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SOME EXPERIMENTAL TECHNIQUES AT STORAGE RINGS

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Two experimental techniques that have been developed at the COoler SYnchrotron COSY-Jülich are presented:

(i) The energy of a stored polarized proton or deuteron beam can be precisely determined by sweeping an *rf* magnetic dipole or solenoid field over a spin resonance. This perturbation induces a beam depolarization, which is maximal at the spin resonance's frequency. That frequency, together with the beam revolution frequency, determines the beam's kinematic γ factor, which can thus be measured with high accuracy. Therefore, the beam energy can be determined about one order of magnitude more precisely than with conventional methods based on orbit length measurements. The technique has been used at COSY for an experiment aiming at a high-precision measurement the mass of the η meson.

(ii) The repeated passage of a coasting ion beam through a thin internal target leads to a beam-energy loss and a shift of its revolution frequency. This shift is proportional to the beam-target overlap and thus allows one to measure the target thickness and hence the luminosity during the corresponding experiment. This effect has been studied quantitatively with a 2.65 GeV proton beam impinging on a hydrogen cluster-jet target at the ANKE spectrometer. After a careful error evaluation the luminosity, could be determined with an accuracy of better than 5%.

1. Introduction

The two major problems facing experimentalists working with internal targets at a storage ring, such as that at COSY-Jülich or the HIRFL-CSR Cooler Storage Ring at Lanzhou, are (*i*) knowing the absolute momentum of the circulating beam, and (*ii*) establishing the absolute normalization for any cross section measured. Both these difficulties can be overcome and the methods to achieve this and some results are reported here briefly.

Although the frequency of COSY is known to high accuracy, the position of the beam, and hence the length of the orbit, is far more uncertain and this leads to an

*Past designation: Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany error in the momentum of $\Delta p/p \approx 10^{-3}$. This is very significant when measuring meson production, where the cross section varies very fast near a threshold. An example of this is the production of the η meson in the two-body $dp \to {}^3\mathrm{He}\,\eta$ reaction,[1,2] where the mean c.m. energy above threshold could be deduced with a precision of about 9 keV. However, one would need more than a factor of ten better determination of the momentum in order to reach the World precision for the mass of the η meson. As we shall see, this can, surprisingly, be achieved through the use of polarized deuterons!

In an ideal scattering experiment with an external beam, the particles pass through a wide uniform target of known thickness. If the fluxes of the incident and scattered particles are measured, the absolute cross section of a reaction can be determined. In contrast, the overlap of the beam with an internal target of a storage ring is hard to establish with precision.

We now address separately these two problems.

2. Determination of the beam energy with high accuracy

In any planar storage ring where the horizontal magnetic field vanishes, the spin of each beam particle precesses around the vertical fields of the ring's dipole magnets. The spin tune ν_s, which is the number of spin precessions during one turn around the ring, depends on the particle's Lorentz energy factor γ through

$$\nu_s = G\gamma, \tag{1}$$

where $G = (g-2)/2$ is the gyromagnetic anomaly of the particle.[3]

The vertical polarization can be perturbed by a horizontal *rf* magnetic field using, for example, a solenoid. This can induce an *rf* depolarizing resonance that can flip the spin direction of the stored beam. The resonance frequency is given by

$$f_r = f_0(k \pm \nu_s), \tag{2}$$

where f_0 is the circulating frequency and k is an integer.

With $k = 1$, it then follows that

$$\gamma = \frac{1}{|G|}\left(1 - \frac{f_{\mathrm{res}}}{f_0}\right). \tag{3}$$

Each of the factors on the right can be measured with high accuracy. In the deuteron case, the gyromagnetic anomaly $G_d = -0.1429873$, with an uncertainty in the last figure, and the circulating frequency f_0 is known to about $\pm 2 \times 10^{-6}$. The central value of the resonance frequency f_r can be determined by ramping the rf solenoid and measuring the amount of beam depolarization over the ramping region. For this purpose a solenoid was placed inside one of the straight sections of COSY and the resulting field changes were along the direction of the beam.

To investigate the precision that this technique might provide for the deuteron beam momentum for the foreseen ANKE η-mass studies using the $dp \to {}^3\mathrm{He}\,\eta$ reaction,[4] a test measurement was performed where the conditions would be as

Table 1. Nominal and measured deuteron momentum.

	value	abs. error	unit
nominal measured f_0	1.399995	$\pm 2 \times 10^{-6}$	MHz
nominal γ_0	1.93998		
nominal momentum p_0	3118.0	± 3.1	MeV/c
measured f_r	1.011831	$\pm 2 \times 10^{-6}$	MHz
measured γ_m	1.93906	$\pm 1.23 \times 10^{-5}$	
measured momentum p_m	3115.98	± 0.03	MeV/c

close as possible to the final ones. The nominal momentum of the polarized deuteron beam was set to be 3118.0 MeV/c, which corresponds to a revolution frequency of 1.399995 MHz. The precision with which the closed orbit length inside COSY is known gives a momentum uncertainty of ±3.1 MeV/c in the present case. The precision of the measured revolution frequency f_0 is a little above ±1 Hz. In the full analysis this was enlarged to a 2 Hz uncertainty (see Table 1).

A relative polarization of the beam was measured with the EDDA facility (carbon target)[5]. Errors in the analyzing powers used to calibrate this polarimeter are unimportant because it is only the frequency dependence of the signal that is relevant. Figure 1 shows the variation of the deuteron beam polarization as a function of the *rf* solenoid frequency f_r with statistical errors. The major contribution to the width of the signal comes from the momentum spread of the deuteron beam inside COSY of about $\delta p/p \approx 2 \times 10^{-4}$. This value agrees with that deduced from the earlier ANKE experiment that was based upon the study of the kinematics of the $dp \to {}^3\mathrm{He}\,\eta$ nuclear reaction.[1]

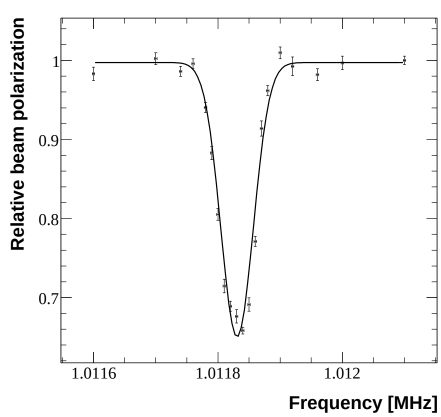

Fig. 1. Variation of the measured deuteron polarization with the frequency of the perturbation induced by the *rf* solenoid.

A direct fit to the data of Fig. 1 with a gaussian plus a constant yields a mean resonance frequency of $f_r = 1.011831$ MHz ± 1.0 Hz, though at this preliminary stage we assume the more conservative 2 Hz uncertainty, as summarized in Table I. It then follows that $\gamma = 1.93906 \pm 0.000012$ and the measured momentum $p = 3115.98 \pm 0.03$ MeV/c. The result under these test conditions give $\Delta p/p \approx 10^{-5}$ and this would contribute an error in the mass of the η meson that was comparable with the 9 keV/c^2 that follows from the uncertainty in the measurement of the $dp \to {}^3\text{He}\,\eta$ reaction.[1] The method therefore has the potential to yield a result that is more accurate than any of the other recent measurements.

Let me finish this section by stressing that the $dp \to {}^3\text{He}\,\eta$ measurement is one of kinematics and not of cross section.[6] When the deuteron beam momentum is close to the production threshold, the forward and backward ^{3}He in the c.m. system have very similar laboratory momenta and are both seen simultaneously on the ANKE focal plane. It is therefore simply a question of lowering the beam momentum until the whole kinematic ellipse collapses to a point within error bars to give the threshold momentum that is independent of the calibration of the ANKE magnet. Of course, some extrapolation to threshold is required in practice but one is helped here by the fact that the cross section remains at almost its maximal value down to an excess energy of 1 MeV.[1]

3. Determination of the target thickness and luminosity from beam energy losses

Experiments with an internal target at a storage ring have the added complication that the target thickness cannot be simply established through macroscopic measurements because of the uncertain beam-target overlap. The overall normalization of the cross section for a particular process is therefore generally measured relative to that of a calibration reaction. Effectively one is measuring only the ratio of two cross sections. However, there are often difficulties in finding a suitable calibration reaction with known cross section. As a consequence, it is highly desirable to find an alternative, more absolute, way to measure the effective target thickness and beam-target luminosity L inside a storage ring. As we have recently shown,[7] this is possible in practice by studying the energy loss of the beam as it repeatedly passes through the target.

When a charged particle passes through matter it loses energy through electromagnetic processes and this is also true inside a storage ring where a coasting beam goes through a thin target a very large number of times. The energy loss, which is proportional to the target thickness, builds up steadily in time and causes a shift in the frequency of revolution in the machine. This can be determined by measuring the Schottky spectra. Knowing the characteristics of the machine and, assuming that contributions to the energy loss outside the target can be accounted for, the effective target thickness can be deduced.

3.1. *Beam-target interaction, energy loss, and emittance growth*

The formula for the effective target thickness n_T can be easily derived.[7]

$$n_T = \left(\frac{1+\gamma}{\gamma}\right) \frac{1}{\eta} \frac{1}{(dE/dx)m} \frac{T_0}{f_0^2} \frac{df}{dt} \,. \tag{4}$$

As before, f_0 is the mean machine frequency for a beam energy T_0 and γ is the corresponding Lorentz factor. The result is inversely proportional to the stopping power dE/dx and the mass m of the beam particle. When the beam particles in a closed orbit lose momentum p the frequency f of the machine changes:

$$\frac{\Delta p}{p_0} = \frac{1}{\eta} \frac{\Delta f}{f_0} \,, \tag{5}$$

and this defines the so-called *frequency-slip parameter* η. Once this parameter is known, one only has to measure the rate of change of the machine frequency df/dt in order to determine n_T.

The η-parameter can be measured by varying the field strength in the bending magnets by a few parts per thousand. As seen from Fig. 2, the resulting frequency change is quite linear and the slope α leads to a value of $\eta = 1/\gamma^2 - \alpha = -0.115 \pm 0.003$ for a proton beam with a momentum of 3.463 GeV/c. Because one is here above the transition point, the frequency actually increases when the particles lose energy.

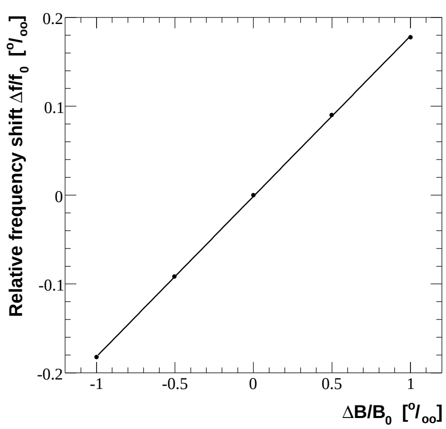

Fig. 2. Variation of the revolution frequency with field strength in the bending magnets.

In addition to energy loss, the beam also experiences emittance growth through the multiple small angle Coulomb scattering in the target. However, under typical experimental conditions of a proton beam incident on a cluster-jet target containing $n_T = 2 \times 10^{14}$ cm^{-2} hydrogen atoms, an initial horizontal width of 1.2 mm increases to only 1.36 mm over a 10 min period and this is not a serious effect.

3.2. *Measurement of the target thickness by energy loss*

The frequency shift Δf is measured by analyzing the Schottky noise of the coasting proton beam at a sequence of times. The origin of the Schottky noise is the statistical distribution of the particles in the beam, which gives rise to current fluctuations that induce a voltage signal at a beam pick-up. The measured current is proportional to the square root of the number of particles in the ring and this must be squared to give the Schottky power spectrum, which is representative of the momentum distribution. The centroids of these power spectra yield the desired frequency shifts. The results of measurements at ten equally spaced intervals in time are shown in Fig. 3 in the case of proton-proton interactions at 3.463 GeV/c. The results are quite linear, apart from the first point when the magnets have not stabilized, and from this one can deduce a value of $df/dt = (0.163 \pm 0.003)\,\mathrm{Hz/s}$.

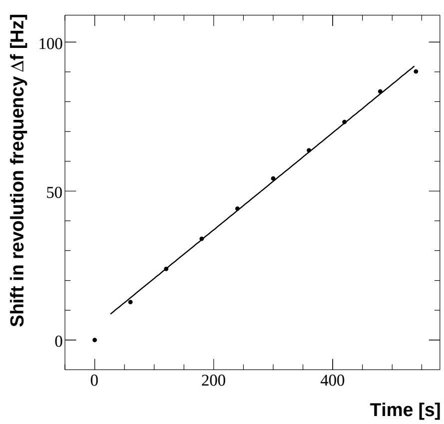

Fig. 3. Typical mean frequency shifts derived from the Schottky power spectra at ten equally spaced intervals of time. The first point is low because the COSY magnets had not then reached their steady state.

The biggest uncertainty in the methodology comes from the estimation of contributions to the energy loss from interactions with the residual gas. When the target is switched off there is an effect that is typically about 5% of that with the target. However, since the pressure in the target region of COSY is significantly higher than elsewhere in the ring, it appears that some gas is boiled off from the target. This effect is harder to quantify, leading to a doubling of the error in the corrected frequency shift; $(df/dt)_{\mathrm{corr}} = (0.151 \pm 0.006)\,\mathrm{Hz/s}$. For a representative cycle this gives an effective target thickness of $n_T = (2.6 \pm 0.13) \times 10^{14}\mathrm{cm}^2$. The 5% error here is made up of 4% from the corrected frequency shift rate and 3% from the measurement of the η parameter.

3.3. *Luminosity deduced from the effective target thickness*

The luminosity can be deduced from the effective target thickness by multiplying by the mean ion particle current n_B, as determined in the same cycle by using a high precision beam current transformer. As a consequence the error in the luminosity is at the same 5% level as that found for the effective target thickness. Depending on the cycle, the values of the luminosity obtained during the experiment ranged between 1.3 and $2.7 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

3.4. *Comparison with proton-proton elastic scattering*

In order to try to provide an independent check on the energy-loss method, we also measured elastic proton-proton scattering. For this purpose the momentum of a forward-going proton was determined using the ANKE forward detector. It is important to note that this only covers small laboratory angles, between about 4.5° and 9.0°. In addition to the 5% from luminosity, the major uncertainties in deducing the differential cross section are 8% from the acceptance correction, and 5% from each of the track reconstruction and data-taking efficiencies. The total systematic error is therefore about 12%.

Our results for the laboratory differential cross section for *pp* elastic scattering at 2.65 GeV are shown in Fig. 4. Also shown is the prediction of the SP07 solution from the SAID analysis.[8] Although this has the right shape, it lies about 20% higher than our data. The same problem arises in the SAID description of published data at 2.83 GeV[9] (also shown in the figure) and at 2.87 GeV.[10] This problem probably comes about because there are generally relatively few data points in the *pp* database in the small angle region. One should also note the SAID disclaimer that *'our solution should be considered at best qualitative between 2.5 and 3 GeV'*.[8]

4. Summary and Outlook

In this presentation we have shown that it is possible to determine with very high precision the momentum of a circulating polarized deuteron beam and exactly the same methodology is applicable for proton beams. The test experiment reported here gives, very conservatively, an uncertainty on the 10^{-5} level, which is sufficient for any experiment envisaged at COSY. Since then data have been taken to determine the mass of the η meson with unparalleled precision[4] but, in view of this need for accuracy, the analysis will take several more months to complete.

Of even greater potential impact is the fact that, under the specific experimental conditions described here, the energy loss of a coasting ion beam interacting with a cluster-jet target can be used to determine target thickness and beam-target luminosity. The method is simple in principle and independent of the properties of particle detectors used. It relies on the fact that the particles pass through the target more or less the same number of times so that they build up the same energy shift. This is confirmed here by the fact that the Schottky spectrum at the end of a

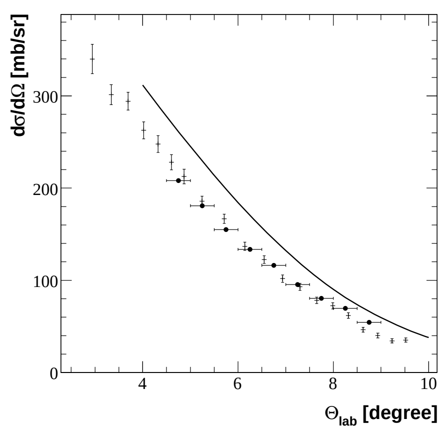

Fig. 4. Laboratory differential cross section for elastic proton-proton scattering at 2.65 GeV. The ANKE points, shown by closed circles with bin widths, have systematic uncertainties of ±12%. The curve is the SP07 solution from the SAID analysis group[8] and the crosses are experimental data at 2.83 GeV.[9]

cycle has a similar shape to that at the beginning. The method does not have to be evaluated for every cycle and need only be used to calibrate monitoring equipment.

For the standard lattice setting used at COSY-ANKE, the value of the slip parameter η passes through zero for a beam energy of $T_p \approx 1.2$ GeV and so the beam energy range from 1.0 to 1.6 GeV is not well suited for the energy-loss technique. On the other hand the method can be applied for deuterons up to about 1.9 GeV, which is almost the upper limit of the COSY range. Furthermore, since the energy loss is of electromagnetic origin, it could equally well be used with beams of α-particles or the heavier ions that will be available at CSR-Lanzhou.

The density of a cluster-jet target may be the ideal compromise for implementing the energy-loss approach to luminosity studies. For very thin foil targets the beam dies too quickly for reliable frequency shifts to be extracted. On the other hand, the overall thickness of a polarized gas cell target is less than that with the cluster jet so that the ring-gas will provide a larger fraction of the energy loss. The ring-gas effects will also be more important because of greater contamination of the vacuum by the target. It is therefore clear that a detailed analysis of the specific conditions is required to determine the accuracy to be expected in a particular experiment.

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References

1. T. Mersmann *et al.*, *Phys. Rev. Lett.* **98** (2007) 242301.
2. C. Wilkin *et al.*, *Phys. Lett. B* **654** (2007) 92.
3. A.D. Krisch *et al.*, *Phys. Rev. ST Accel. Beams.* **10** (2007) 071001.
4. A. Khoukaz *et al.*, *COSY Proposal* # **187**, (2007) *http://www.fz-juelich.de/ikp/cosy/en/index.shtml.*
5. J. Bisplinghoff *et al.*, *Nucl. Instr. Methods A* **329** (1993) 151; F. Bauer, K. Büßer, *Nucl. Instr. Methods A* **431** (1999) 385, *http://kaa.desy.de/edda/Edda.html.*
6. A. Khoukaz, *talk of this conference.*
7. H.J. Stein *et al.*, *Phys. Rev. ST Accel. Beams.* **11** (2008) 052801.
8. R.A. Arndt, I.I. Strakovsky, and R.L. Workman, *Phys. Rev. C* **62** (2000) 034005; R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, and R.L. Workman, *Phys. Rev. C* **76** (2007) 025209; *http://gwdac.phys.gwu.edu/.*
9. I. Ambats *et al.*, *Phys. Rev. D* **9** (1974) 1179.
10. T. Fujii *et al.*, *Phys. Rev.* **128** (1962) 1836.