Baryon Spectroscopy at COMPASS

Alexander Austregesilo for the COMPASS Collaboration

Technische Universität München, Physik-Department E18, James-Franck-Straße,
D-85748 Garching, Germany
E-mail: Alexander.Austregesilo@cern.ch

Abstract. Diffractive dissociation of the beam proton is one of the dominant processes for
the 190 GeV/c positive hadron beam impinging on a liquid hydrogen target in COMPASS.
The status of the analysis of the reactions \( pp \rightarrow pf \pi^+ \pi^- p_s \) and \( pp \rightarrow pf K^+ K^- p_s \) will
be presented, where dominant features of the light baryon spectrum become clearly visible.
Furthermore, partial-wave analysis techniques to disentangle these spectra are discussed.

1. Introduction

COMPASS [1] is a fixed-target experiment at the CERN SPS for the investigation of structure
and spectroscopy of hadrons. The experimental setup features a large-acceptance and high-
resolution spectrometer including particle identification and calorimetry and is therefore ideal
to address a broad range of different final states. During a total of 9 weeks in 2008 and 2009, a
190 GeV/c positive hadron beam impinging on a liquid hydrogen target was used primarily to
study the production of exotic mesons and glueball candidates at central rapidities.
Since the trigger system introduced no bias on the kinematics of the forward-going particles,
these data give a unique possibility to study diffractive dissociation of the beam protons.
This peripheral scattering process is characterised by its four-momentum transfer distribution,
the slope of which approximately reflects the radius of the target particles. The prerequisite
of coherent production translates into an upper limit for the mass of diffractively produced
resonances of a few GeV/c^2 [2]. Exclusive events with three charged particles in the final state
have been selected, this data set will be the starting point for a dedicated partial-wave analysis.
Hadron-induced reactions are complementary to the existing data from photo- and
electroproduction experiments like CBELSA or CLAS and may help to obtain a more complete
picture of the baryon spectrum [3]. In particular poorly known parameters like widths and
branching ratios of high-mass and high-angular-momentum states may become accessible.

2. Event Selection

Currently, only the data recorded during two weeks with proton beam in 2008 have been fully
reconstructed and can therefore be presented here. This fraction is estimated to be around 10%
of the total amount of data recorded in COMPASS with a proton beam in both years, 2008 and
2009.

The events were triggered by the incoming beam in coincidence with the recoiling proton \( p_s^{\text{(low)}} \)
from the reaction. The dedicated recoil particle detector (RPD) around the target consists of
two concentric rings of scintillators which measure time-of-flight and energy loss of the recoiling
particles. Plotting the latter against the velocity $\beta$ calculated from the time-of-flight information (cf. Figure 1), a very pure proton signal becomes apparent. Thus it can be safely assumed that the target protons remain intact. On the other hand, the interaction is required to have a squared four-momentum transfer $t'$ to the recoil proton larger than $0.07\text{GeV}^2/c^2$ in order to fall within the acceptance of the RPD. This effect explains the sharp cut at low values of $t'$ as shown in Figure 4.

As the positive secondary hadron beam at 190 GeV/c consists of a mixture of 75% protons, 24% pions, and less than 1% kaons, the incoming beam particles were identified by two CEDAR detectors (ChErenkov Differential counter with Achromatic Ring focus) which achieved a nearly complete separation (cf. Figure 2). In addition, particle identification was applied to distinguish between the fast proton $p_f$ and the positive meson in the final state. As the COMPASS RICH (Ring Imaging ChErenkov) detector does not allow proton identification directly in a large fraction of our kinematic range (cf. Figure 3), $\pi^+$ and $K^+$ signals were used, respectively.

Only exclusive events were selected, where all particles in the reaction were detected and their energy as well as charge sum match the incident beam. As the beam energy is not measured within the COMPASS hadron beam setup though, events were chosen whose reconstructed total energy lies within $\pm 5\text{GeV}/c^2$ around the most probable value (cf. Figure 5). In addition the information about the azimuthal angle of the recoil proton from the RPD was used to select events, where the recoil proton and the forward going three body system ($p_f\pi^+\pi^-$ or $p_fK^+K^-$) are back-to-back in the plane transverse to the beam. Both cuts have a big overlap and the resulting data sample includes merely a negligible contribution of non-exclusive background.

**Figure 1.** Energy loss vs. velocity of recoil particle in RPD

**Figure 2.** Separation of $p$ and $\pi^+$ beam particles in CEDAR detectors

**Figure 3.** Cherenkov angle $\theta_{Ch}$ vs. particle momentum in RICH detector

**Figure 4.** Squared four-momentum transfer

**Figure 5.** Total energy of $p_f\pi^+\pi^-p_s$ system. (Filled) With cut on azimuthal correlation. Selected range indicated by vertical lines.
3. Diffractive dissociation of protons into $p_f \pi^+\pi^-$ final states

In Figure 6, the invariant mass distribution of the $p_f \pi^+\pi^-$ system is shown. This excited proton spectrum is foreseen to be studied in detail by the means of partial-wave analysis. Few distinct structures can be observed at positions where there are several known $N^*$ and $\Delta$ resonances with $N\pi\pi$ decay modes. Due to many ambiguities, it is not possible to assign resonances to these structures without a full partial-wave analysis of the data. For higher masses, the multitude of excited baryons creates a smooth curve which has a shoulder around 2.2 GeV/$c^2$.

Essential for the partial-wave analysis will be resonances in the $p\pi^\pm$ and $\pi^+\pi^-$ subsystems which will appear as intermediate states, the so-called isobars. The $\pi^+\pi^-$ invariant mass distribution in Figure 9 shows clear signatures of $\rho^0(770)$, $f_0(980)$ and $f_2(1270)$. A similar set of resonances was observed in the diffractive dissociation of pions into $\pi^-\pi^+\pi^-$ [4].

In Figures 10, 11 and 12, the three-body invariant mass is illustrated versus the invariant masses of the three possible sub-systems. Many of the features described above become even more apparent here.
4. Diffractive dissociation of protons into $p_fK^+K^-$ final states

A different aspect of the baryon spectrum becomes accessible when the pions are replaced by kaons in the event selection described above. However, the number of events is considerably lower and therefore the unambiguous identification of resonances is more difficult.

While no special features can be seen in the three-particle invariant mass spectrum (cf. Figure 13), the subsystems do show interesting structures. Most prominent is the very narrow $\phi(1020)$ peak that appears as expected in the $K^+K^-$ invariant mass as shown in Figure 14. In
addition the invariant mass distribution exhibits structures at masses of known resonances like the \(a_2(1320), f_0(1500),\) and the \(f'_2(1525).\)

A sharp baryon resonance, the \(\Lambda(1520) D_{03}\), can be found in the invariant mass spectrum of the \(p K^-\) combination (cf. Figure 15). Higher baryon excitations with strangeness are visible for example around 1.7 and 1.8 GeV/c, although less pronounced. As expected, the \(p K^+\) spectrum (cf. Figure 16) does not show any significant structures. The distributions for the subsystems can be studied in more detail dependent on the three-body invariant mass (cf. Figures 17, 18 and 19).

5. Partial-Wave Analysis

The selected data set will be the starting point for a dedicated partial-wave analysis. The incoming beam proton scattering off the target is excited into an intermediate state \(X\), with quantum numbers which can differ from those of the initial state. This reaction can be assumed to proceed via \(t\)-channel Reggeon exchange, thus justifying the factorisation of the total cross section into a resonance and a recoil vertex without final state interaction. Considering only subsequent two-body decays of \(X\) (i.e. isobar model) \[4\], three different decay topologies into the same final state \(p_f K^+ K^-\) are possible which are shown in Figure 20.

Taking the observed invariant mass spectra into account (cf. Section 4), possible isobar candidates are

- \(R_{\pi\pi} : (\pi\pi)_S, \rho^0(770), f_0(980), f_2(1270), \ldots\)
- \(R_{\pi\pi^-} : \Delta^0(1232) P_{33}, N(1440)P_{11}, N(1650)S_{11}, \Delta(1700) D_{33}, \ldots\)
- \(R_{\pi\pi^+} : \Delta^{++}(1232) P_{33}, \ldots\)

5
The intermediate resonance $X$ is characterised by the quantum numbers $IJ^P_M$ where $I$ stands for the isospin of the particle, $J$ represents its spin, $P$ its parity and $M$ its spin projection on the $z$-axis. The Isobars $R_1$ have spin $S$ and a relative orbital angular momentum $L$ with respect to the bachelor particle $R_2$. The decay is therefore fully characterised by

$$IJ^P_M R_1 \begin{bmatrix} L \\ S \end{bmatrix} R_2$$  

(1)

The standard PDG nomenclature for baryons in $\pi N$ systems $L_{2I,2J}$ is used to unambiguously identify the baryonic isobars $R_{p\pi}$ for the notation specified in Equation (1). The partial-wave analysis will be carried out by a program developed at Brookhaven [5] and adapted for COMPASS [6]. $D$-functions and the canonical basis will be used to evaluate the decay amplitudes. Furthermore, parity conservation will be taken into account by using the so-called reflectivity basis [7] thereby significantly reducing the number of fit parameters.

6. Conclusions
In the years 2008 and 2009, the COMPASS experiment collected a unique data set with a proton beam impinging on a liquid hydrogen target. The interest in these data apart from the main goal, the search for glueballs produced at central rapidities, is motivated. As the diffractive dissociation of the beam proton plays a dominant role, the high resolution spectrometer combined with the clean trigger provides an excellent opportunity to explore the baryon spectrum. Thorough event selection studies led to a clean exclusive data sample where structures at positions of known resonances become already apparent in the invariant mass distributions. Partial-wave analysis techniques, similar to those that have been successfully used to study meson spectroscopy at COMPASS [8], will be employed to disentangle these data and to pinpoint parameters of the baryon spectrum. The inclusion of all data recorded in 2009 will further extend the data set approximately by a factor of 10 so that COMPASS has great potential to contribute to light-quark baryon spectroscopy.

Acknowledgements
This work is supported by the German Bundesministerium für Bildung und Forschung, the Maier-Leibnitz-Labor der LMU und TU München, and the DFG Cluster of Excellence Origin and Structure of the Universe. The participation at the International Nuclear Physics Conference 2010 was supported by the student travel grant.

References
[1] COMPASS Collab. (P. Abbon et al.) The COMPASS Experiment at CERN Nucl. Instr. Meth. A577, 455 (2007)
[2] U. Amaldi, M. Jacob and G. Matthiae Diffraction of Hadronic Waves Ann. Rev. Nucl. Part. Sci. 26, 385 (1976)
[3] E. Klempt and J.-M. Richard Baryon Spectroscopy Rev. Mod. Phys. 82, 1095 (2010)
[4] COMPASS Collab. (M. G. Alexeev et al.) Observation of a $J^{PC} = 1^{-+}$ exotic resonance in diffractive dissociation of 190 GeV/c $\pi^-$ into $\pi^- \pi^- \pi^+$ Phys. Rev. Lett. 104, 241803 (2010)
[5] J. P. Cummings and D. P. Weygand, An Object-Oriented Approach to Partial Wave Analysis arXiv:physics/0309052v1
[6] S. Neubert et al., http://sourceforge.net/projects/rootpwa
[7] S. U. Chung and T. L. Trueman, Positivity conditions on the spin density matrix: A simple parametrization Phys. Rev. D11, 633 (1975)
[8] F. Nerling Meson spectroscopy at COMPASS these proceedings