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POLARIZED ATOMIC HYDROGEN AS A TARGET FOR HIGH-ENERGY STORAGE RINGS

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ABSTRACT

The use of a polarized atomic hydrogen beam ('polarized jet') as internal target for high-energy accelerators and storage rings is discussed, in particular in view of the application to the UA6 experiment at the CERN $\bar{p}p$ Collider.

1. SOME HIGHLIGHTS ON SPIN EFFECTS IN HIGH-ENERGY SPIN PHYSICS

There are many physics arguments to justify a deeper study of spin effect in high-energy particle physics. During the last decade, the discovery of large polarization or asymmetry effects for inclusive production of mesons or hyperons tends to persuade us that it is no longer an 'inessential complication' for the comprehension of strong interactions. Many exclusive processes exhibit also large spin effects, but we will limit our comments on inclusive reactions and especially on one of those well-established and intriguing polarization effects observed in the inclusive production of Λ^0 hyperons,

$$p + p \to \Lambda^0 (\bar{\Lambda}^0) + X .$$

In a review talk given at the Marseilles conference, Heller [1] pointed out the main features of this effect:

i) All hyperons are produced polarized perpendicularly to the production plane. Anti-hyperons are not.

ii) Above p_T of 1 GeV/c the polarization is independent of p_T and increases linearly with x. Below p_T of 0.8 GeV/c the polarization varies linearly with p_T to 0 for p_T = 0.

iii) The polarization is virtually independent of the c.m.s. energy. If anything, it increases with energy.

iv) A nuclear target reduces the polarization with increasing A.

This process does not require any polarization in the initial state since the Λ's decay plane in respect to the production plane reveals the polarization.

For the inclusive production of π^0's on a polarized target the experimental results are not as clear as those for the hyperons. The two reactions,

$$p + p\uparrow \rightarrow \pi^0 + X \qquad \text{with } p_p = 24 \text{ GeV/c}$$

and

$$\pi^- + p\uparrow \rightarrow \pi^0 + X \qquad \text{with } p_\pi = 40 \text{ GeV/c} ,$$

were performed at 90° c.m.s. Both reactions for p_T above 1 GeV/c have a π^0 production largely asymmetric according to the spin direction, up or down, with respect to the production plane. The asymmetry is negative for $pp\uparrow$ and positive for $\pi^- p$ [2, 3].

These two reactions require a solid-state polarized target. However, the unpolarized bound carbon nucleons dilute the effect, and moreover the dilution factor is not simply the ratio of the free protons (polarized) upon the bound nucleons but it is kinematically dependent especially on x and p_T, like the asymmetry effect, and must be experimentally measured. The possible systematic errors and the statistical precision affect the final result. A clear target will be of great importance for improving those experiments.

Recently a strong spin alignment has been observed [4] in $p + \bar{p} \rightarrow \varrho + X(\varrho \rightarrow \pi^+\pi^-)$, whilst the

$$p + p \rightarrow \varrho + X$$

shows no alignment. This process does not require any polarization in the initial state.

These few examples show that for mesons and hyperons, inclusively produced by hadron reactions, the spin effects we observe have more or less the same magnitude and sign effect.

A consequence of the foregoing is that it will be useful to compare the well-established spin effect produced by protons with those produced by $\bar{p}$, where antiquarks are valence quarks.

Another fact is that quark and gluon spin does not wash out even in the multiparticle states and seems to be preserved in the apparent chaos by a well-defined collective structure similar to that described by Preparata [5]. Another less general attempt is also made by Gustafson [6].

It will be also interesting to look at the spin effect with e^+e^- and e^-p interactions at the highest possible energy, for the same final states. The collective structure for such interacting particles will be rather different from those produced in hadron-hadron collisions. What happens to the spin memories?

In this context, spin effects in lepton pair and direct photon production, where we have essentially the annihilation of a $q\bar{q}$ pair, will be excellent candidates for short-range investigation.

Finally, the spin correlation between the initial and final states will be of great importance for the study of the large spin memories in hadronic collisions. Using the polarization of hyperons or mesons in the final state we can measure the strength of the spin coupling in the production mechanism.

In this framework it is conceivable that spin effect is related to the properties of the colour field which is responsible for the confinement of quarks and gluons in hadronic matter. This kind of effect will be very constraining for the theory, especially for perturbative QCD where in the first order the prediction is essentially zero. Quantitative predictions from theory are, up to now, rather poor, and at this time our greatest need is for further theoretical work.

From all the foregoing, and after two decades of spin interaction experiments in high-energy physics, it followed that a pure H or D polarized target was essential. That was the first motivation for proposing in 1977, at CERN, the use of a polarized jet target compatible with the SPS Collider for spin-effect experiments [7]. Furthermore, it became evident that a denser H_2 jet was an ideal fixed target for $p\bar{p}$ physics. Both H↑ and H_2 jet targets were successfully built in 1980 with densities of $\sim 10^{12}$ and $\sim 10^{14}$ atoms per cm^3, respectively [8].

The features that make jet targets attractive for fixed-target experiments are:

i) the targets are small and well-defined;

ii) low density, which permits accurate detection of low-energy particles and electromagnetic final states;

iii) parasitic operation;

iv) heavier gases can be used, e.g. N_2, O_2, ..., Ar, Xe.

Other advantages of polarized jets are:

i) clean target (pure hydrogen or deuterium);

ii) high polarization, ~ 95%;
iii) low systematic errors (typical spin reversal time ~ 1 kHz);
iv) small instrument asymmetry (weak magnetic field on the target, ~ 20 G to maintain the polarization);
v) flexibility: spin can be easily oriented in any direction with respect to the beam.

The colliding mode of operation gives an extremely low surrounding background. At UA6, for a displacement of few millimetres away from the stored beam, the monitor counting rate is absolutely zero. Then, the jet and beam crossing point (1 mm × 3 mm) can be considered as a unique non-ambiguous coordinate for all kinds of particles emerging from the target.

2. THE UA6 EXPERIMENT

The UA6 physics programme is mainly to compare pp and $p\bar{p}$ reactions at ~ 25 GeV c.m.s. energy with a high luminosity and good efficiency for $\bar{p}$, both particles having the same structure with quarks and antiquarks. But the final interest of UA6 is to make a study in 1988, taking advantage of the ACOL programme, which will increase the $\bar{p}$ intensity stored in the CERN $p\bar{p}$ Collider by a factor of 10. For this period we expect to set up an improved version of the polarized jet which we built in 1980 (~ 10^{12} atoms per cm^2) with a density of ~ 10^{13} atoms per cm^2. The corresponding luminosity will be ~ 2×10^{29} for $\bar{p}$ and more than 10^{30} for p with 95% polarization. The UA6 design will give us the possibility to study the spin effect in the following inclusive reactions from initial $p + p\uparrow$ or $\bar{p} + p\uparrow$ states:

$$\pi^0 + X , \quad \eta + X , \quad \gamma + X , \quad e^+ + e^- , \quad \Lambda^0(\bar{\Lambda}^0) + X ,$$

and certainly a few other such as low-t elastic scattering and inclusive diffraction dissociation in a range of $0.001 < |t| < 0.1\ (GeV/c)^2$ [9].

The experiment, installed at the CERN $p\bar{p}$ Collider [10] consists essentially of an internal gas target (at present an unpolarized hydrogen cluster target), of a forward double-arm spectrometer plus calorimeter, and of a recoil spectrometer to study elastic and inelastic cross-sections in the momentum range $0.001 \lesssim t \lesssim 0.1$. The experiment runs parasitically during the $p\bar{p}$ Collider runs and allows comparison of pp and $p\bar{p}$ reactions under almost identical conditions.

3. LUMINOSITY

When a stored beam crosses the jet target, the luminosity L is expressed by

$$L = N f_{rev} n d G \quad cm^{-2}\ s^{-1} ,$$

where

n = number of nuclons per cm^3,

d = target dimension in beam direction in centimetres,

N = number of circulating particles,

f_{rev} = revolution frequency (multitraversal) in s^{-1},

G = geometrical factor (beam-jet overlap) ~ 1.

The number of circulating particles can be expressed by $N = aN_B$, where a is the number of bunches stored, and N_B is the number of particles in a bunch; $n \cdot d$ is the superficial number of nucleons in cm^{-2}, $n_s = n \cdot d$. The luminosity L is now given by

$$L = aN_B f_{rev} n_s .$$

Owing to the short length of the stored bunches (4 ns in the case of the SPS), the event rate must in general be limited to not much more than one event per bunch crossing. This condition imposes for the luminosity per bunch, $L_{B_{max}}$ = L/a:

$$\sigma_{tot} L_{B_{max}} / f_{rev} \lesssim 1.$$

With $\sigma_{tot} \approx 4 \times 10^{-26}\ cm^{-2}$ for 315 GeV/c p or $\bar{p}$, and $f_{rev} \approx 4 \times 10^4\ s^{-1}$, we have for $L_{B_{max}}$:

$$L_{B_{max}} \approx 10^{30}\ cm^{-2}\ s^{-1}$$

and the overall maximum luminosity L_{max},

$$L_{max} \simeq a \times 10^{30}\ cm^{-2}\ s^{-1} .$$

For the $p\bar{p}$ Collider with six bunches,

$$L_{max\ (p\bar{p}\ Coll.)} = 6 \times 10^{30}\ cm^{-2}\ s^{-1}\ .$$

The maximum useful jet density $n_{s_{max}}$ is

$$n_{s_{max}} = \frac{1}{N_B \sigma_{tot}} \simeq \frac{2.5 \times 10^{25}}{N_B}$$

for a typical value of the number of particles in a bunch, $N_B = 2.5 \times 10^{11}$,

$$n_{s_{max}} \simeq 10^{14}\ \text{atoms per cm}^2\ .$$

The beam crossing the jet will be perturbed in two ways:

i) by intensity losses due to interactions;

ii) by multiple Coulomb scattering which increases the transverse emittance.

For the $p\bar{p}$ Collider these two effects are negligible. The loss of luminosity over 24 hours is less than 10% for a hydrogen jet of 10^{14} atoms per cm^2. At a lower energy the multiple scattering effect will be dominant, but a beam-cooling system will preserve the luminosity.

The cluster jet used at present in the UA6 experiment has a target thickness of up to 4×10^{14} atoms per cm^2, giving a luminosity of about $8 \times 10^{29}\ s^{-1}$ with 6×10^{10} $\bar{p}$ stored. From 1987 onwards, the number of stored $\bar{p}$ is expected to be ten times higher.

Existing polarized atomic beams as used in polarized ion sources produce densities of up to about 5×10^{11} atoms per cm^3 with beam diameters of about 1 cm. Even with the increased future $\bar{p}$ intensity, luminosity with such an atomic beam would be down two orders of magnitude from our present level.

In the following we would like to discuss ideas for improving the density of the polarized atomic beam used as a jet target.

4. IMPROVEMENTS OF THE CLASSICAL ATOMIC BEAM

It follows from the theory of atomic beam focusing that lowering the speed of the atoms by cooling the nozzle of the dissociator increases the density of the beam. Measurements on polarized ion sources indicate improvements proportional to $T^{-1/2}$ [11-13], whilst a naïve argument would suggest a behaviour proportional to $T^{-3/2}$. The discrepancy can be explained by the combination of three effects:

i) The beam velocity remains significantly higher than the velocity corresponding to the nozzle temperature.

ii) For a given gas input, the forward intensity decreases with decreasing beam velocity, probably due to increased scattering on rest gas and in the beam itself [12, 14, 15].

iii) An atomic-beam system with a given geometry cannot make optimal use of a beam of a velocity different from the one for which it was designed.

For the first effect, adding an 'accommodator' at nozzle temperature [13, 16] or at some intermediate temperature [14] is useful, but mean velocities much below about 800 m/s for high gas throughput have not been obtained.

Scattering on background gas can be reduced by a higher pumping speed, mainly in the first stage, but especially in the case of a continuously operated beam there are obvious technical limits.

As for the focusing system, it is becoming common practice first to measure the velocity distribution under realistic conditions and then to design a magnet system for this condition. In the absence of a more general theory, ray tracing or acceptance diagram techniques [17] are being used.

We estimate that by following this procedure, and in spite of the problems mentioned above, an atomic beam target with a thickness of a few 10^{12} atoms per cm^2 and a size of the order of a centimetre can be built. This is an acceptable, but not comfortable, target thickness for a large part of our experimental programme.

5. THE STORAGE CELL

As a means of substantially increasing the target density, it has been proposed to inject the atomic beam into a target cell with walls with low recombination probability and with low conductance passages for the accelerator beam [18]. Although this certainly uses the atoms most efficiently and may produce target densities of 10^{14} atoms per cm^2 or more, it presents some major drawbacks in the environment of our experiment.

On the one hand, since even the thinnest conceivable cell wall is orders of magnitude thicker than the target, it has to remain comfortably away from the accelerator beam in order not to produce background for us or for the other collider experiments. We have estimated a minimum size of about 30 x 50 mm^2 (no low-beta insertion); similar sized openings would be required between the differential pumping stages upstream and downstream of the target, resulting in a rather poor performance of the whole system.

On the other hand, the recoil experiment could not run at all, since it requires a target size not significantly above a centimetre and no wall at all.

6. LOW CROSSING ANGLE

The idea of crossing the atomic beam with the accelerator at a small angle [19] again has the drawback of the 'long' target, and moreover it is not clear that one could gain very much, since, owing to the size of the accelerator chamber and the last sextupole, the crossing would move downstream into a region of lower average density.

7. MIRRORS

With decreasing beam velocity, a 'mirror'-type optical system may become feasible [20]. For reasonable reflection angles between beam and mirror (~ 12°) and realistic magnetic fields near the surface (~ 2 T), mean beam velocities below about 700 m/s are necessary. In practice, achromatic focusing of all atoms within the geometrical acceptance of the mirrors, together with a higher transmission probability due to the lower average pressure, should give a significantly higher target density than a sextupole system with the same input beam. Polarization should be excellent, since there is no straight trajectory between the nozzle and the target region.

8. MULTIPLE TARGET BEAMS

Compared to an ionizer with a long cylindrical ionization region, the angular acceptance of a target can be very large. In our geometry, for instance, a region of ±30° could be easily accommodated. It does not seem possible to design a single atomic beam of such a large size, but at least part of the phase space could be used by combining several jets such that they cross at the target point. Using very compact sextupoles, a number between 4 and 8 appears appropriate. The principle can be equally well applied to mirror systems. Provided the throughput is not limited by the pumping speed of the (common) first stage, the target density would be multiplied by the same factor.

9. VERY COLD ATOMS

'Very cold' (i.e. < 1 K) atoms [21] are becoming very attractive as polarized atom sources, in particular since a promising method for extraction from the high-field region has been proposed [22]. It has been estimated [23] that a density of around 10^{14} atoms per cm^2 with a duty cycle of 0.1 could be expected.

We see a problem in the necessity to cover the inside of the cold box with superfluid helium. Accidental evaporation of the film could contaminate the accelerator vacuum system with helium and could also lead to a dumping of the stored beam, with possibly severe perturbations for the other collider experiments. Moreover, the production of D↓ seems to present technological problems.

10. CONCLUSION

The use of a polarized atomic beam as a target is particularly advantageous for the study of spin effects in high-energy inclusive reactions. To cover the interesting region in x and p_T, a target thickness of 10^{13} atoms per cm^2 or more is desirable.

We expect to achieve a target density of a few 10^{12} atoms per cm^2 with a cooled, optimized, classical atomic beam, and assume that with a mirror system and/or a multiple target beam, densities beyond 10^{13} atoms per cm^2 are feasible without abandoning the basic geometry of the experiment.

REFERENCES

[1] K. Heller, Proc. 6th Int. Symp. on High-Energy Spin Physics, Marseilles, 1985, ed. J. Soffer [J. Phys. (France) 46 (1985) C2-121].

[2] J. Antille et al., Phys. Lett. 94B (1980) 523.

[3] A.P. Meschanin et al., Proc. Second Workshop on High-Energy Spin Physics, Serpukhov, 1985, p. 60.

[4] B.V. Batyunya et al., Phys. Rev. Lett. 55 (1985) 562.

[5] G. Preparata:
a) Proc. Int. Symp. on High-Energy Physics with Polarized Beams and Targets, Lausanne, 1980, eds. C. Joseph and J. Soffer [Experiencia 38 (1981) 121].
b) Ref. 1, p. C2-13.
c) To appear in Proc. Int. Conf. on a European Hadron Facility, Mainz, 1986, to be published.

[6] G. Gustafson, Polarization and Confinement, Ref. 3, p. 212.

[7] CERN-Lund-Michigan-Rockefeller Collaboration, CERN Proposal SPSC/77-77, 28 August 1977.

[8] CERN-Lausanne-Michigan-Rockefeller Collaboration, CERN Proposal SPSC/80-63, 19 August 1980, and L. Dick et al., Proc. Int. Symp. on High-Energy Physics with Polarized Beams and Targets, Lausanne, 1980, eds. C. Joseph and J. Soffer [Experiencia 38 (1981) 212].

[9] R. Cool, Ref. 1, p. C2-237.

[10] G. Valenti (CERN-Lausanne-Michigan-Rockefeller Collaboration), Proc. 5th Topical Workshop on Proton-Antiproton Collider Physics, Saint-Vincent, 1985, ed. M. Greco (World Scientific Publ. Co. Ltd., Singapore, 1985), p. 534.

[11] P.F. Schultz, E.F. Parker and J.J. Madsen, *in* Proc. 5th Int. Symp. on Polarization Phenomena in Nuclear Physics, Santa Fe, 1980, eds. G.G. Olsen et al. (AIP Conf. Proc. No. 69, 1981).

[12] Y. Wakuta, Y. Koga, H. Hasuyama and H. Yamanda, Nucl. Instrum. Methods 147 (1977) 461.

[13] W. Grüebler, Proc. Workshop on Polarized Proton Ion Sources, Vancouver, 1983, eds. G. Roy and P. Schmor [AIP Conf. Proc. 117 (1984) 1].

[14] J.C. Berney, W. Kubischta and L. Dick, Velocity measurements of a cooled atomic hydrogen beam, this Workshop.

[15] A.V. Evstigneev, S.G. Popov and D.K. Toporkow, Nucl. Instrum. Methods A238 (1985) 12.

[16] A. Hershcovitch, A. Kponou and T.O. Niinikoski, Cooling high-intensity atomic hydrogen beams to liquid-hydrogen temperatures, this Workshop.

[17] W.Z. Zhang, P.A. Schmelzbach, D. Singy and W. Grüebler, Nucl. Instrum. Methods A240 (1985) 229.

[18] M.D. Barker et al., Ref. 11, p. 931.

[19] W. Grüebler, Proc. Workshop on Polarized Targets in Storage Rings, Argonne, 1984 [Argonne Nat. Lab. ANL-84-50 (1984)], p. 223.

[20] G. Brautti, Nucl. Instrum. Methods 116 (1974) 609.

[21] T.J. Greytak and D. Kleppner, *in* New Trends in Atomic Physics, Les Houches, 1982, eds. G. Grynberg and R. Stora (North-Holland Pub. Co., Amsterdam, 1984), p. 1125.

[22] T.O. Niinikoski, Ref. 5a, p. 191.

[23] T.O. Niinikoski, Hyperfine Interactions 22 (1985) 277.