Why and how to search for charm pentaquarks with HERA II data

Uri Karshon
Weizmann Institute of Science
Rehovot, Israel

Future Physics with HERA Data - 11-13 November 2014

Some experiments, mainly fixed target at low energy, observed $\approx$ 10 years ago a narrow exotic baryon state

$\Theta^+(1530) \to K^+ n$ **or** $K^0 p$ **with S=+1**

$\Rightarrow$ **Strange pentaquark candidate ($uudd\bar{s}$)**

as predicted by Diakonov et al. based on SU(3) Skyrme model.

Many high energy experiments, mainly colliding beams, did not see a Θ^+ signal.

The ZEUS experiment saw a $\Theta^+ \to K^0 p$ signal with the HERA I data (1995 - 2000). H1 did not see it and published upper limits for its production. With HERA II data (2003 - 2007), ZEUS did not see such a signal.

After the Θ^+ "discovery", charm pentaquarks were also searched for. H1 looked for the charm pentaquark $\Theta_c^0 = uudd\bar{c}$ in $M(D^* p)(+c.c.)$ and found such a candidate at 3.1 GeV.

ZEUS did not confirm this state and gave upper limits for its production which were not compatible with the H1 Θ_c signal.

With HERA II data, H1 did not see such a signal.

Other experiments did not see it as well in $D^* p$ and Dp.

A recent summary: "Present status on experimental search for pentaquarks" (hep-ex 1403.4455) concluded that "Since the first observation of the pentaquark-like baryon state θ^+, this field has aroused much interest, but even the existence of the pentaquark is debatable up to now."

If a pentaquark is found and confirmed, it will provide a major testing ground for low-energy QCD dynamics.

Theoretical grounds for heavy and light pentaquarks are quite different.

Some theorists claimed that the original prediction of Diakonov et al. is not valid (T.D.Cohen, PLB 581,175,2004) or wrong (R.Jaffe, Conference talks, 2005).

Many theorists think that heavy pentaquarks are more likely to exist than strange ones. In particular, recent observations of exotic X,Y,Z states, some of which are claimed to be tetraquarks, show that "heavy flavours may play an important role for stabilizing the hadronic structures beyond the traditional $q\bar{q}$ and qqq composites." (Li and Liu, hep-ph 1409.3332).

Li and Liu suggest that "the pentaquark $b\bar{c}qqq$ would have very distinctive quantum number from the regular three-quark baryons" and suggest to search for such baryons at LHCb.

For the HERA II data, both H1 and ZEUS had a MicroVertex Detector (MVD) enabling to reconstruct secondary vertices from weakly decaying particles.

Most theories predict a **stable heavy charm pentaquark** with $M < 2.8$ **GeV**, i.e. **below the DN threshold**:

- Studied by various authors in quark models with flavour spin interaction and Skyrme models (1993-1998)
- Attracted renewed interest after pentaquark "discovery" of 10 years ago (PLB 590, 185, 2004; PLB 595, 293, 2004)
- Such states appear naturally in a coupled channel approach, and in combined large N_c and heavy quark QCD limit (PRD 71, 036004, 2005; PRD 72, 074010, 2005)
- In a constituent quark model with diquark configuration, attraction is more effective for a heavy pentaquark (hep-ph/0507105; AIP Conf. Proc. 775, 32, 2005; PLB 604, 175, 2004)
- Similar results obtained in a Skyrme model (Z.Phys.A 359, 83, 1997) and in QCD sum rule calculations (hep-ph/0510304)

Negative experimental result for $\Theta_c^0 \to D^*N, DN$ could be due to stability of charm pentaquark.

$\Rightarrow$ **Should be searched for in weak decays.**

In addition to a Θ_c^0 pentaquark candidate, C.Gignoux et al. (PLB 193,323,1987) and H.J.Lipkin (PLB 195,484,1987), motivated by a quark model with colour-spin hyperfine interaction, suggested also the existence of a charm-strange pentaquark.
They predicted a doublet of states:

$P_{\bar{c}s}^0 = \bar{c}suud$, $P_{\bar{c}s}^- = \bar{c}sddu$ **at a mass around** ≈ 2.9 **GeV**

If this kind of pentaquark exists above the threshold for a strong decay, one should search for such decays, e.g.:

$P_{\bar{c}s}^0 \to D_s p$; $P_{\bar{c}s}^- \to \Lambda D^-$

If a charm pentaquark Θ_c^0 exists with a mass below the threshold for a strong decay (i.e. below $M(D) + M(p) \approx 2.8$ GeV), it will decay weakly, e.g.:

$\Theta_c^0 \to K_s^0 \pi^- p$ **require p, π^- from a secondary MVD vertex**
K_s^0 pointing to this vertex

$\Theta_c^0 \to K^+ \pi^- \pi^- p$ **all 4 particles from secondary MVD vertex**

If a charm-strange pentaquark $P_{\bar{c}s}$ exists below the strong decay threshold, it will decay weakly, e.g.:

$P^0_{\bar{c}s} \to \phi\pi^- p; \phi \to K^+K^-$

$P^0_{\bar{c}s} \to K^{*0}K^- p; K^* \to K^+\pi^-$

$P^0_{\bar{c}s} \to (K\bar{K})^0 p\pi^-$

$P^0_{\bar{c}s} \to \Lambda K^+\pi^-$

$P^-_{\bar{c}s} \to \phi\pi^-\pi^- p; \phi \to K^+K^-$

$P^-_{\bar{c}s} \to K^{*0}K^-\pi^- p; K^* \to K^+\pi^-$

$P^-_{\bar{c}s} \to \Lambda\pi^-\pi^- K^+$

$P^-_{\bar{c}s} \to \Lambda\pi^- K^0$ **(a very clean channel !)**

where all decaying particles come from a secondary MVD vertex

Preliminary analyses on some of the above channels from ZEUS HERA II data were performed by Yuriy Onishchuk (University of Kyiv) and Andrii Verbytskyi (Max-Planck-Institut, Muenchen, Germany). No signal was seen.

Karliner,Lipkin (private communication):
Any detection of $p(\bar{p})$ or $\Lambda(\bar{\Lambda})$ emerging from a MVD secondary vertex (unless coming from a Λ_c) could hint at the existence of an exotic baryon

Interesting suggestion: Tag $c(\bar{c})$-quark and look in same event for $p(\bar{p})$ or $\Lambda(\bar{\Lambda})$ from a secondary vertex associated with the $\bar{c}(c)$
$\Rightarrow$ Clear signature for exotic baryon. For example:

- **Select D^{*+}+dijet direct photon ($x_\gamma > 0.75$) events**
- **Look for p or Λ from a secondary vertex in the "untagged" jet (originated from a $\bar{c}$)**

Conclusions

- **The existence of the strange pentaquark $\Theta^+(1530)$ has not been established**
- **Heavy pentaquarks have a more solid theoretical ground and may exist**
- **Most theories predict heavy pentaquarks stable against strong interaction $\Rightarrow$ Should be searched for in weak decays**
- **Using MVD secondary vertices, one should search for the strong decays of $P_{\bar{c}s}$ to $D_s p$; ΛD^- etc.**
- **Many possible weak decay channels of Θ_c^0 and $P_{\bar{c}s}$ can be searched for with MVD secondary vertices**
- **Any detection of $p(\bar{p})$ or $\Lambda(\bar{\Lambda})$ from MVD secondary vertex (unless from Λ_c) may imply an exotic baryon**

Andrii Verbytskyi - A possible use case for data preservation

Exotic hadron searches can be done in the Data Preservation mode

- **The question of exotic hadrons (Pentaquarks) at HERA has a long and complicated history;**
- **Possible future discovery of exotic hadrons will immediately raise a question about re-analysis of HERA data;**
- **The analysis requires usage of all tracking information stored in "Common Ntuples", considerable track selection and multi-vertexing. As a result, the analysis will be very CPU consuming.**

Example:

- **The reconstruction speed of $P^{-}_{\bar{c}s} \rightarrow \pi^{-} K^{0}_{S}\Lambda$ is 620 events/sec./core for Xeon E5520@2.27GHz; Full processing time for HERA II data is 160 hours.**
- **Conclusion: the analysis is unrealistic without usage of multiple cores.**

Backup: A previous search for $P^0_{\bar{c}s}$

The two weak decays of the $P^0_{\bar{c}s}$ were searched for by the E791 Fermilab experiment (500 GeV π^- beam on nuclear targets)
E.M. Aitala et al., PRL 91,44,1998 PLB 448,303,1999
by requiring the $P^0_{\bar{c}s}$ decay particles to come from a secondary vertex, measured with their silicon microstrip detectors

Assuming a $P^0_{\bar{c}s}$ lifetime of **0.4 ps** and $M(P^0_{\bar{c}s})$ between **2.75 - 2.91 GeV**, they obtain 90% upper limits for the ratio

$\frac{\sigma_{P^0} BR_{P^0 \to \phi\pi p}}{\sigma_{D_s} BR_{D_s \to \phi\pi}}$ between **0.022 - 0.046** and for the ratio

$\frac{\sigma_{P^0} BR_{P^0 \to K^* K p}}{\sigma_{D_s} BR_{D_s \to K^* K}}$ between **0.016 - 0.036**

Statistics is small: $\approx 330\ D_s^{\pm} \to \phi\pi^{\pm}$
$16\ P^0_{\bar{c}s}$ **candidates between**
$2.4 < M(\phi\pi p) < 3.1$ **GeV**

Backup: Anti-deuteron production

Connection between pentaquark and $\bar{d}$ production mechanism?

- **Both are made up of multiquarks**
- **Both are not seen in e^+e^-**
- **In both cases coalescence models were used to explain the production mechanism**

M.Karliner (PENTAQUARK2006): If $\bar{d}/\bar{p}$ ratio same in e^+e^- and in PHP, and assuming H1 PHP value (5×10^{-4}), LEP experiments should have seen hundreds of $\bar{d}$, since they see $\approx 10^6$ $\bar{p}$'s, and no $\bar{d}$'s

M.Karliner (private communication): Observation of $\bar{d}$ in ep DIS is even more interesting (large energy/momentum transfer expected, as in e^+e^-) $\Rightarrow$ More resemblance expected between DIS and e^+e^- vs. PHP and e^+e^-

ZEUS saw for the first time in DIS $\approx 90\bar{d}$ with 1996-2000 data

S.Chekanov et al., Nucl. Phys. B786, 181, 2007.

$\approx$ same $\bar{d}/\bar{p}$ ratio as H1 ratio in PHP