the real limits are.

II. Basic Plan

The basic proposed arrangement is shown if Fig. 1 protons are taken from the AGS and stacked in the ISA ring #1 until a $6\text{x}10^{14}$ proton charge is achieved. These protons are bunched into one or a few short pulses, each is extracted, focused to a very small spot and targeted on a short irridium target. The antiprotons made are collected by a horn system and injected and held in a single bucket of a high frequency rf system in the second ring.

The process is repeated and the next bunch of antiprotons placed in the next rf bucket of the second ring and so on until all bunches are full.

Finally, the first ring is filled with protons in the other direction and $\bar{p}p$ interactions take place at the 6 intersection regions.

In this basic proposal no cooling is employed and the principles used to attain maximum luminosity are those that produce the highest possible antiproton phase space density from the target. These are: 1) the proton bunch used to target is as intense and as short in times as possible; 2) the target is as small as possible; and 3) the protons used to target are at the highest possible energy (see Fig. 2 and later discussion). It is an inevitable consequence of these conditions that the target will be heated to a very high temperature and will, in fact, evaporate. This we do not believe is a fundamental problem and it will be discussed again below.

The final luminosity of $\bar{p}p$ is a function of the crossing angle, bunching and so on, but if the crossing is tune shift limited and is at an intersection with the same β as that for pp then we can write the luminosity:

$$L_{\bar{p}p} = I_{pp} \times \frac{n_{\bar{p}}}{n_p}, \tag{1}$$

where $n_{\bar{p}}$ and n_p are the total number of $\bar{p}$'s and p's stored.

In practice one would employ stochastic cooling to reduce the vertical $\bar{p}$ emittance until it matched the p emittance. In this case standard crossing angles would be employed and the relation of Eq. (1) is obvious.

The number of $\bar{p}$'s made per proton on target can be written

$$\frac{\partial n_{\bar{p}}}{\partial n_p} \approx \frac{1}{\sigma_a} \cdot E\frac{\partial^3\sigma}{\partial p^3}\, \varepsilon\, \frac{\Delta p}{p}\, \pi p_\perp^{\,2} \tag{2}$$

where σ_a is the total absorption cross section, $E\,\partial^3\sigma/\partial p^3$ is the invariant $\bar{p}$ production cross section, ε the targeting efficiency (taken as 0.3), $\Delta p/p$ is the momentum acceptance for $\bar{p}$'s, $p_\perp$ is the transverse momentum acceptance for $\bar{p}$'s.

Finally we can write the luminosity

$$L_{\bar{p}p} = L_{pp} \cdot \frac{\partial n_{\bar{p}}}{\partial n_p} \cdot m, \tag{3}$$

where m is the number of ISA cycles used to make $\bar{p}$'s (assuming that the stack used to make $\bar{p}$ has the same number of protons as that used for pp interactions).

The values of all these parameters for the case (I) we are discussing are given in Table I. I will now discuss these parameters in turn.

a) $L_{pp} = 10^{33}$ is that given at the high luminosity small crossing angle intersections in the current ISA proposal.

b) The invariant cross section is plotted in Fig. 2 taken from estimates made by Cronin,[2] the values plotted are for $\bar{p}$ momenta in the central region which would be 14 GeV for 400-GeV pp interactions. Since collection must take place above the ISA transition energy of 20 GeV, a correction has to be made. Assuming collection at 21 GeV and a $(1\text{-}x)^6$ dependence an invariant $\bar{p}$ production of 0.055 is obtained.

c) Target efficiency of 0.3 is taken, which corresponds to that obtained from a thick target. It is a conservative figure.

d) The momentum acceptance of 1.5% is that of the ISA ring used to capture.

e) The final parameters: the $p_\perp$, and the total number of cycles m used turn out to be related and in order to evaluate them we have to consider explosive targeting, and rf requirements; big enough subjects to justify sections of their own.

III. Targeting

If the actual target is thin enough then the apparent size of the target is a function of the angular acceptance of $\bar{p}$'s from that target, rising linearly with that angle. Under these circumstances, the transverse momentum accepted rises only as the root of the machine acceptance and we obtain:

$$\pi p_\perp^{\,2} = \frac{2p^2A}{l} = \pi(175\ \text{MeV})^2, \tag{4}$$

where p is the captured momentum (21 GeV)

A is the ISA acceptance ($1{\cdot}4\ \pi\ 10^{-6}$ meter steradians)

l is the length of the target (6 cm irridium).

The apparent target diameter is given by

$$d = \sqrt{\frac{2A}{1\pi}} \approx 0.4 \text{ mm}. \qquad (5)$$

The actual target cannot be greater than this value and the question must be asked: How long will such a target remain when hit by the protons? Will it remain long enough? This leads me into the question of target heating.

The temperature reached in the target may be estimated by

$$T = \frac{\partial E/\partial x}{k \;\; \rho} \; \frac{n/h}{\pi \; r^2} = 125{,}000°\text{C}, \qquad (6)$$

where $\partial E/\partial x$ = beam heating (22 MeV/cm)

n = number of p's per ISA fill (6×10^{14})

h = number of ISA bunches extracted separately (4)

k = specific heat of target (0.036)

ρ = density of target (19.3)

r = target radius (0.2 mm)

The $\partial E/\partial x$ estimate is certainly optimistic since it ignores secondary particles, but the k estimate is very conservative since at such temperatures there will be a high degree of ionization.

I have also ignored all cooling due to radiation and conduction which again makes it a conservative calculation. At best the order of magnitude is probably right so I continue.

The ion velocity at this temperature is:

$$v = \sqrt{\frac{2kT}{m}} = 0.24 \; 10^6 \text{cm/sec}$$

and this better be less than r/t where t is the bunch length

$$t \lesssim 80 \text{ n seconds}$$

which brings one to the next question: Can the bunch be this short?

Longitudinal phase space conservation demands that

$$ht \frac{\Delta p}{p} = \text{constant } (\approx 6\times10^{-9} \text{ sec})$$

which gives for $h = 4$, $t = 80$ n sec

$$\frac{\Delta p}{p} = 2.0\%$$

This is the momentum spread in the proton beam just before targeting and is acceptable.

Finally, we must ask: What rf system is needed to make the bunch?

IV. RF Systems

The procedure to make such a short bunch would be to slowly lower the rf voltage until the buckets are half filled (V = 2 kV) and then apply an eighth harmonic saw-tooth shaped high voltage (800 kV) for a 1/4 synchrotron cycle. This is a lot of rf but not excessive in view of its use for a short pulse at a fixed frequency.

RF is also required to hold the $\bar{p}$ bunches. The requirements are

t = 80 n sec

$\frac{\Delta p}{p}$ = 1.5%

p = 21 GeV

p(transition) = 20 GeV

f = 10 M/hz.

The voltage needed turns out to be ≈130 kV, which is not unreasonable.

V. Luminosities

All we now need to obtain luminosities is the number of ISA cycles used (m) in Eq. (3).

If no cooling is used, then the filling will have to stop when all buckets of the $\bar{p}$ rf system are full. There are 120 buckets, 4 are filled per ISA cycle and thus the ring is full after

$$m = 30 \text{ cycles}.$$

The final luminosity in this case is then

$$\dot{L}_{\bar{p}p} = 0.6\times10^{30}.$$

This is a reasonable value considering that NO COOLING has been used to stack and the time required if the ISA were cycled every 6 minutes would be only 3 hours.

If stochastic cooling (momentum or transverse) is employed once every 3 hours and further stacking schemes are used (see '77 Summer Study), then the process can be repeated, say 10 times, and a luminosity of 0.6×10^{31} achieved after a stacking time of the order of 30 hours.

VI. Further Improvements

Further improvement in luminosity can not reasonably be obtained by further stacking since the time required is already excessive. We must restudy Eq. (2) and make our improvements there. Targeting must clearly be improved but there is a limit to what can be done. More can be gained if the $\Delta p/p$ can be increased and the $p_\perp$ acceptance increased. These can both be improved if a special 21-GeV capture and cooling ring is built. A $\Delta p/p$ of 6% would not be unreasonable and with $A = 6\pi \; 10^{-6}$ m steradians $p_\perp$'s up to 350 MeV would be captured. The apparent target diameter would be increased to 0.8 mm, thus easing the target heating problem. The cycle now could involve a single proton bunch (h=1) that would be targeted and the $\bar{p}$'s captured and debunched in the transfer ring. During the following 6 minutes, as the ISA was refilled, the $\bar{p}$'s would be cooled and finally stacked in the second ring just prior to receiving a new $\bar{p}$ burst. The rate of $\bar{p}$ production would be 16 times that without the transfer ring and after 30 hours of stacking, a luminosity of 10^{32} might be achieved.

Conclusion

The figures given above may well be optimistic, but they indicate some basic points:

1) It is better to use high-energy protons to make $\bar{p}$'s.

2) The maximum possible $\Delta p/p$ and $p_\perp$ should be accepted and the latter requires a smaller acceptance (A) at high

momenta than low.

3) ISABELLE is well suited to meet these requirements, especially if a 21-GeV capture/transfer ring is built.

4) $\bar{p}p$ luminosities over 10^{31} should be achievable with reasonable stacking times.

Finally, one should remark that the $\bar{p}p$ interactions at ISABELLE would be with all the experimental advantages this would bring together with the greater ease of long-term storage and smaller tune-shift problems.

References

[1] L. G. Pondrom, Proc. 1977 BNL Summer Workshop, BNL 50721, p. 372.

[2] J. W. Cronin, Proc. 1977 Fermilab Workshop on Colliding Beams.

TABLE I

Options	I stack in ISA without cooling	II stack in ISA with cooling	III capture $\bar{p}$'s in transfer ring	
L_{pp}	10^{33}	10^{33}	10^{33}	$cm^{-2}sec^{-1}$
$\frac{1}{\sigma_a} E \frac{\partial^3 p}{\partial p^3}$	.055	.055	.055	GeV^{-2}
ε	.3	.3	.3	
$\frac{\Delta p}{p}$	1.5	1.5	6	%
$\pi_{p_\perp}{}^2$	$\pi(.175)^2$	$\pi(.175)^2$	$\pi(.35)^2$	GeV^2
m	30	300	300	
$L_{\bar{p}p}$	$.6\times10^{30}$	$.6\times10^{31}$	10^{32}	$cm^{-2}sec^{-1}$

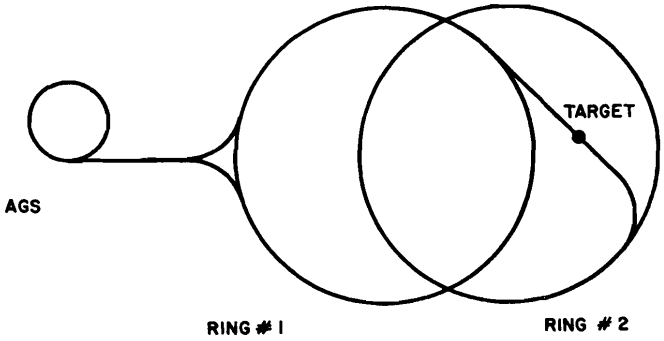

Fig. 1. $\bar{p}p$ arrangement at ISABELLE.

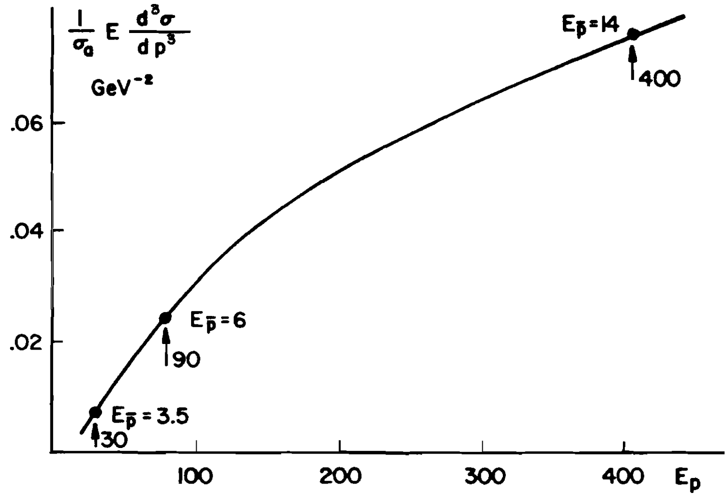

Fig. 2. Antiproton production versus proton energy.

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