The PANDA Physics Program: 
Strangeness and more
F. Iazzi – INFN Torino & Politecnico di Torino (on behalf of PANDA Coll.)

Summary

- FAIR and PANDA
  - FAIR Complex: Beams, Experiments
  - PANDA @ FAIR: Antiprotons @HESR

- Strangeness Physics @ PANDA:
  - \( S= -2 \) hyperons and hypernuclei
  - \( \Xi^- \) production and interaction with nucleus and nucleon, production technique for Doubly Strange systems and expected rates

- Hadron Spectroscopy: multiquark states, open and hidden charm mesons, charmed baryons, hybrids and glueballs

- Nucleon structure: electric and magnetic proton form factors
FAIR Project
(Facility for Antiproton and Ion Ring)

Facility highlights:

High quality and very intense:

• beams of primary ions
• beams of secondary ions
• beams of high energy antiprotons

Cooperating Countries:

Australia, Austria, China, Finland, France, Germany, Greece, Holland, Hungary, India, Italy, Romania, Poland, Russia, Spain, Sweden, Switzerland, United Kingdom, USA

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Facility for Antiproton and Ion Research

Injectors:
- UNILINAC
- P-LINAC
- SIS18

Synchrotron
- SIS100

Cooler & Storage Rings
- CR
- (RESR)
- NESR

Antiproton Ring
- HESR

- Antiproton Cu target
- Super FRagment-Separator

6/29/2015

Antiproton Ring
- HESR

Existing facilities
New facilities
### FAIR facility: the Experiments

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**CBM:**
- Hot and dense hadronic matter at low energy
- Contribution to full mapping of the QCD phase diagram

**PANDA (@HESR):**
- Double Hypernuclei and Hyperon Physics
- QCD: charmed meson spectroscopy
- Nucleon structure
The antiproton ring: HESR $\rightarrow$ PANDA

**H E S R**

Racetrack-shaped ring: 574 m length

Phase space cooling:
- Electron cooling: up to 9 GeV
- Stochastic cooling: full energy range

Momentum resolution: $\Delta p/p \leq 4 \cdot 10^{-5}$

**Momentum range (acceleration/deceleration inside):**
- $1.5 - 15$ [GeV/c] ($0.795 - 14.1$ [GeV])
- Revolution frequency: $\approx 5 \times 10^5$ Hz

**p$_{\text{bar}}$ production rate:** $1 \times 10^7$ /s @ CR (3GeV) $\rightarrow 10^{10}$ stored p$_{\text{bar}}$ @ HESR ($\approx 15'$)

**Luminosity (for target thickness $4 \times 10^{15}$ [H atoms/cm$^2$]):**
- High luminosity mode: $2 \times 10^{32}$ [cm$^{-2}$s$^{-1}$]
- High resolution mode: $1 \times 10^{31}$ [cm$^{-2}$s$^{-1}$]
- Beam lifetime $> 30'$
PANDA Experiment: main user of HESR

Taking profit of:
- **High** antiproton luminosity/intensity
- **Wide** antiproton momentum range
- **High** antiproton momentum resolution

**PANDA PHYSICS PROGRAM**

Strangeness Physics & Neutron Stars

- Meson spectroscopy
  - open charm
  - charmonium
  - exotic states
    - glueballs
    - hybrids
    - molecules/multiquarks
- EM form factors of the proton
- Charm in nuclei
- **Doubly strange systems:**
  - $\Xi^-$ - $\Xi_{\bar{b}}$ production
  - Doubly strange systems:
    - $\Lambda\Lambda$ - Hypernuclei
    - $\Xi^-$ - Hypernuclei
    - $\Xi^-$ - Hyper-atoms
NN, YN, YY strong interactions enter in description of features of NS & Pulsars:

1) Composition of NS is influenced by hyperons potential depths (fixed by data from Hypernuclei & Hyperatoms measurements)

2) Maximum mass of NS is influenced by the presence of hyperons and their interactions

3) Also 3-body forces YNN, YYN, YYY could play a role: needs of data from $\Delta \Delta$ hypernuclei

4) Non mesonic weak decays ($\Lambda N \leftrightarrow NN$, $\Sigma N \leftrightarrow NN$, $\Delta \Delta \leftrightarrow \Delta N$) in the dense medium regulate the stability of r-modes of pulsars and the emission of gravitational waves
Accessible Baryons @ HESR energy range

B-B_{bar} states are produced by antiprotons in:
\[ p_{\bar{p}} + p \rightarrow B + B_{\bar{p}} \]

Hyperons:
- \( \Lambda_s, \Lambda_{s \bar{p}} \)
- \( \Sigma_s, \Sigma_{s \bar{p}} \)
- \( \Xi_s, \Xi_{s \bar{p}} \)
- \( \Omega_s, \Omega_{s \bar{p}} \)

Charmed Baryons:
- \( \Lambda_C, \Lambda_{C \bar{p}} \)
- \( \Sigma_C, \Sigma_{C \bar{p}} \)
- \( \Xi_C, \Xi_{C \bar{p}} \)
- \( \Omega_C, \Omega_{C \bar{p}} \)

Investigation of:
- \( p + p_{\bar{p}} \rightarrow \Xi^- + \Xi^+ \)
- \( p + p_{\bar{p}} \rightarrow \Xi^0 + \Xi^0_{\bar{p}} \)

inserting \( \Xi^- \) inside nuclei (atoms):
creation of Doubly Strange systems
\( p + p_{\text{bar}} \rightarrow \Xi + \Xi_{\text{bar}}: \) cross sections

**p + p_{\text{bar}} \rightarrow \Xi + \Xi_{\text{bar}} & decays**

- **Differential cross sections**
- **Testing (violation of) OZI rule**

\[ \Xi^- + N: \sigma_{\text{el}} \leq 28 \text{mb} \quad (\Xi^- \text{ produced in } (K^- , K^+) \text{, with } p(K^-) = 1.66 \text{GeV/c}) \quad (\text{Ahn06, PLB633}) \]

\[ \Xi^- + \text{nucleus: mean free path in nucleus} \approx 4.7 \text{fm} \quad (p(\Xi^-) = 0.6 \text{GeV/c}) \quad (\text{Aoki98NPA644}) \]

\[ K^- + ^{12}\text{C} \rightarrow K^+ + ^{12}\text{B}_{\Xi}: \quad \frac{d\sigma}{d\Omega}(\theta_k < 8^\circ) \approx 89 \text{[nb/sr]} \quad (\text{Khaustov00, PRC61}) \]

**Scarce data:** only total & (few) scattering cross sections
Investigation of these systems gives important information for the NS physics

Strangeness Physics @PANDA: $S=-2$ Systems

3 different systems contain double strangeness ($S = -2$)

**Exotic Hyperatom:**
a $\Xi^-$ hyperon is captured in an atomic orbit

**Doubly Strange Hypernucleus:**
a $\Xi^-$ hyperon is captured inside a nucleus

($\Xi^-$ hypernucleus)

**Double Hypernucleus:**
a nucleus is made by nucleons and 2 $\Lambda$'s
($\Lambda\Lambda$ hypernucleus)
What can be known from $\Xi^-$ hyper-atom?

Hadronic atom, sensitive to E.M. + strong forces

**Formation of $\Xi^-$ atom**

- $\Xi^-$ captured in a high atomic level ($\approx n_0 \sqrt{m_\Xi/m_e}$)
- Atomic cascade $\rightarrow$ X rays emission $\rightarrow$ precise mass measurements
- In a low level $n_{\text{abs}}$:
  - atomic orbit overlaps periphery of nucleus,
  - nuclear interaction shifts and broadens the level,
  - due to broadening, $\Xi^-$ is absorbed into the nucleus

Only shift and width of the last level ($n_{\text{abs}}$) of the cascade can be measured $\rightarrow$ parameters for (optical) Potential

In NS: hyperon population is sensitive to potential depth fixed also by hyperonic atom data

$\Xi^-$ and $\Omega^-$ are completely missing due to difficult production

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What can be known from $\Xi^-$ hyper-nucleus?

Physics with $\Xi^-$ Hypernuclei:

- Nuclear structure: spectroscopy $\rightarrow$ nuclear potential

- $\Xi$-N strong interaction:
  - short range: 2s-quarks come into play; long range: bosons exchange

  What in neutron stars ($\Lambda$-rich matter)? does “Pauli blocking” suppress strong interaction $\Xi N \rightarrow \Lambda\Lambda$?

- In medium effects: change of $\gamma$-mass effects on magnetic moment ...

- $\Xi$-N weak interaction: Non Mesonic Weak Decay
  
  - $\Xi p \rightarrow \Lambda n$ ($E_{\Lambda}=95$ [MeV], $p_{\Lambda,N}=469$)
  
  - $\Xi N \rightarrow \Sigma N$ ($E_{\Sigma}=55$ [MeV], $p_{\Sigma,N}=366$)

  (In nuclei: expected suppressed by strong interaction, $\Gamma_{\Lambda N} \approx 0$, $\Gamma_{\Sigma N} \approx 0$)

Also $\Xi$-N non mesonic decay does play a role in restoration of local $\beta$-equilibrium?

Very scarce data
Each point is single observation, no statistics
What can be known from $\Lambda\Lambda$ hyper-nuclei?

**Physics with $\Lambda\Lambda$ Hypernuclei:**

- $\Lambda\Lambda$ **strong interaction (only possible in double hypernuclei):**
  - YY potential: attractive/repulsive?
  - short range: interaction of 2 s-quarks
  - long range: bosons exchange ($\Lambda\Lambda \to \Lambda\Lambda$: only non strange, $I=0$ mesons ($\omega, \eta...$) are exchanged)
  - hyper-fragments distribution: dependence on YY potential and on $\Xi$ nuclear level
  - strong decay: $\Lambda\Lambda \to H$ particle? ($H = uuddss$, strongly bound): seems ruled out, but $B-B$ molecule?

- **Weak interaction: several channels, mesonic and non mesonic**
  - NON mesonic: restoration of local $\beta$-equilibrium

- $\Lambda\Lambda$ **weak interaction (only possible in double hypernuclei):**
  - Hyperon Induced Non Mesonic Weak Decay
    - $\Lambda\Lambda \to \Lambda n$: (expected $\Gamma_{\Lambda n} \ll \Gamma_{\text{free}}$) ($p_{\Lambda/n} = 433$ MeV/c)
    - $\Lambda\Lambda \to \Sigma^- p$: (expected $\Gamma_{\Sigma p} \ll \Gamma_{\text{free}}$) ($p_{\Sigma/p} = 321$ MeV/c)

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**Strong interaction:**

- very few data

**Weak interaction:**

- lot of channels but no data

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Production of $S = -2$ Systems using Antiprotons

$$\sigma(\bar{p} + A \rightarrow \Xi^- + \Xi) \approx 2 \cdot A^{\frac{2}{3}} [\mu b]$$

Kaon production from $\Xi_{\text{bar}}$ annihilation

$$\Xi_{\text{bar}} + N \rightarrow K_{\text{bar}} + K_{\text{bar}} + \pi + \ldots \text{ [tagging } \Xi \text{ production } \rightarrow \text{ trigger]}$$

Elastic scattering in nucleus: strong slowing down
Production of $S = -2$ Systems using Antiprotons

\[ \sigma(\bar{p} + A \rightarrow \Xi^- + \Xi) \approx 2 \cdot A^{2/3}[\mu b] \]

Kaon production from $\Xi_{\text{bar}}$ annihilation

X-ray emission

$\Xi_{\text{bar}} + N \rightarrow K_{\text{bar}} + K_{\text{bar}} + \pi + \ldots$ [tagging $\Xi$ production $\rightarrow$ trigger]

Elastic scattering in nucleus: strong slowing down

Capture into nucleus: Strong and Coulomb forces

slowing down in matter (with decay)

$\Xi$ capture into atomic levels and hyperatomic cascade

$p$
Production of $S = -2$ Systems using Antiprotons

$$\sigma(\bar{p} + A \rightarrow \Xi^- + \Xi) \approx 2 \cdot A^{\frac{2}{3}} [\mu b]$$

Kaon production from $\Xi_{bar}$ annihilation

X-ray emission

$\gamma$ – emission from absorption

$\gamma$ – emission from conversion

$\pi$ – emission from $\Lambda$ decay

Elastic scattering in nucleus: strong slowing down

$\Xi_{bar} + N \rightarrow K_{bar} + K_{bar} + \pi + \cdots$ [tagging $\Xi$ production $\rightarrow$ trigger]

Capture into nucleus: Strong and Coulomb forces

$\Xi$ capture into atomic levels and hyperatomic cascade

$\gamma$ (28 MeV)

$\Xi^- p \rightarrow \Lambda \Lambda$ conversion + $\Lambda \Lambda$ sticking

$\Lambda + \Lambda$ decay (MWD,NMWD... )

$\Phi_{28}$

Capture into nucleus:

Strong and Coulomb forces

$\Xi$ capture into atomic levels and hyperatomic cascade

$\gamma$ – emission from absorption

$\gamma$ – emission from conversion

$\pi$ – emission from $\Lambda$ decay
Two-target Technique @ PANDA

- Optimization of $\Xi^-$ rate
- Optimization of the $\Xi^-$ slowing down
- Independently changing the hypernuclear target by:
  - designing primary target: inside beam pipe
  - using full antiproton rate
designing secondary target to approach the ratio: $\Xi^-$stop/ $\Xi^-$prod $\approx 2 \times 10^{-3}$ (from simulations)

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Detection of:

- $\pi^\pm$, $K^\pm$
- $\gamma$, X-rays,
- $p$, fragments (?)
Work in progress

Set-up:
• Design of targets and HPGe $\gamma$-detectors
• Construction of prototypes
• Tests of their performances:
  • HPGe in Fringing Magnetic field,
  • Performances of the internal and external targets

Software:
• Set-up and event simulation
• Event Reconstruction
Work in progress: HPGe design, prototype and test

1) Tests of single Ge crystal performances in fringing magnetic field:
   a) Resolution worsens by ≈10% (acceptable)
   b) Efficiency: unaltered
   c) Performances after long time work (1 year): constant

2) Activities toward a prototype of HPGe Cluster Array:
   a) MC study of the cluster geometry for:
      i. Tests on radiation damage
      ii. Tests on pile-up
      iii. Analysis of the pulse shape

3) Cooling system:
   a) Electrochemical cooler under study, to save space

Courtesy of A. Sanchez, M. Steiner & I. Kojouharov
Work in progress: Secondary Active Target

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Design of Active Target (MC)

3 side sectors, made of:
- Alternate layers absorber-μstrip
- 3 absorbers: $^9$Be, $^{10,11}$B, $^{12,13}$C

Courtesy of A.Sanchez&S.Bleser& SERSTII

Under test:
- Read-out space
- Minimization of material budget
Work in progress: Internal Target & Shifter

1) 4 Prototypes of internal target realized (diamond disk in Si ring, sizes: 13mm x 100μm x 3μm)

2) Tests under proton beam (BackScattering):
   a) Homogeneity and purity: 99.9%

3) Tests by μ-Raman Spectroscopy:
   a) phase modification (D-phase to G-phase) only on wire border
   b) ... ensuring good mechanical resistance
   c) ... good thermal and electric conductivity

4) Still to do:
   a) Cutting disk into C-shape, for beam steering (problems of brittleness, due to asymmetry

5) Storage of spare targets: shifter under study
   a) problems of: Vacuum leakage & Lubricant sublimation (piezo-motor?)
Reconstruction mainly consists of:

(Courtesy of A. Sanchez)

- Track finding & Tracking: (Kalman & GEANE)
- PID: Energy loss in: Si μ-strips (pions, protons, light fragments) in STT & SciTil, (Kbar’s for trigger)

Expected results:
- Beam steering \( \rightarrow \approx 100 \Xi^- / s \)
- \( \rightarrow \approx 10^{-2} \Lambda \Lambda / s \) (\( \approx 2.5 \times 10^4 / \text{month} \))
- Efficiency/channel \( \approx 10^{-3} / \text{ch} \)
- \( \rightarrow 50-100 \Lambda \Lambda \) hypernuclei/ch (detected in 4 months)

Using detectors:
- Si μ-strips in secondary target: tracking (+ energy loss for PID?)
- TOF system: time of track (improvements under study)
- STT: Energy loss \( \rightarrow \) PID (K’s)
- HPGe’s: γ’s, X-rays
Meson Spectroscopy@ HESR (1)

Charmed Final States @ HESR : Open Charm

\[ p + pbar \rightarrow \text{Charmed Mesons} \]

- D (1869) + Dbar
- D*(2010) + D*bar
- D*(2400) + D*bar
- D*(2420) + D*bar
- D*(2460) + D*bar

\[ p + pbar \rightarrow \text{Charmed Strange Mesons} \]

- \( Ds(1968) + Ds\text{bar} \)
- \( Ds*(2112) + Ds*\text{bar} \)
- \( Ds0*(2317) + Ds0*\text{bar} \)
- \( Ds1(2460) + Ds1*\text{bar} \)
- \( Ds2*(2573) + Ds2*\text{bar} \)
Meson Spectroscopy @ HESR (2)

Charmed Final States @ HESR: Charmonium

Final State mass [GeV]

p + pbar \rightarrow c + cbar

\begin{align*}
\eta_c(1S) &\quad \psi(3770) \\
J/\psi (1S) &\quad X(3872) \\
\chi_{c0} (1P) &\quad \chi_{c2} (3929) \\
\chi_{c1} (1P) &\quad Y(3940) \\
h_{c} (1P) &\quad \psi(4040) \\
\chi_{c2} (1P) &\quad \psi(4160) \\
\eta_c(2S) &\quad Y(4260) \\
\psi(2S) &\quad \psi(4415)
\end{align*}

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Meson Spectroscopy @ HESR (3)

Final States @ HESR: Gluonic Excitations

- **Hybrids:**
  - $dd_{\bar{g}}$; $uu_{\bar{g}}$, $ss_{\bar{g}}$
  - $cc_{\bar{g}}$

- **Glueballs:**
  - $gg$; $ggg$

- **Molecules:**
  - $qq_{\bar{q} \bar{q}}$
  - $qq_{\bar{q} \bar{q}}$
  - $cc_{\bar{q} \bar{q}}$

$p + p_{\bar{p}}$
EM proton TL-Form Factor in the PANDA range

EM F. F. in time-like region studied in:

- $\text{e}^+\text{e}^- \rightarrow p_{\text{bar}}+p$
- $p_{\text{bar}}+p \rightarrow \text{e}^+\text{e}^- \ (\text{PANDA})$
- Proton time-like F.F. measured by several experiments at low $q^2$
- but due to low statistics measured only $|G_E|$ and $|G_M|$ under assumption $|G_E| = |G_M|$

@PANDA: $q^2_{\text{Max}} \approx 29 \text{ GeV}^2$

High luminosity ($10^{32}$) $\rightarrow$ high statistics
Conclusions

The physics of doubly strange systems is a field with interesting aspects, also concerning some features of Neutron Star description:

• strong interaction (Ξ-nucleus, Ξ-N and ΛΛ)
• weak interaction (mesonic and non-mesonic decay)

but widely unexplored:

• few units of ΛΛ and Ξ hypernuclei and no Ξ hyper-atoms

PANDA: special set-up dedicated to: Ξ-hyper-atoms, Ξ-hyper-nuclei, ΛΛ hyper-nuclei

Highlights of PANDA:

• Hyperon production by antiprotons @ 3 GeV/c
• Intense antiproton beam together with the “steering technique”
• Double target system (flexible choice of hyper-nuclear targets)
• High resolution γ detection in coincidence with π detection

Expected results:

• High statistics in single channels for different hyper-nuclei
PANDA compared with other facilities

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Strangeness in NS: onset dependence on potential

Hyperon population is highly sensitive to the in-medium potential

Particle fraction vs baryon density:
- a) only interacting hyperons
- b) Interacting hyperons & Δ

Schaffner-Bielich
NPA2010

Drago&al
PRC90
The investigation of the baryon-baryon interactions is crucial for a deeper understanding of nuclei, structure of neutron matter and astrophysics aspects, etc...

Chiral effective field theories have tried since long time to describe baryon-baryon interaction and recently also lattice QCD calculations allowed to approach nuclear physics in terms of fundamental theory of the strong interaction.

The experimental investigation of the nature of baryon bound states has gone in parallel with meson spectroscopy, nevertheless there are still many open problems and there is lack of high quality data.
The experimental data set available is far from being complete. All strange hyperons and single charmed hyperons are energetically accessible in pp collisions at PANDA.

In PANDA $pp \rightarrow \Lambda \Lambda$, $\Xi \Xi$, $\Sigma \Sigma$, $\Omega \Omega$, $\Lambda_c \Lambda_c$, $\Sigma_c \Sigma_c$, $\Omega_c \Omega_c$ can be produced allowing the study of the dependences on spin observables.

By comparing several reactions involving different quark flavors the OZI rule and its possible violation, can be tested.
Baryon spectroscopy @ PANDA startup version

Assumptions:
- 10x lower luminosity
- PANDARoot with idealised tracking

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<th>$\Lambda$ $\Lambda_{\text{bar}}$</th>
<th>$\Xi$ $\Xi_{\text{bar}}$</th>
<th>$\Omega$ $\Omega_{\text{bar}}$</th>
<th>$\bar{\Lambda}_c^+ \Lambda_c^-$</th>
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<tr>
<td>1.64 GeV/c</td>
<td>$2 \times 10^5$ h$^{-1}$</td>
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<td>$\Lambda_c \Lambda_c^{(\text{bar})}$</td>
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<tr>
<td>4 GeV/c</td>
<td>$4 \times 10^4$ h$^{-1}$</td>
<td>2500 h$^{-1}$</td>
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<tr>
<td>15 GeV/c</td>
<td>$2 \times 10^4$ h$^{-1}$</td>
<td>(≈ 1000 h$^{-1}$)</td>
<td>(30 h$^{-1}$)</td>
<td>((5 day$^{-1}$))</td>
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1. Single strangeness production: $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$\hspace{1cm} OK
2. Double strangeness production: $\bar{p}p \rightarrow \Xi\Xi$\hspace{1cm} OK
3. Triple strangeness production: $\bar{p}p \rightarrow \Omega^+\Omega^-$\hspace{1cm} Probably OK
4. Charm production: $\bar{p}p \rightarrow \bar{\Lambda}_c^+ \Lambda_c^-$\hspace{1cm} Questionable

Courtesy of: P. Gianotti – INFN LNF
Physics with \( \Lambda\Lambda \) hypernuclei: status of art (II)

\( \Lambda\Lambda \) hypernuclei Weak decay: a lot of final states, new B.R.

**MESONIC WEAK DECAY OF 1 \( \Lambda \)**

\[ \Lambda\Lambda Z^A \rightarrow \begin{cases} \Lambda Z^A + \pi^0 \\ \Lambda (Z+1)^A + \pi^- \end{cases} \]

\[
\Gamma_{\pi^0}^{(\Lambda)} \\
\Gamma_{\pi^-}^{(\Lambda)}
\]

\[ 86.7 \leq p_{\pi^0} \leq 103.9 \]

\[ 88.4 \leq p_{\pi^-} \leq 100.6 \]

**NUCLEON INDUCED NON-MESONIC WEAK DECAY OF 1 \( \Lambda \)**

\[ \Lambda\Lambda Z^A \rightarrow \begin{cases} \Lambda Z^{A-2} + n + n \\ \Lambda (Z-1)^{A-2} + n + p \end{cases} \]

\[
\Gamma_n^{(\Lambda)} \\
\Gamma_p^{(\Lambda)}
\]

\[ 391.1 \leq p_n \leq 416.7 \]

\[ 391.2 \leq p_p \leq 414.6 \]

**HYPERON INDUCED NON-MESONIC WEAK DECAY OF 1 \( \Lambda \) (HINMWD)**

\[ \Lambda\Lambda Z^A \rightarrow \begin{cases} Z^{A-2} + \Lambda + n \\ Z^{A-2} + \Sigma^- + p \end{cases} \]

\[
\Gamma_{\Lambda n}^{(\Lambda)} \\
\Gamma_{\Sigma p}^{(\Lambda)}
\]

\[ 402.2 \leq p_\Lambda \leq 433.0 \]

\[ 275.8 \leq p_\Sigma \leq 318.9 \]

\( \Gamma_{\Lambda n}^{(\Lambda)} / \Gamma_{\Sigma n}^{(\Lambda)} \approx \frac{1}{2} \)

\( \Gamma_{\pi^0}^{(\Lambda)} / \Gamma_{\pi^-}^{(\Lambda)} \approx \frac{1}{2} \)

momentum range is approximately calculated for \( Z=6,7;A=12; \)

\( B.E.(\Lambda)=11[\text{MeV}]; \)

\( B.E.(N)=8[\text{MeV}], \)

neglecting \( \Delta B_{\Lambda\Lambda} \)

\[ \text{+ fragmentation} \]
\( \Lambda \Lambda \) hyper-nuclei

\( \Lambda \Lambda \) weak interaction
(only possible in double hypernuclei)

Hyperon Induced Non Mesonic Weak Decay

- \( \Lambda \Lambda \rightarrow \Lambda \, n \) : (expected \( \Gamma_{\Lambda n} \ll \Gamma_{\text{free}} \)) \( p_{\Lambda/N} = 433 \text{ MeV/c} \)
- \( \Lambda \Lambda \rightarrow \Sigma^- p \) : (expected \( \Gamma_{\Sigma p} \ll \Gamma_{\text{free}} \)) \( p_{\Sigma/N} = 321 \text{ MeV/c} \)

Calculations in absence of H-dybaryon: \( \Gamma_{\Lambda N} , \Gamma_{\Sigma N} \) small

(TakahashiNP2003, ParrenosPR2002, ItonagaNP2001)

High statistics is needed to confirm
Open Charm: the case $D_{s0}^*(2317)$

@PANDA: $p + p_{\overline{b}} \rightarrow D_{s0}^*(2317) + D_s{\overline{b}}$

(scan around threshold: $p_{th} \approx 8.9$ [GeV/c])

From simulation of the excitation function ($@9.88$ [GeV]):

$\Delta \Gamma (p_{\overline{b}} + p \rightarrow D_{s0}^*(2317) + D_s{\overline{b}}) < 100$ [KeV]

$D_{s0}^*(2317) =$
- 2-meson molecule?
- conventional meson?

- Total & partial width play crucial role to answer above questions

- Precise measurements of $\Gamma$ are required ($LQCD$ calculations have poor precision; e.g., in:

$D_{s0}^*(2317) \rightarrow D_s + \pi$,

$6 < \Gamma < 140$ [KeV])
Charmonium: the case $X(3872)$

$X(3872) =$
- conventional charmonium?
- diquark-antidiquark?
- tetraquark?
- molecular state?

Features:
- $\Gamma = 1.2 \text{ [MeV]}$ (th); < 1.2 (ex)
- $2 < \sigma_X(\Gamma_T) < 443 \text{[nb]}$ (th)
- $\sigma_X$ strongly depends on $\Gamma_T$
- $M \approx M(D^0D^{0*})$ (@threshold)
- $J^P = 1^{+\pm}$

Precise measurements of $\Gamma$ are required

From simulations:
$p + \text{pbar} \rightarrow X(3872) \rightarrow J/\psi + \pi^+ + \pi^-$
$\Gamma (MC) = 100 \rightarrow \Gamma (Rec) = 87 \pm 17 \text{[KeV]}$
Periodic interference structures in time like proton form factors

Andrea Bianconi and Egle Tomasi-Gustafsson
To appear in Physical Review Letters

Proton Charge and Magnetic distribution

Space-like FFs are real

\[ q^2 < 0 \]

\[ e+p \rightarrow e+p \]

Time-Like FFs are complex

\[ q^2 > 0 \]

\[ p+\bar{p} \leftrightarrow e^++e^- \]

Asymptotics
- QCD
- analyticity

Geometric distribution

Proton Charge and Magnetic distribution

Periodic interference structures
The cross section for $p + p \rightarrow e^+ + e^-$ (1 $\gamma$-exchange):

$$\frac{d\sigma}{d(\cos \theta)} = \frac{\pi \alpha^2}{8m^2 \sqrt{r - 1}} \left[ \tau |G_M|^2 (1 + \cos^2 \theta) + |G_E|^2 \sin^2 \theta \right]$$

$\theta$: angle between $e^-$ and $\bar{p}$ in cms.

The Time-like region

Expected QCD scaling $(q^2)^2$

- The Experimental Status
  - No individual determination of GE and GM
  - TL proton FFs twice larger than in SL at the same $Q^2$
  - Steep behaviour at threshold
  - Babar: Structures? Resonances?

S. Pacetti, R. Baldini-Ferroli, E. Tomasi-Gustafsson, Physics Reports, 514 (2014) 1

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