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STORAGE RINGS FOR π +p, ETC, SCATTERING

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A B S T R A C T

It is suggested that storage rings can be used to perform high c.m.s. energy scattering experiments with unstable hadrons.

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Storage rings were originally designed to perform experiments with particles which satisfy the following two conditions. First, they are charged. Particles with no charge cannot be guided along a closed path by a homogeneous magnetic field. Second, they have "long lifetime". By this we mean that the particles live long enough to permit a sufficient number of revolutions in the storage ring ¹⁾.

Only the proton, the electron and, for certain purposes, the muon (together with their antiparticles) satisfy both of these conditions. Of all the strongly interacting particles, only the proton is suited for storage ring experiments as originally conceived !

In this note we investigate the possibility of using storage rings for a more general class of experiments : $X + p$ scattering. The discussion is not restricted to any particular storage ring, but the CERN-ISR is used as an illustrative example.

To perform such experiments, we suggest the following procedure. Fill up two storage rings with protons. The protons in one of the rings serve as the "target beam". The protons in the other ring form the "primary beam", which is used to produce a beam of secondary particles, X , for example pions. The secondaries are produced on a H_2 gas target placed in the way of the primary beam.

The usual solid state (or liquid) targets under full impact are not suited for the present purpose. First, they would evaporate instantly at primary beam intensities we plan to use. Second, they would cause too much disturbance in the primary beam (see below), unless at least one of their dimensions is made microscopic.

We choose H_2 gas as the target material for the following reason. When a beam crosses a dilute target, the number of secondaries produced in it per second, N_X , is proportional to the inelastic nuclear cross-section, σ_N . On the other hand, the beam undergoes multiple Coulomb scattering, and the mean square angular deflection increases with the

differential Coulomb scattering cross-section, σ_c' . After traversing the target a certain number of times, the primary particles are scattered out of the beam into the walls of the ring. In this manner, the target limits the lifetime ²⁾, τ , of the beam ³⁾. If the angular deflection caused by the gas target is of the same order of magnitude, or higher, than that caused by the residual gas in the ring, then τ decreases roughly linearly with the number N_t of target atoms (or molecules if the target is molecular) per cm^2 , and, therefore, with N_x :

$$\tau \propto \frac{\sigma_N}{\sigma_c'} N_x \quad (1)$$

Since σ_N is an approximately linear function of nucleon number, while σ_c' is an approximately quadratic function of the atomic number, one expects that the gas with the highest σ_N/σ_c' ratio is either H_2 or He. A more detailed calculation ³⁾ shows that for He, $\sigma_c'(\text{He})$ is actually about twice as large as $2 \cdot \sigma_c'(\text{H}_2)$. For scattering of 30 GeV protons on H_2 , the $\sigma_N(\text{H}_2)$ is close to 60 mbarns, while $\sigma_N(\text{He})$ has not been measured at high energies, and can only be extrapolated ⁴⁾ to be close to $2\sigma_N(\text{H}_2)$. Consequently, unless for a special reason one prefers some other material, we suggest H_2 as the target material.

To get an idea of the orders of magnitude involved, consider as an example the planned intersecting storage ring (ISR) at CERN ⁵⁾. For a H_2 gas target $N_t \approx 1.5 \cdot 10^{14} \text{ cm}^{-2}$, $3 \cdot 10^{15} \text{ cm}^{-2}$, $9 \cdot 10^{15} \text{ cm}^{-2}$ respectively, when $\tau \approx 5 \text{ hr}$, $\frac{1}{2} \text{ hr}$, 10 min .

The above considerations are not affected by the shape of the gas target. It may be made thin if good localization of the source of secondaries is desired. Thickness of a few millimetres causes no difficulties. Alternatively, a less dense but thicker target may be employed. Particularly when placed in a strongly curved section of the ring, this dilutes the secondaries in space, making their monitoring easier. Particles of the gas target should be injected at high velocities across the beam, to reduce their diffusion into the ring. Thermal velocities, of the order of 10^5 cm sec^{-1} are easily achieved, and are sufficient ⁶⁾.

Let us denote by N_p the total number of primary protons stored in the ring, by L the circumference of the ring, and by m_x the multiplicity per interaction of the secondaries produced. Let the gas target cover the whole cross-section of the primary beam, and assume the velocity of the primaries to be approximately c , the velocity of light. The total number of secondaries produced per second is

$$N_x \approx m_x \sigma_N N_t N_p \frac{c}{L} \quad (2)$$

A fraction R of the produced secondary beam is led subsequently to collide with the target proton beam. Let the (average) angle of intersection of these two beams be α , the height of the target proton beam h , and the cross-section for $X+p$ scattering $\sigma(X+p)$. Then, if all particles travel with velocities close to c , the number per second of $X+p$ scatterings will be

$$N(X+p) \approx \sigma(X+p) N_x N_p \frac{2}{hL} \frac{1}{2 \sin \frac{\alpha}{2}} R \quad (3)$$

As an illustration, let us again consider ⁵⁾ the planned ISR at CERN, using the improved parameters ⁷⁾. For this machine ⁸⁾, $L = 942$ m, $N_p = 10^{16}$, $h = 2$ cm, $\alpha \approx 14.8^\circ$ the energy of the circulating protons ≈ 30 GeV. Let us assume $\sigma(X+p) \approx 30$ m barn when X is any elementary particle. The multiplicity of production for pions in proton-proton collisions at 30 GeV is ⁹⁾ $m_{\pi^+} = 2.5$, and $m_{\pi^-} = 1.49$. Using these parameters the values of N_{π^+} and $N(\pi^+p)$ were calculated, and are given in the Table, for three values of $\cdot$. The N_{π^-} and $N(\pi^-p)$ can be obtained by multiplying the corresponding N_{π^+} and $N(\pi^+p)$ by 0.60.

The random scatterings into the wall due to Coulomb scattering, can be reduced by focusing the primary beam onto a smaller cross-section in the region of the gas target ¹⁰⁾. If one reduces the linear

dimensions of the cross-section by a factor F , then both the horizontal and the vertical angular acceptance increase by a factor F . This fact can also be used to improve the performance of gas targets. When the number of particles lost from the beam by Coulomb scattering is much larger than those undergoing nuclear scattering, then N_x and $N(x+p)$ increase roughly quadratically with F , otherwise the increase is slower. The effect of F on N_x and $N(x+p)$ is illustrated in the Table, for H_2 target and the improved CERN-ISR.

The ratio R depends on the geometry of the particular storage ring considered ¹¹⁾. Using conventional magnets, R can be about 0.1 or higher ¹²⁾. Using superconducting magnets and higher F , the R can reach values of the order of unity. Generally speaking, this is so, because at high energies the secondaries are produced within a small solid angle, and in intersecting storage rings sections of the two rings can be brought close to each other (of the order of a metre).

For kaon production, m_K and N_K are about an order of magnitude lower than m_π and N_π respectively. Therefore, $N(K+p)$ is expected to be about an order of magnitude smaller than the corresponding $N(\pi+p)$.

If the secondary and target beams intersect near the region where the primary and target beams normally intersect, then to avoid being swamped by $p+p$ scattering events, one can simply displace the plane of the primary (or target) beam so that it does not intersect the target beam.

Events coming from secondary particles being scattered on background gas can be easily discriminated against : they contain only one energetic particle travelling close to the secondary beam direction. The $X+p$ events have higher c.m.s. energy, and contain two energetic particles travelling in opposite directions (in coincidence).

Momentum selection of the secondaries, if desired, may be achieved by imposing a vertical magnetic field (e.g., the field of the storage ring itself), and placing the target into the inner ring. This field will deflect the particles in the plane of the ring, but cannot prevent them from intersecting the other ring somewhere, unless their energy is smaller than a preset value. The position and angle of intersection is thus a function of momentum ¹³⁾.

The positively charged secondary beam will be contaminated with protons ⁹⁾. Highly perfected threshold or Cerenkov counters may be useful tools to discriminate against the proton background. More realistically, the effect of this background may be subtracted out, if we know its energy spectrum and the relevant proton-proton cross-sections. On the other hand, the negatively charged secondary beam is bent in a magnetic field in the opposite direction as the protons, and, therefore, does not contain any proton background.

When the primary beam hits the gas target, neutrons are also produced. These travel virtually straight through the magnetic field, and could be used to perform $n+p$ scattering at high c.m.s. energies. The counting rates depend on the magnetic fields available to guide the primary proton and target proton beam near their region of intersection. When only conventional magnets are available, and also when superconducting magnets can be used, the $N(n+p)$ is about the same order of magnitude as the corresponding $N(\pi^+p)$.

Strange particles constitute only about 10% of the secondary beam. As a first approximation, one can ignore them and assume that all secondaries are pions or nucleons.

The experiment can be done, while other experimental areas of the storage ring are used for other purposes.

The method here described is meant for proton storage rings. It cannot directly be applied to lepton storage rings, because for a gas target in a lepton beam the σ_N'/σ_c is much smaller.

If one performs the above described experiments with the CERN-ISR, then the c.m.s. energies most conveniently accessible are between about 30 and 42 GeV for π^+p scattering, and between about 40 and 60 GeV for $n+p$ scattering. The only other way I know to do these experiments is to build a machine capable of producing protons with energies up to 900 GeV and up to 1,800 GeV respectively.

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		$F = 1$	$F = 2$	$F = 3$	$F = 10$
N_{π^+}	$\tau = 5 \text{ hr}$	$1.46 \cdot 10^{11} \text{ sec}^{-1}$	$1.78 \cdot 10^{11} \text{ sec}^{-1}$	$1.85 \cdot 10^{11} \text{ sec}^{-1}$	$1.91 \cdot 10^{11} \text{ sec}^{-1}$
	$\tau = 0,5 \text{ hr}$	$2.78 \cdot 10^{12} \text{ sec}^{-1}$	$3.38 \cdot 10^{12} \text{ sec}^{-1}$	$3.53 \cdot 10^{12} \text{ sec}^{-1}$	$3.66 \cdot 10^{12} \text{ sec}^{-1}$
	$\tau = 0,203 \text{ hr}$	$7.04 \cdot 10^{12} \text{ sec}^{-1}$	$8.55 \cdot 10^{12} \text{ sec}^{-1}$	$8.91 \cdot 10^{12} \text{ sec}^{-1}$	$9.20 \cdot 10^{12} \text{ sec}^{-1}$
$N(\pi^+ + p)$	$\tau = 5 \text{ hr}$	$R.6.31 \text{ hr}^{-1}$	$R.7.68 \text{ hr}^{-1}$	$R.8.00 \text{ hr}^{-1}$	$R.8.27 \text{ hr}^{-1}$
	$\tau = 0,5 \text{ hr}$	$R.1.20 \cdot 10^2 \text{ hr}^{-1}$	$R.1.46 \cdot 10^2 \text{ hr}^{-1}$	$R.1.52 \cdot 10^2 \text{ hr}^{-1}$	$R.1.57 \cdot 10^2 \text{ hr}^{-1}$
	$\tau = 0,203 \text{ hr}$	$R.3.04 \cdot 10^2 \text{ hr}^{-1}$	$R.3.70 \cdot 10^2 \text{ hr}^{-1}$	$R.3.85 \cdot 10^2 \text{ hr}^{-1}$	$R.3.97 \cdot 10^2 \text{ hr}^{-1}$

For a H_2 target in the improved CERN-ISR, the number of $\pi^+ + p$ scattering events, $N(\pi^+ + p)$, and the quantity N_{π^+} are shown as a function of the beam lifetime, τ , and the linear focusing coefficient F .

REFERENCES

- 1) - The number of revolutions must be at least $\frac{1}{2}$ to make the storage ring meaningful. It increases with increasing particle energy only if the magnetic field is increased simultaneously.
- 2) - The lifetime of the beam is defined as the time after which only a fraction $1/e$ of the particles originally in the beam survives. (Immediately after injection the beam decay is non-exponential, but we shall neglect this effect here.)
- 3) - E. Fischer - CERN ISR-VAC/67-16 (1967).
- 4) - G. Belletini et al. - Nuclear Phys. 79, 609 (1966).
- 5) - Design Study of the Intersecting Storage Rings (ISR), CERN-AR-SG/64-9 (1964).
- 6) - Those particles which are scattered into the beam by the primaries, can be pumped away by conventional methods. For H_2 gas (as opposed to He gas), the technique of freezing out can be applied, without major difficulties.
- 7) - E. Courant, E. Keil and A.M. Sessler - CERN-ISR-TH 67-12 (1967).
- 8) - The h and α could be varied fairly easily.
- 9) - R. Hagedorn and J. Ranft - CERN Preprint TH. 715 (1966), and private communication.
- 10) - Focusing the beam will in general require modification of some section of the storage ring, to compensate for the unwanted effects of the introduced field gradients.
- 11) - The question of what values can R attain in the CERN-ISR is now being studied.
- 12) - This can be seen by actually constructing a simple system of magnetic fields in which $R \approx 0.1$. With more sophisticated arrangements and stronger fields, one could reach higher R values. Consider a homogeneous magnetic field of 25 kgauss in a region 3 metre long, and whose width is about 10 cm near the gas target, and of the order of 50 cm near the region where the secondaries and primary protons intersect the target proton beam. A horizontal magnetic field, roughly perpendicular to the secondary beam is applied, to focus pions, with around 10 GeV onto the target proton beam. Then the number of pions with momentum between 7.5 and 12.5 GeV/c, and which intersect the target proton beam, will be of the order of 10% of all pions produced, when $F = 1$. The value of R also depends

somewhat on the charge of the pions, and on the momentum range in which one is interested. To avoid focusing the primary beam, it is sufficient to separate it from the secondaries immediately after production by a strong homogeneous magnetic field. The CERN-ISR, e.g., will tolerate at least 80 kgauss acting over a 150 cm long section.

- 13) - By focusing the target beam at (a) certain point (s) in the region where it intersects the secondary beam, and also focusing (a sector of the) secondary beam, one may be able to increase the counting rate due to pions of certain momenta.