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Measurement of the absolute differential cross section of proton–proton elastic scattering at small angles

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ABSTRACT

The differential cross section for proton–proton elastic scattering has been measured at a beam kinetic energy of 1.0 GeV and in 200 MeV steps from 1.6 to 2.8 GeV for centre-of-mass angles in the range from 12°–16° to 25°–30°, depending on the energy. A precision in the overall normalisation of typically 3% was achieved by studying the energy losses of the circulating beam of the COSY storage ring as it passed repeatedly through the windowless hydrogen target of the ANKE magnetic spectrometer. It is shown that the data have a significant impact upon the results of a partial wave analysis. After extrapolating the differential cross sections to the forward direction, the results are broadly compatible with the predictions of forward dispersion relations.

For beam energies above about 1 GeV there are relatively few measurements of proton–proton elastic scattering at centre-of-mass (c.m.) angles θ from 10° to 30°, i.e., between the region of major Coulomb effects and the larger angles where the EDDA Collaboration has contributed so extensively [1–3]. The lack of information on the differential cross section and analysing power inevitably leads to ambiguities in any *pp* partial wave analysis (PWA) at high energies [4]. The ANKE Collaboration has recently published proton analysing powers in this angular domain at 796 MeV and five other beam energies between 1.6 and 2.4 GeV using a polarised proton beam [5] and these led to a revision of the SAID PWA [4] in order to accommodate the data. The major uncertainty in such a measurement is the precision to which the beam polarisation can be determined, beam-target luminosity and equipment acceptance playing only secondary roles. This is far from being the case for the differential cross section where, in order to provide accurate absolute values, both the luminosity and acceptance must be mastered with high precision [6]. The difficulties encountered

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in earlier experiments in making absolute measurements were discussed most clearly in Ref. [7], whose normalisation was used as the standard for the EDDA work [1,2].

As was the case for the analysing power [5], the present studies of the differential cross section were carried out using the ANKE magnetic spectrometer [8] sited inside the storage ring of the COoler SYnchrotron (COSY) [9] of the Forschungszentrum Jülich. Only the Forward Detector (FD), which measured fast protons from elastic pp scattering over a range of up to 12°–30° in c.m. polar angles and ±30° in azimuth, was used in the analysis. The FD comprises a set of multiwire proportional and drift chambers and a two-plane scintillation hodoscope, the counters of which were used to measure the energy losses required for particle identification [10].

The biggest challenge that has to be faced when measuring the absolute value of a cross section in a storage ring experiment is to establish the beam-target luminosity at the few percent level even though the overlap of the beam and target cannot be deduced with such precision from macroscopic measurements. It has been shown that this can be achieved by studying the energy loss through electromagnetic processes as the coasting uncooled beam passes repeatedly through the target chamber. There is a resulting change in the frequency of the machine that can be determined with high accuracy by studying the Schottky power spectrum of the beam [11]. The amount of electromagnetic interaction is proportional to that of the strong proton–proton scattering, whose measurement was the goal of the experiment

The statistical distribution of particles in the beam is at the origin of the Schottky noise. This gives rise to current fluctuations that induce a voltage signal at a beam pick-up. The Fourier analysis of the voltage signal, i.e., of the random current fluctuations, by a spectrum analyser delivers power distributions around the harmonics of the revolution frequency. Over a 300 s cycle, the Schottky signals were recorded every 10 s with a 189 ms sweep time, thus giving effectively instantaneous spectra. The frequencies were measured with the existing Schottky pick-up of the stochastic cooling, which is optimized to operate in GHz region [12]. The harmonic number 1000 of COSY revolution frequency was measured with a more precise analyser than the one used in our previous work [11].

Some examples of these measurements scaled to harmonic number 1 are shown in Fig. 1 for circulating proton beam energies of 1.0 and 2.0 GeV. After subtracting the background noise, the mean frequency f of the beam at each instant of time was evaluated from the centroid of the distribution. Such values, which are indicated by the vertical lines, allow f to be determined as a function of time t over the 300 s cycle.

The important point to notice in Fig. 1 is that the direction of the frequency change is different at low and high energies; the energy of this transition from one regime to the other depends upon the lattice settings of the accelerator [11]. Since the luminosity is proportional to $\mathrm{d}f/\mathrm{d}t$, it means that there is a range of beam energies where the fractional errors are so large as to make the Schottky method of little practical use. This explains the gap in our data from 1.0 GeV to 1.6 GeV.

It was shown in Ref. [11] that the effective number of target particles per unit area, n_T, that interact with the proton beam is given by

$$n_T = \left(\frac{1+\gamma}{\gamma}\right)\frac{1}{\eta}\frac{1}{(\mathrm{d}E/\mathrm{d}x)m}\frac{T_p}{f^2}\frac{\mathrm{d}f}{\mathrm{d}t}, \quad (1)$$

where m is the proton mass. The cluster-jet target [13] used in this experiment was very thin and, as a result, the energy changes over a 300 s cycle were extremely small ($\Delta E/E \approx 2-4\times10^{-4}$). Under such conditions one can take f and T_p to be the initial values of

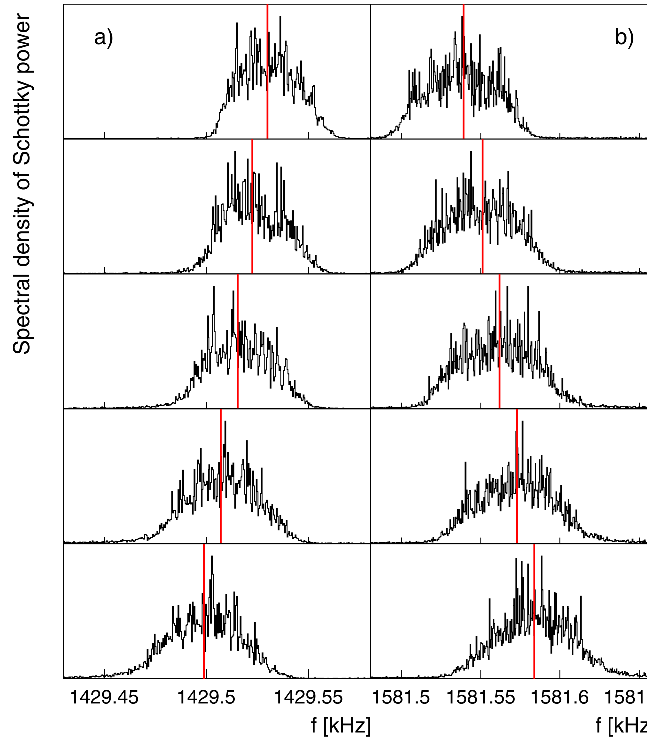

Fig. 1. Schottky power spectra obtained during one 300 s cycle and scaled to harmonic number 1 for (a) 1.0 and (b) 2.0 GeV beam energies. Although the data were recorded every 10 seconds, for ease of presentation, only the results from every 60 s are shown, starting from top to bottom. The mean frequencies are indicated by the vertical (red) lines.

the frequency and kinetic energy of the beam and γ as the corresponding Lorentz factor. The value of the stopping power $\mathrm{d}E/\mathrm{d}x$ at a given energy is to be found in the NIST–PML database [14]. The remaining quantity in Eq. (1), the so-called frequency-slip parameter η, shows how the beam revolution frequency changes with momentum. Under COSY conditions this parameter changes sign at $T_p \approx 1.3$ GeV.

Although the value of η can be estimated semi-quantitatively by a computer simulation of the acceleration process, greater precision is achieved by a direct measurement, where the change in the revolution frequency induced by adjusting the strength in the bending magnets by few parts per thousand is studied [11]. This was investigated in separate runs at each of the beam energies with the target switched off [6].

A small frequency shift is also produced by the interaction of the beam with the residual gas in the COSY ring and this was measured using dedicated cycles, where the ANKE cluster target was switched on but the beam was steered away from it. This precaution was necessary because the target produces additional background in the vicinity of the ANKE target chamber [11].

The measurement of the beam intensity, n_B, is a routine procedure for any accelerator and is performed at COSY using the high precision Beam Current Transformer device. These measurements were carried out every second over the 300 s cycle and then averaged. The final results are accurate to better than 10^{-3} [11]. The luminosity in the experiment is then the product of beam and target factors, $L = n_B n_T$.

The Forward Detector was the subject of a very detailed study [15] and only some of the salient points are mentioned here. The setup parameters were adjusted in a geometry tuning procedure, with the use of the exclusive $pp \to pp$, $pp \to pn\pi^+$, $pp \to pp\pi^0$, and $pp \to d\pi^+$ reactions. In the last case, both the d