
Супер чарм-тау фабрика 中国超级陶粲装置

# cornucopia of antineutrons and hyperons from super $J/\psi$ factory for next-generation nuclear and particle physics high-precision experiments

Marek Karliner
Tel Aviv University

Joint work with Changzheng Yuan
IHEP, Beijing

IFJ/Zoom, June 1, 2021

PRL, in press
and
arXiv:2103.06658

**róg obfitości antyneutronów i hyperonów**
**z super-fabryki $J/\psi$**
**dla nastepnego pokolenia precyzyjnych eksperymentów**
**w dziedzinie fizyki jądrowej i cząstek elementarnych**

# executive summary

- $N$-$N$ and $N$-$\bar{N}$ forces fundamental to visible universe
- $p$–$p$, $p$-$n$, $n$-$n$, $p$-$\bar{p}$, $n$-$\bar{p}$ well studied,
  but scarce data on $p$-$\bar{n}$ and $n$-$\bar{n}$
- new high-quality source of $\bar{n}$: $e^+e^- \to J/\psi \to \bar{n}p\pi^-$
  with $J/\psi$ at rest
- $p$, $\pi^-$ tagged $\Longrightarrow$ $\bar{n}$ momentum determined precisely
  on event-by-event basis
- BR$(J/\psi \to \bar{n}p\pi^-) = (2.12 \pm 0.09) \times 10^{-3}$
  BESIII : $10^{10}$ J/$\psi$-s $\Longrightarrow$ 20 million $\bar{n}$; under study now
  super charm factory: $10^{12}$ $J/\psi$-s $\Longrightarrow$ 2 billion $\bar{n}$
  select $\bar{n}$ with specific $\vec{p}$ $\Longrightarrow$ high-quality tunable virtual $\bar{n}$ beam
- use variety of custom removable targets; in BESIII: beam pipe
- similarly: all (anti)hyperons – $\Lambda$,$\Sigma$,$\Xi$,$\Omega^-$, strangeness-tagged $K^0$, $\bar{K}^0$
- $N\bar{N}$ annihilation, $s\bar{s}$ in $N$, ~~OZI~~, (multi-strange) hypernuclei, exotics. . .

Scattering experiments using many different kinds of beams are the mainstay of experiments investigating fundamental interactions and structure of matter at subatomic level.

Beams of long-lived charged particles and of photons are easy to produce and so many experiments using charged projectiles have been carried out during more than 100 years since the trailblazing experiment shooting $\alpha$ particles into gold foil enabled Rutherford to infer the existence of the atomic nucleus.

Since then, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, proton, antiproton, photon and various heavy ion beams have been produced and have served as enablers of many scientific breakthroughs.

Beams of some neutral particles, like neutrons and neutrinos are relatively easy to produce, but difficult to control, i.e. have large momentum spread.

Beams of other neutral particles, such as antineutron and $K^0/\bar{K}^0$, and of long-lived hyperons ($\Lambda$, $\Sigma^{+,-}$, $\Xi^{0,-}$) and their antiparticles ($\bar{\Lambda}$, $\bar{\Sigma}^{-,+}$, $\bar{\Xi}^{0,+}$) have great physics potential, but typically are much more difficult to produce and control.

Although potentially extremely useful for investigating nonperturbative QCD and nuclear structure, experimental studies using antineutron beams have been very limited till now, due to the severe difficulties in accumulating sufficient number of antineutrons with known flux and momentum.

- previously $\bar{n}$ from $\bar{p}p \to \bar{n}n$:

  BNL E-767, $100 < p_{\bar{n}} < 500$ MeV

  OBELIX, $50 < p_{\bar{n}} < 400$ MeV

  $\bar{n}N$ vs. $\bar{p}N$: $\bar{N}N$ annihhilation w/o Coulomb corrections

  but in $\bar{p}p \to \bar{n}n$: low stats, $p_{\bar{n}}$ hard to control

These experiments enabled quite a wide range of physics topics to be studied, from nuclear physics to hadron spectroscopy, albeit with limited statistics. Scattering of antineutrons on nuclei made it possible to investigate nucleon-antinucleon annihilation inside matter, without complications due to Coulomb interaction.

In these experiments antineutrons were produced in proton-antiproton annihilation via charge exchange (CEX) $p \to n$.

The disadvantages of this method are obvious: production rate is low and antineutron momentum and direction are hard to control. Selection of antineutrons with momentum in a specific direction results in discarding a large fraction of antineutrons. Further higher rate experiments have been proposed, utilizing high-intensity antiproton beams, but within this approach one does not expect a significant improvement in the antineutron accumulation rate.

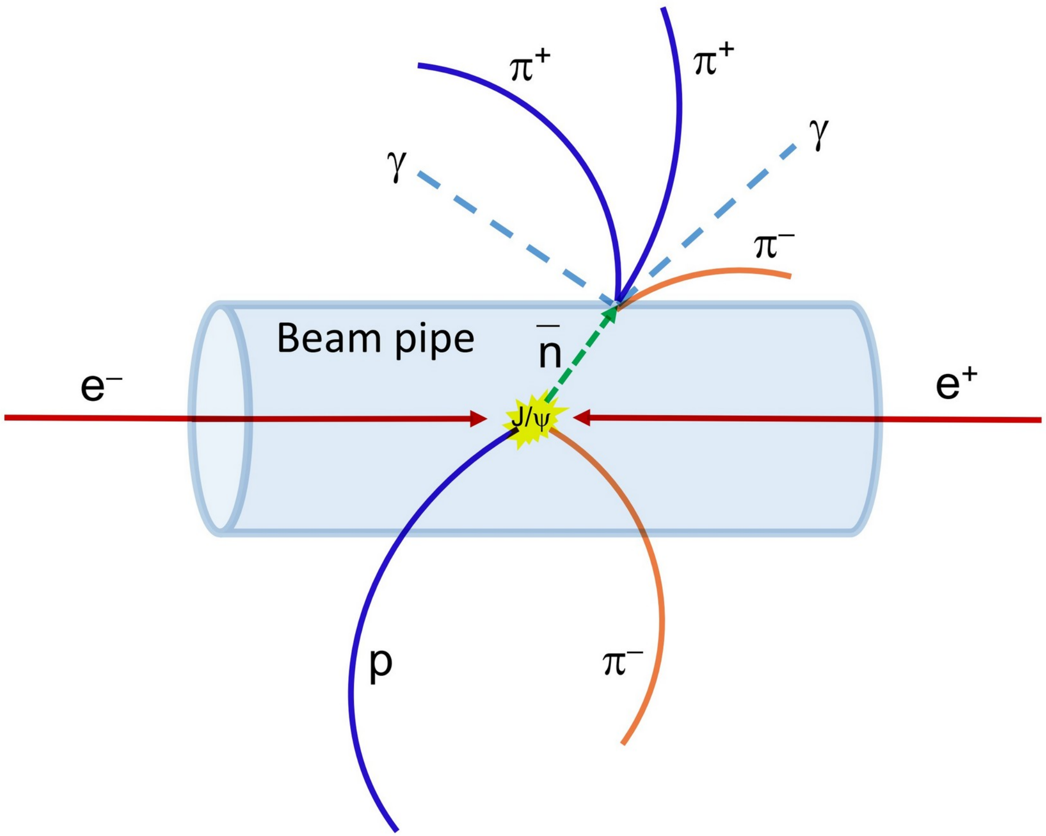
Ground state $SU(3)$ octet hyperons ($\Lambda$, $\Sigma^{+,-}$, $\Xi^{0,-}$) and their antiparticles have relatively long lifetime (typical $c\tau$ of a few cm) and are essential for investigating several important physics questions, including hyperon-nucleon interaction and and the possible role of hyperons in neutron stars.

The relevant experimental studies started in 1960s and have lasted for more than half a century, using $\pi^{\pm}$ or $K^{\pm}$ beams shot into bubble chambers or Scintillating Fiber (SciFi) targets. The statistics of these experiments are low, with typically a few tens to a few hundreds observed events.

with $J/\psi$ factory as a source of antineutrons and hyperons, a wide range of novel high-precision physics measurements can be carried out.

- antinucleon-nucleon interaction
- OZI violation
- nonvalence $s\bar{s}$ component of the nucleon
- (anti)hyperon-nucleon interaction
- (multi-strange) hypernuclei
- light hadron spectroscopy incl. exotics
- x-section of antineutrons with material for calibration of MC simulation codes for particle physics and medical apps, such as FLUKA and GEANT4

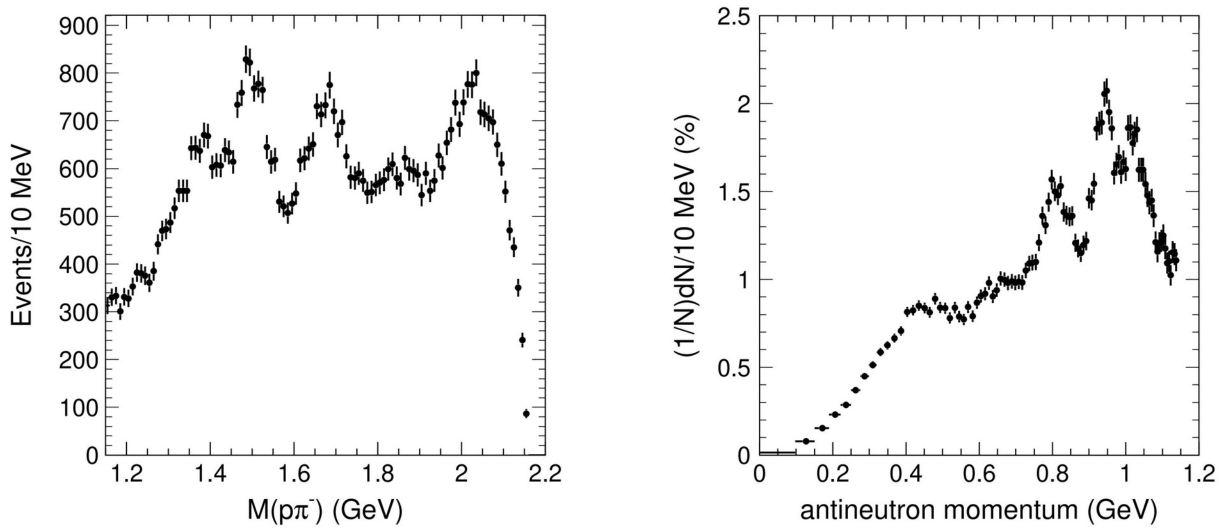
- new source: $J/\psi \to \bar{n} p \pi^-$ in BESIII:




Schematic diagram of $e^+e^- \to J/\psi \to p\pi^-\bar{n}$, followed by $\bar{n}$ interaction with a proton in the beam pipe material, $\bar{n}p \to \pi^+\pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$.

# BESIII:

$0 < p_{\bar{n}} < 1174$ MeV



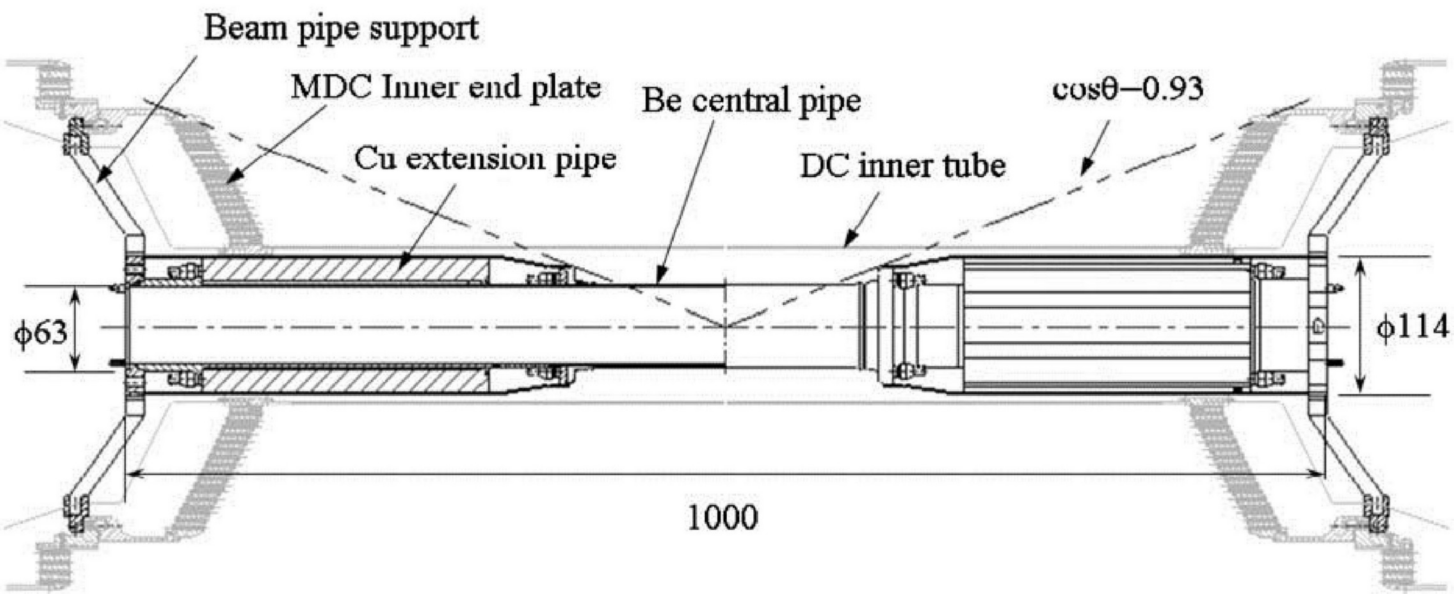

Invariant mass distribution of $p\pi^-$ from $J/\psi \to p\pi^-\bar{n}$ selected from BES experiment (left), and the corresponding antineutron momentum distribution (fraction of events in 10 MeV/$c$) (right). The plots have been remade with data in Ref. [25].

$\Delta|p_{\bar{n}}| <$ few MeV $\quad\quad \Delta(p_{\bar{n}}$ direction$) <$ few mrad

$\sim$40% tagging efficiency $\Longrightarrow$ 8 million tagged $\bar{n}$

under study now in BESIII

BESIII data already taken, but detector material close to the interaction point in the inner detector serves as effective Be and C targets.
+ can put other target material into current detector




Cross sectional view of the BESIII interaction region . The dimensions are in mm.

with $\sigma(\bar{n}p) \approx \sigma(\bar{n}n) \approx 100$ mb
expect 1–2% of tagged $\bar{n}$-s interact with Be & 1-2% with C fiber target

so $\sim$100,000 $\bar{n}$ + Be events and $\sim$100,000 $\bar{n}$ + C events

# Hyperon and antihyperon sources from $J/\psi$ decays

- $\Lambda$, $\Sigma^{+,-}$, $\Xi^{0,-}$ & $\bar{\Lambda}$, $\bar{\Sigma}^{-,+}$, $\bar{\Xi}^{0,+}$
  can be produced copiously in $J/\psi$ decays & tagged like $\bar{n}$
  $c\tau \sim$ few cm $\Longrightarrow$ only some make it to beam pipe/MDC
  but surviving fraction significant

TABLE I: Hyperon and antihyperon production at BESIII. The yield of hyperons is the same as that of antihyperons, since particles and antiparticles are produced with the same rates in $J/\psi$ (or $\psi(2S)$) decays via strong or electromagnetic interactions. $p_{\rm max}$ is the maximum momentum of the antihyperon, $n^Y_{\rm BP}$ is the number of tagged antihyperons reaching the beam pipe; "—" means not available.

| Antihyperon | $c\tau$ (cm) | decay mode | Branching Fraction ($\times 10^{-3}$) | $p_{\rm max}$ (MeV/$c$) | $n^Y_{\rm BP}$ ($\times 10^5$) |
|---|---|---|---|---|---|
| $\bar{\Lambda}$ | 7.89 | $J/\psi \to \Lambda\bar{\Lambda}$ | 1.89 | 1074 | 26 |
| | | $J/\psi \to pK^-\bar{\Lambda}$ | 0.87 | 876 | 9 |
| $\bar{\Sigma}^-$ | 2.40 | $J/\psi \to \Sigma^+\bar{\Sigma}^-$ | 1.50 | 992 | 4 |
| | | $J/\psi \to \Lambda\pi^+\bar{\Sigma}^-$ | 0.83 | 950 | 1 |
| $\bar{\Sigma}^+$ | 4.43 | $J/\psi \to \Lambda\pi^-\bar{\Sigma}^+$ | — | 945 | — |
| $\bar{\Xi}^0$ | 8.71 | $J/\psi \to \Xi^0\bar{\Xi}^0$ | 1.17 | 818 | 7 |
| | | $J/\psi \to \Xi^-\pi^+\bar{\Xi}^0$ | — | 685 | — |
| $\bar{\Xi}^+$ | 4.91 | $J/\psi \to \Xi^-\bar{\Xi}^+$ | 0.97 | 807 | 3 |
| | | $J/\psi \to \Xi^0\pi^-\bar{\Xi}^+$ | — | 686 | — |
| $\bar{\Omega}^+$ | 2.46 | $\psi(2S) \to \Omega^-\bar{\Omega}^+$ | 0.05 | 774 | 0.05 |
| | | $\psi(2S) \to K^-\Xi^0\bar{\Omega}^+$ | — | 606 | — |

## super $J/\psi$ factory: plentiful source of $\bar{n}$ and (anti)hyperons

- design $\mathcal{L} \gtrsim \mathcal{O}(100) \times$ current $\mathcal{L}$ avail. at BESIII
  specific proposals: STCF (Beijing), SCTF (Novosibirsk)
- detectors improvments vs. BESIII: tracking, particle id, $\gamma$ detection
- $10^{12}$ $J/\psi$ events/yr $= 100 \times$ BESIII total dataset
- likely much more, due to accelerator & detector improvements
  BEPCII: $\Delta E_{CM}$ @$J/\psi$ $= 0.9$ MeV, vs. $\Gamma(J/\psi) = 93$ keV
  proposed monochromator scheme: $\Delta E_{CM}$ much smaller
  $\Longrightarrow$ further dramatic increase in peak xsec
- expanded range of physics topics
  via interchangable custom targets inside the detector
- higher momenta of baryons & antibaryons from
  asymmetric $e^+e^-$ beams $\Longrightarrow$ $J/\psi$ in motion & $\psi(2S)$
- subdetector for specific final states, e.g. $d$, triton, heavier nuclei...

## super $J/\psi$ factory: cornucopia of quality beams

- traditional setups:
  need many different kinds of beams
  for different dedicated experiments

- need to share accelerator time among them,
  require large manpower and funding

- in contrast,
  here exps with different beams at same time
  no additional infrastructure
  minimal further investments