Opportunities for Polarized He-3 in RHIC and EIC

September 28-30, 2011

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~100 graduates of which 27 theorists and 14 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are one hundred and four proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSF, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the winter of 2011.

N. P. Samios, Director
October 2011

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Introduction

The workshop on opportunities for polarized He-3 in RHIC and EIC was targeted at finding practical ways of implementing and using polarized He-3 beams. Polarized He-3 beams will provide the unique opportunity for first measurements, i.e. to a full quark flavor separation measuring single spin asymmetries for π^+ , π^- and π^0 in hadron-hadron collisions. In electron ion collisions the combination of data recorded with polarized electron proton/He-3 beams allows to determine the quark flavor separated helicity and transverse momentum distributions.

The workshop had sessions on polarized He-3 sources, the physics of colliding polarized He-3 beams, polarimetry, and beam acceleration in the AGS Booster, AGS, RHIC, and ELIC. The material presented at the workshop will allow making plans for the implementation of polarized He-3 beams in RHIC.

新生命碰撞

Nuclei as heavy as bidders
Through collision
Generate new states of matter

核子重如牛

Workshop on Opportunities for
Polarized He-3 in RHIC and EIC --
sponsored by the RIKEN BNL
Research Center

28-30 September 2011
Universe
US/Eastern time zone

Workshop goals and organization

Wolfram Fischer

28 September 2011

Workshop goals

“We are planning a workshop to explore the opportunities for polarized He-3 in RHIC and EIC. The workshop is targeted at finding practical ways of implementing and using polarized He-3 beams. Polarized He-3 beams will provide the unique opportunity for first measurements, i.e. to a full quark flavor separation measuring single spin asymmetries for p^+ , p^- and p^0 in hadron-hadron collisions. In electron ion collisions the combination of data recorded with polarized electron proton/He-3 beams allows to determine the quark flavor separated helicity and transverse momentum distributions.”

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Can we have colliding ^3He beams in RHIC within 3-4 years?

→ Need a plan with milestones.

Why now?

1. Demand for ^3He in physics program

2. Technology available

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· **More details in Elke's presentation (next)**

Participants

- **37 registered participants**
- **From 8 institutions**
- **On 3 continents**

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Program

Four sessions:

1. Polarized ^3He source

5 2. Physics with colliding polarized ^3H beams

3. Polarimetry at low and high energies

4. Polarized ^3He in Booster, AGS, RHIC, and EIC

Presentations and discussions

- **Presentations are generally 30+15 min**
- **Have left enough discussion time after each talk, please use it**
- **Have additional discussion time at end of each session (moderated)**
- **Upload talk, email, or have on USB drive**

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WHY ARE WE DISCUSSING POLARISED He-3 BEAMS NOW?

Is all in place to start work on polarized He^3 ??

- ☐ Need some years to implement a polarized He^3 beam
- ☐ Decadal planning process in full swing

Polarized Beams in RHIC

The BNL Accelerator Complex

RHIC polarized protons - luminosity and polarization

- $\langle P \rangle$ increased from 37% to 46% at 250 GeV in Run-11
still significant effort needed to reach goal of 70%
also for 100 GeV Beams
- Building blocks for pp design luminosity at 250 GeV demonstrated in Run-9 and Run-11
need to be put together plans to go beyond
- Expect no significant increase in luminosity at 100 GeV before electron lenses

Summary

Polarized He-3 production, storage and transport

S.Karpuk

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Polarization of ^3He by optical pumping techniques is well known since the early 1960s with first applications in fundamental physics experiments.

The polarization apparatus in Mainz is based on the method of optical pumping of metastable ^3He atoms in a weak gas discharge at a gas pressure of about 1 mbar. Our concept of production of the hyperpolarized ^3He includes a remote type of operation, where the ^3He is spin-polarized in a central production facility from where it is transported to users. The hyperpolarized ^3He is stored and transported in relaxation-poor glass vessels, which are blown from specially developed iron free glass. Without internal coating, polarization decay times of up to 250h are observed, sufficient for shipping the hyperpolarized gas all around the world using specially designed transport units, which provide a homogeneously magnetic field to guide the spins. After usage the ^3He gas can be recovered, the transport vessels are refilled with freshly polarized gas and the cycle starts again.

The current status of the polarization apparatus as well as storage, administration and recovery will be presented.

Concept of central production of the hyperpolarized ^3He

^3He polarizer in Mainz

Central production: storage and transport I

iron-free aluminosilicate-glass flasks
(GE-180) on special demand from
Schott Duran Group Mainz

Volume: $V \approx 1,1$ litre

Transport pressure: $p = 2.7$ bars

$$T_1^{\text{wall}} = 250 \text{ h}$$

- 10 surface-coating
- 10 time-consuming bake-out procedure
- high T_1 -reproducibility after re-use

Paramagnetic relaxation of spin polarized ^3He at bare glass surfaces (Eur. Phys. J. D 38 (2006) 427)

Paramagnetic relaxation of spin polarized ^3He at coated glass walls (Eur. Phys. J. D 38 (2006) 439)

Relaxation of spin polarized ^3He by magnetized ferromagnetic contaminants (Eur. Phys. J. D 38 (2006) 445)

Central production: storage and transport II

$$\frac{1}{T_1} = \frac{1}{T_1^{grad}} + \frac{1}{T_1^{wall}} + \frac{1}{T_1^{dd}}$$

$$\frac{1}{T_1^{grad}} = D \cdot G_r^2$$

**G. D. Cates, S.R. Schaefer,
and W. Happer, Phys. Rev.
A 37, 2877 (1988)**

$$T_1^{grad} \approx \frac{1}{6900} \frac{p[\text{bar}]}{G_r^2[\text{cm}^{-2}]} \quad T_1^{grad} \propto \frac{1}{G_r^2}$$

$$\vec{r}_r = \sqrt{(\vec{\nabla} B_x)^2 + (\vec{\nabla} B_y)^2} / B \quad Z \uparrow \uparrow \vec{B}$$

S.Hiebel, T.Großmann, D.Kiselev,
J.Schmiedeskamp, Y.Gusev, W.Heil, S.Karpuk,
J.Krimmer, E.W.Otten, Z.Salhi “Magnetized boxes
for housing polarized spins in homogeneous fields“,
Journal of Magnetic Resonance **204** (2010) 37-49

**Magnetically shielded
transport box**

$$|\text{grad} B/B| \leq 10^{-3}/\text{cm} \Rightarrow \\ T_1^{grad} \geq 400 \text{ h (@2.7 bar)}$$

Summary

- Concept of central production of the hyperpolarized ^3He :
He production facility, storage and transport, gas administration, ^3He recovery
- Applications of hyperpolarized ^3He in different fields of physics and applied science

Metastability Exchange Optical Pumping (MEOP) of ^3He in situ

Hyperpolarized helium-3 is used as a contrast agent for lungs magnetic resonance imaging that has recently reached the pre-clinical applications. The main method to hyperpolarize ^3He is the metastability exchange optical pumping (MEOP). Optical pumping is performed in standard conditions at low pressure (mbar) and low magnetic field (≈ 1 Gauss). A complete update of a low field polarizer dedicated to all animal lungs imaging resulted in a production of 3-4 scc/min for a polarization between 30 to 40%.

Since few years, MEOP has also been studied at higher pressures and higher magnetic fields in small sealed cells. It showed that, thanks to hyperfine decoupling effect induced by high magnetic field, it was possible to efficiently polarize at higher pressure (67 mbar). Experiments done at 4.7 and 1.5 T are reported in this presentation. The first ones show a beneficial (higher polarization values) and a negative effect (lower production rates) of the magnetic field. The second ones highlight the advantage of using an annular beam shape of the laser that matches the distribution of 2^3S state atoms at higher pressure. Polarization values of 66.4% at 32 mbar and 31% at 267 mbar were obtained in 20 mL sealed cells and a 10 times increase in the production rate compared to best standard conditions.

Motivated by these results a high-field polarizer working inside MRI scanner in hospital was built leading to a 30-40% polarization of ^3He with a 4 times higher flow than the low field polarizer (10-15 scc/min). This led to the first human lung images made in Poland.

Concerning possible applications in EBIS, it is shown in this presentation that MEOP can be performed in both low and high magnetic field with a sufficient production rate. An accurate and absolute method of optical detection of polarization is proposed.

Guilhem Collier

Jagiellonian University, Institute of Physics, Krakow, Poland

2. Upgrade of a low field polarizer

- Design similar to Protlab in Paris
 - More homogeneous guiding field
 - New NMR more sensitive and calibrated with optical absorption method
 - New storage cell (longer T1), OP cell
 - New Laser 10W Keopsys
 - New design of peristaltic compressor higher efficiency, easier to replace tube
 - $30\% < M < 40\%$
 - Gas flow: $3 < f < 5$ scc/min
- ⇒ 2-4 min for rat, ⇒ 1h for human

Results accepted for publication in Optica applicata

guilhem Collier

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3. Systematic studies at high magnetic field

Can we polarize at higher pressures ?

Yes, at high magnetic field !

$$P \cdot \rho \approx 90$$

Previous results published in Nikiel et al in 2007 (67 mbar):

Hyperfine decoupling at high magnetic field inhibits some relaxation channels !

Field [T]	Pump line	M [%]	t_b [s]	T_1 [s]	n_m [at cm ³]	R [mbar s]
1.5	f2 ^m	43	8.4	1934 ± 32	2.4 · 10 ¹¹	0.33
	f4 ^m	10	3.5			0.29
	f2 ^p	30	5.8			0.33
	f4 ^p	20	4.2			0.31
2	f2 ^m	51	10.1	569 ± 26	8.5 · 10 ¹¹	0.32
	f4 ^m	31	8.9			0.22
	f2 ^p	38	8.0			0.30
	f4 ^p	32	7.9			0.26

3. Systematic studies at high magnetic field

Magnetic field dependence

☆ 67 mbar

○ 32 mbar

Hyperfine decoupling has 2 different effects:

- Mstat increases with magnetic field !
- But efficiency decreases, hyperfine decoupling slows down the build-up process.

Steady state polarization and production rate of optical pumping as a function of magnetic field B at fixed pump laser power (0.5 W) and weak discharge

Open symbols obtained in our superconducting magnet 0-2 T (Magnex scientific) and solid ones in Bruker 4.7 T (collaboration with insitute of nuclear physics in Krakow)

- Results obtained with different lasers!

Experimental setup, data analysis and dependence with magnetic field **to be published soon !**

3. Systematic studies at high magnetic field

- Repeat experiments at 1.5 T with optimum laser conditions and new cells

Polarization and production rate vs pressure at 1.5 T with use of axicons

- 25% increase of Mstat
- Factor 10 increase in efficiency compare to low field !
- 31% achieved at 267 mbar (67% at 32 mbar)
- Axicons not usefull at 1.3 mbar.

→ **compact polarizer for lung imaging applications**

Main idea: Use the guiding field of the most commonly used scanner (1.5T) to produce quickly hyperpolarized ^3He for medical applications (lung MRI)

Polarized ^3He Source Development at MIT

- Development of a design concept to produce polarized $^3\text{He}^{++}$ using existing EBIS
- In the process of putting together a laboratory on the MIT campus to support the realization of this source

Charles Epstein and Richard Milner

Work supported by:

- The DOE Office of Nuclear Physics, R&D Program for Next Generation Nuclear Physics Accelerator Facilities
- MIT Department of Physics

*With thanks to: J Alessi, G Collier,
D. Kleppner, P-J Nacher, A Pikin*

Goal

- $\approx 3 \times 10^{12}$ /sec (500 particle nA), 70% polarized $^3\text{He}^{++}$ into RHIC
- To produce a polarized $^3\text{He}^{++}$ source using the existing Electron Beam Ionization Source (EBIS) at BNL
- Requires a source of polarized ^3He atoms which are directed into the EBIS
- Pulsed structure: ≈ 1 second pulse, ≈ 3 seconds off

Concept

FIGURE 4. Schematic layout showing definition of variables

- Locate ^3He gas in a glass pumping cell in the fringe field of the EBIS solenoid (field ~ 0.1 Tesla)
- Polarize gas at ~ 1 torr pressure in pumping cell using metastability exchange optical pumping
- Measure polarization in pumping cell using pump-probe technique
- Feed polarized atoms via calibrated leak in pumping cell along tube into EBIS
- Plan to test concept by collecting sample of atoms at end of beam tube and measuring their polarization using NMR

Details

FIGURE 4. Schematic layout showing definition of variables

- $\approx 10^6$ bounces in 1 meter long transfer tube
- Negligible wall depolarization
- Transfer time ≈ 1 msec
- Configure test where polarized atoms are contained in storage cell at the end of the transfer line – can measure the loss of polarization using NMR

Magnetic Field Gradients

- $\approx 0.1\text{T}$ Field outside EBIS (solenoid fringe)
- Contains strong gradients, depolarization in ≈ 1 second
- Cancellation coil is necessary to prevent quick depolarization

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FIGURE 5. Setup schematic (not to scale)

Major tasks ahead

- Polarize sealed cells: $V \approx 100 \text{cm}^3$ to $P \approx 80\%$
- Develop feed system with a calibrated leak
- Develop pump-probe measurement of polarization
- Construct test at BNL using EBIS solenoid
- Measure polarization of sample of atoms using NMR

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Polarized He-3 Beams from EBIS

**Jim Alessi, E. Beebe, S. Pikin,
D. Raparia, A. Zelenski**

Also help/slides from R. Milner, F. Simons, C. Epstein; MIT,
Bates

Brief overview / status of EBIS

Options for polarized He-3

EBIS Status

- Rhic EBIS and all systems making up the new EBIS preinjector are operating.
- EBIS has delivered beams routinely to Booster for NSRL Biology
 - 38 days; He^{2+} , Ne^{5+} , Ar^{10+} , Fe^{20+} , and Ti^{18+}
- EBIS has operated above its design value of 10A electron beam (12A).
- Extracted ion charge with He gas injection reached 85% of the electron charge in the trap
- Intensity at Booster input has met the project goals, but several improvements are being implemented to reach the required intensity at Booster extraction. (MEBT steering, additional matching quad at Booster input, and increased gap of the inflector).
- Ion intensity at electron beam $\sim 10\text{A}$ is being worked up to the design goal this fall for U^{40+} , Au^{32+} and Cu^{11+} for RHIC in FY2012

EBIS Based Preinjector

Ions	He – U
Q / m	$\geq 1/6$
Current	> 1.5 emA
Pulse length	10–40ms (few-turn injection)
Rep rate	5 Hz
EBIS output energy	17 keV/u
RFQ output energy	300 keV/u
Linac output energy	2 MeV/u
Time to switch species	1 second

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Principle of EBIS Operation

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Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.

- The total charge of ions extracted per pulse is $\sim (0.5 - 0.8) \times (\text{\# electrons in the trap})$
- Ion output per pulse is proportional to the trap length and electron current.
- Ion charge state increases with increasing confinement time.
- Output current pulse is $\sim$ independent of species or charge state!

Ion Yields from Rhic EBIS (and Test EBIS)

- Output scaled with trap length (Test EBIS vs. RHIC EBIS)
- Output scales with electron beam

Gold produced in RHIC EBIS for 9 & 10 Amps has not yet been optimized
(It is expected to follow the trend for electron beams up to 7.6A).

Summary

EBIS is operational

Using EBIS as an ionizer for polarized He-3 looks feasible, but can be demonstrated with some relatively straightforward experiments (1 year?)

There are solutions for the spin precession after the linac

Rigidity of the beam at injection into the Booster is lower than what has previously been done – do we need to test this? (try injecting protons from EBIS)

Production of polarized $^3\text{He}^{++}$ beam in EBIS.

- Injections of ^3He gas polarized in the external cell into EBIS.
- ^3He polarization inside the EBIS.
- Injections of polarized $^3\text{He}^+$ ion beam into EBIS.

September 28, 2011

Requirements to the 3He^{++} source

- Intensity $\sim 2 \cdot 10^{11}$ 3He^{++} ions/pulse
- Maximum polarization $> 80\%$.
- Spin flip every pulse.
- Minimal changes to the operational EBIS.

EBIS ionizer for polarized ^3He gas (proposal).

Direct optical pumping of the "fast" $^3\text{He}(2S)$ beam (proposal).

- After Na-neutralizer cell almost 100% of He-atoms are in (2^3S_1) state. Energy defect-0.38 eV.
- Direct optical pumping can produce near 100% nuclear polarization in $\text{He}(2S)$ states. $P(\text{He}^{++}) \sim 80\text{-}90\%$.

Selective ionization of ${}^3\text{He}_1$ metastable atoms in $\text{He}^* + \text{N}_2$ collisions .

High Field MEOP

- Problems:
- Required space inside the EBIS for the pumping cell, RF-coil.
- Pumping and probe laser beams inside the EBIS.
- He-3 polarimetry.
- Pulsed valve inside the high field.

Traveling the Helicity Structure of Nucleons with $p\text{-}^3\text{He}$ and $e\text{-}^3\text{He}$ Collisions

Marco Stratmann

BROOKHAVEN
NATIONAL LABORATORY

marco@bnl.gov

outline

found on www.quantum.physik.uni-mainz.de

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- current status of helicity PDFs
- sea quark helicity PDFs in $p + {}^3\text{He}$ single-spin asymmetry A_L for W bosons
- opportunities in $e + {}^3\text{He}$ pol. DIS with "neutrons" ; Bjorken sum

special interest in helicity PDFs

holy grail: proton spin sum - a key measurement at a future EIC

$A^+=0$ gauge version

Jaffe, Manohar; Ji; ...

$$\frac{1}{2}\hbar = \langle P, \frac{1}{2} | J_{\text{QCD}}^z | P, \frac{1}{2} \rangle = \underbrace{\sum_q \frac{1}{2} S_q^z}_{\text{total u+d+s quark spin}} + \underbrace{S_g^z}_{\text{gluon spin}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{angular momentum}}$$

"quotable" properties of the nucleon

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$$\Delta f(x) \equiv f_+^{N_+}(x) - f_-^{N_-}(x)$$

requires good knowledge of $\Delta g(x)$ and $\Delta \Sigma(x)$ for a given Q^2
not to mention orbital angular momentum (OAM)

- low x needed to capture most of the 1st moment integrals, e.g. $S_g = \int_0^1 \Delta g(x) dx$
- however, should not focus too much on one moment; want to know full x -dep. !
- picture emerging from present data still rather fuzzy and inconclusive

helicity PDFs: emerging picture

DSSV: de Florian, Sassot, MS, Vogelsang; PRL101 (2008) 072001; PRD80 (2009) 034030

flavor separation with semi-inclusive DIS

at LO: $d(\Delta)\sigma^H \simeq \sum_{q=u,\bar{u},\dots,b} (\Delta)q(x, Q^2) D_q^H(z, Q^2)$

extra weight
for each quark

allows for full flavor separation if enough hadrons are studied
actual analysis of data requires NLO QCD where x, z dependence is non-trivial

relevant quantities/measurements:

(un)polarized SIDIS cross sections

- for $u, \bar{u}, d, \bar{d}, s, \bar{s}$ separation need $H = \pi^+, \pi^-, K^+, K^-$ (nice to have more)

complications/additional opportunities:

- PDF information entangled with fragmentation functions
- should be not a problem: already known pretty well (DSS), more data (Belle, LHC, ...)
- EIC: if needed, can play with x & z integration/binning to reduce uncertainties
(needs to be studied in more detail)

conclusions

certainly a relevant goal to aim for a full u,d flavor separation at RHIC
if we want to pursue this further, we can play with "pseudo data" for $p^3\text{He}$

not a free lunch - significant integrated luminosity needed
would compete with other spin goals: more 200GeV running; transverse spin; .

Bjorken sum rule an important target to be pursued at an EIC

most likely, A_L on its own does not justify the effort/investment
need a stronger physics case for ^3He at RHIC (transverse spin effects !?)

Unraveling the transverse structure of nucleons with $p+\text{He-3}$ and $e+\text{He-3}$

Zhongbo Kang

*RIKEN BNL Research Center
Brookhaven National Laboratory*

Workshop on opportunities for polarized He-3 in RHIC and EIC
Brookhaven National Laboratory, Sep 28–30, 2011

Outline

- Introduction
 - 3D structure of the hadron
 - spin as a tool to probe transverse motion

Single spin asymmetries at RHIC

- single inclusive hadron production: p - p , p - n , p - ^3He
- Drell-Yan production: p - p , p - n , p - ^3He

Sivers effect at EIC

- e - p , e - n , e - ^3He

Summary

Exploring the nucleon: of fundamental importance in science

Know what we are made of:
Most abundant particles
around us
Building blocks of all
elements

Fundamental properties:
Proton mass, spin,
magnetic moment,
understand them in terms
of the internal degrees of
freedom

Tool for discovery:
Colliding high energy nucleons
New Physics beyond SM
LHC, Tevatron,
RHIC, HERA, ...

Exploring QCD and
strong interaction:
Confinement,
Lattice QCD,
Asymptotic freedom,
perturbative QCD, ...

Hadron structure

- Proton is made of
 - 2 up quarks + 1 down quarks
 - + any number of quark-antiquark pairs
 - + any number of gluons

So far the picture is more or less one-dimensional

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What about transverse motion?

- Uncertainty principle tells us that parton also carries transverse momentum $\langle k_{\perp} \rangle \sim \Lambda_{\text{QCD}}$
 - How do they move in the transverse plane?
 - Do they orbit, and carry orbital angular momentum?
 - moving from 1-dimension to 3-dimension

Summary

- Spin is a useful tool to probe hadron structure
- Spin-dependent distribution, Sivers function has opposite sign for u and d quark flavor

Polarized He-3 could be used to confirm and verify this opposite sign

If one could tag neutron, it typically leads to larger asymmetries

Still need more data to establish the theory for the transverse spin phenomena: single inclusive jet, direct photon, Drell-Yan

Spectator proton tagging in $e/p + {}^3\text{He}$

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J.H. Lee
BNL

Opportunities for polarized He-3 at RHIC and EIC, Sep 2011

Outline

- Spectator, forward proton tagging for eRHIC and RHIC: What's involved
- Utilizing Roman Pot detectors in
 - $e+^3\text{He}$ at EIC
 - $p+^3\text{He}$ at STAR/RHIC

Forward protons in the key measurements for EIC

- Diffractive proton in exclusive Deeply Virtual Compton Scattering (DVCS) process ($ep \rightarrow e\gamma p$): access to the spatial distribution of partons in the transverse plane: GPD (polarized, unpolarized)
- Spectator protons in polarized $e+^3\text{He}$ in inclusive DIS for polarized neutron structure function $g_1^n(x, Q^2)$ and flavor separation in semi-inclusive DIS
- ...

Forward protons in current and future RHIC physics

- Protons in elastic $p+p$: studying structure of Pomeron (and Odderon)
- Inelastic diffractive protons in central process:
 $p+p \rightarrow p+M_X+p$ to study constituent gluonic degree of freedom
- Spectator protons in polarized $p+^3\text{He}$
- ...

Forward protons

- Scattered with $\sim O(\text{mrad})$: Need Roman Pot to detect

Large angle (high- t) acceptance mainly limited by magnet aperture

59 Small angle (low- t) acceptance limited by beam envelop ($\sim 10\sigma$)

Reconstruction resolution limited by

- beam angular divergence ($\sim O(50\mu\text{rad})$)
- uncertainties in vertex (x,y,z) and transport

Summary

- Spectator tagging necessary for identifying target nucleon in $e/p+^3\text{He}$
- Deflected spectator protons due to different rigidity can be detected using Roman Pots
- A common detector system (“forward proton spectrometer”) can be utilized for measuring diffractive protons and spectator protons in ^3He
- Currently assumed detector design can be optimized for better acceptance and efficiency
- High luminosity and background effects in $p+^3\text{He}$ need to be studied

Low energy He-3 polarimetry

- Polarized He-3 gas polarimetry. NMR, optical polarimeter.
- Lamb-shift polarimeter at 10-100 keV.
- $^3\text{He}^{++}$ beam polarization measurements in elastic scattering in He-4, Deuterium (deuterated polyethylene), Carbon targets at 2 MeV/nucleon (6 MeV total beam energy) in the HEBT transport line.

September 29, 2011

He-3 depolarization in the transfer line.

- Polarized ^3He gas can be transported without depolarization in the plastic tubes (teflon coated metal tubes).
- There is a limitation on the magnetic field gradient in the transport line. The estimations show that there is no depolarization with the real magnetic field of the EBIS superconducting solenoid (Frank Simon, MIT, Bates).

He-3 depolarization in the transfer line.

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- Polarized ^3He in the plastic tubes (teflon coated metal tubes).
- There is a limitation on the magnetic field gradient in the transport line. The estimations show that there is no depolarization with the real magnetic field of the EBIS superconducting solenoid (Frank Simon, MIT, Bates).

NMR calibration of optical measurement of nuclear polarization in ^3He

W. Lorenzon, T. R. Gentile, H. Gao, and R. D. McKeown

W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 9112

(Received 29 June 1992)

We have performed precise NMR measurements in order to calibrate a standard optical technique measuring the polarization of ^3He nuclei. This optical technique requires knowledge of the pressure dependent relationship between the nuclear polarization and the degree of circular polarization of 668-nm light emitted from a ^3He discharge. We determined the nuclear polarization by comparing the adiabatic fast-passage NMR signal from samples of polarized ^3He at pressures between 0.1 and 5 torr to an identical sample of water. For water, the polarization is known from statistical mechanics. The ^3He is polarized using the metastability exchange technique for optical pumping of ^3He . The accuracy of the calibration is $\pm 2\%$, which is required for applications in nuclear physics.

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Possible path forward.

- He-3 polarizing and analyzing apparatus development.
- Tests of He-3 depolarization in transfer line through superconducting solenoid.
- 3He^{++} ion beam production in EBIS, acceleration to
- 2 MeV/nucleon (6 MeV total energy).
- Polarization measurements in elastic scattering 3He beam in 4He target.
- Possibility of polarization optimization with Lamb-shift polarimeter (high statistical accuracy).

Theory of CNl polarimetry with ^3He

Workshop on Opportunities for polarized ^3He in RHIC and EIC

Larry Trueman

2. EARLY RESULTS

Over the next several years many measurements were made at BNL, at first all with proton on carbon or proton targets. There was an earlier measurement made at Fermilab E704, but that program was terminated with large errors on A_N , the up-down asymmetry also called the analyzing power. The BNL measurements were made at 24 GeV/c at the AGS and 100 GeV/c at RHIC. The errors steadily improved.

These values of τ fit the data pretty well. The choice of carbon for a target was pragmatic but also very fortunate: it gives us directly the value for the neutron spin-flip coupling complementing the proton target. The formulas we will use are very simple: The proton asymmetry

$$A_N \frac{d\sigma}{dt} = -\frac{8\pi}{s} \text{Im}(\phi_+ \phi_5^*) \quad (2.1)$$

and the ^3He asymmetry

$$A'_N \frac{d\sigma}{dt} = \frac{8\pi}{s} \text{Im}(\phi_+ \phi_6^*) \quad (2.2)$$

are given in terms of the two spin-flip amplitudes ϕ_5^* and ϕ_6^* , which are standardly parametrized in terms of the non-flip amplitude ϕ_+ as

$$\phi_5 = \tau_p \frac{\sqrt{-t}}{m} \phi_+$$

and

$$\phi_6 = -\tau_n \frac{\sqrt{-t}}{m} \phi_+.$$

Both ϕ_5 and ϕ_6 are complex numbers and are energy dependent.

One of the main objectives of my work was to determine the energy dependence of the flip factors which I did using Regge theory. The energy dependence is found to be important, but the t -dependence is argued to be unimportant over the tiny momentum transfer range of the CNI experiments.

We can use these numbers to evaluate the analyzing power of ^3He . The next figure show the calculated energy dependence of real and imaginary parts.

The real parts just shift the analyzing power up or down uniformly while the imaginary part changes the shape of the predicted curve. Explicitly:

$$A_N(s, t) = F_N(s, t) (\kappa_p/2 - \text{Re}\tau_p(s) - \rho(s) \text{Im}\tau_p(s) (t_c/t) (1 + \text{Im}\tau_p(s)) (1 + \rho(s)^2))$$

$$A'_N(s, t) = F_N(s, t) (\kappa_n/2 - \text{Re}\tau_n(s) - \rho(s) \text{Im}\tau_n(s) (t_c/t) (1 + \text{Im}\tau_n(s)) (1 + \rho(s)^2))$$

Energy dependence of spin-flip factors predicted by Regge model

(a)

proton analyzing power at $p_L=100$ GeV/c

(b)

neutron analyzing power at $p_L=100$ GeV/c

Analyzing powers calculated with

$$\tau_p = 0.014 + 0.002i$$

and $\tau_n = -0.006 - 0.102i$

A_N'

proton -3 Helium colliding beams at 150 GeV/c lab
momentum per nucleon

Theory of CNI polarimetry with ^3He

Workshop on Opportunities for polarized ^3He in RHIC and EIC

1. BACKGROUND

About fifteen years ago Yousef Makdisi called me and Elliot Leader with an interesting question: the RHIC polarimeter group was focusing on the use of a coulomb-nuclear interference polarimeter as a promising way to get a precise measurement of the polarization of the proton beams in RHIC. This requires the precise measurement of the up-down or left-right asymmetry in the very small t region of proton-proton elastic scattering. For the ideal case, discussed many years ago by Schwinger, the asymmetry is exactly calculable in terms of the one-photon exchange amplitude given in terms of α and the anomalous magnetic moment of the proton interfering with the nuclear amplitude which is known in terms of the pp total cross section σ_{tot} and ρ the ratio of real to imaginary parts of the strong pp amplitude. This gives a very nice measurable asymmetry and then directly the beam polarization.

This method assumes that the nuclear amplitude does not have a spin-flip part to interfere with the one-photon exchange non-flip amplitude. And this was the crux of Yousef's question: how well do we know that the nuclear spin-flip is small enough to allow this calculation to be used? It was commonly believed and often insisted upon that the high energy nuclear amplitude was spin independent, but Elliot and I were not sure of that. So we organized a little workshop of unbiased experts: Nigel Buttimore, Jacques Soffer and Boris Kopeliovich to join with Elliot and me to look very hard at the question. The conclusion that we came to was that the parameter r_5 that measures the ratio of flip to non-flip scattering was limited at best, both experimentally and theoretically, to 15% while the experiments to be carried out required a much better limit of 5%. Following up on this over the next few years the five of us went off alone or in various subgroups to see what we could do.

We learned a lot from this experience, but the key conclusion we came to was the best way was to measure τ making use of a polarized hydrogen target. You didn't need to do all the work we did to reach this conclusion, but making a suitable hydrogen target was not an easy job and we did not know at the time if one would be available in time for our experimental program.

Experimental Issues with Carbon Polarimetry for He-3

Haixin Huang
Brookhaven National Lab

To use carbon CNI polarimeter for He-3, the electronics remains the same. The two potential problems are the target heating and Si detector acceptance. The analysis of target heating and Si detector acceptance are performed and the results show that the target heating is not worse than proton for the given He-3 beam conditions. The Si detector acceptance actually will be better than proton case. IN short, there should be no show stopper to use carbon polarimeter for He-3.

Proton Beam Conditions

Intensity: 2×10^{11} /bunch

Emittance: 10π (for estimation purpose only)

Protons:

	Energy	Momentum	γ
AGS Injection	2.36GeV	2.16GeV/c	2.51
AGS Extraction	23.81GeV	23.79GeV/c	25.38
RHIC Store	250GeV	250.00GeV/c	266.45

He-3 Beam Conditions

Intensity: 1×10^{11} /bunch

Emittance: 10π (for estimation purpose only)

	Energy	Momentum	γ
AGS Injection	5.05GeV	4.19GeV/c	1.79
AGS Extraction	33.30GeV	33.18GeV/c	11.83
RHIC Store	501GeV	501.14GeV/c	178.04

For He-3: higher momentum, but lower γ . Acceptance of detectors will be better. The equilibrium temperature is affected by higher energy deposit, larger physical beam size, and lower beam intensity.

Carbon Target Equilibrium Temperature with He-3

RHIC Si Detector Acceptance

Vertical scale gives the acceptance of BNL Si detectors.

The cases for He-3 are not distinguishable from proton case at store.

Summary

- The equilibrium temperature for He-3 is not worse than proton for the given running conditions.
- The detector acceptance is improved due to higher energy.
- Bottom line is that there is no show stopper from polarimeter hardware.

Systematic Uncertainties in Polarimetry: RHIC $\vec{p}\vec{p}$ lessons

W. Schmidke – Brookhaven National Laboratory

79 The systematic uncertainties of the RHIC proton polarization measurement are discussed. The overall polarization scale is set by the polarized hydrogen target polarimeter. The uncertainty on this scale is dominated by the Breit-Rabi polarimeter measuring the target; other systematic effects largely cancel. The proton-carbon polarimeter uncertainty is largely due to the strong dependence of the proton-carbon analyzing power on the scattered carbon energy. Instability in the energy scale of the recoil carbon detection is a contributing factor. However, the passage of scattered carbon nuclei through carbon target material introduces systematic effects through energy loss and multiple scattering. Instability in the target orientation relative to the detectors can shift the measured carbon energy spectrum, leading to sizable uncertainties in the polarization measurement.

H-jet polarization

$$A_N(t) = -\frac{\epsilon_{\text{target}}}{P_{\text{target}}} = \frac{\epsilon_{\text{beam}}}{P_{\text{beam}}}$$

measured : "unpol. beam" avg. $\uparrow$ & $\downarrow$ "unpol. target" avg. $\uparrow$ & $\downarrow$

effective A_N may vary fill-to-fill with varying background

e.g. inelastic $pp \rightarrow pp + X$:

same events used for beam, target ϵ

same bkg., effective A_N ; $\Rightarrow$ background $\sim$ cancels

$$\Rightarrow P_{\text{beam}} = -P_{\text{target}} \frac{\epsilon_{\text{beam}}}{\epsilon_{\text{target}}}$$

- Uncert. Breit-Rabi $\sim 2\%$ (molecular H_2)
- Overall scale uncert. P_2

$A_N(pC) \leftrightarrow$ energy scale

- Analyzing power $A_N(T)$ very steep dependence on ^{12}C kinetic energy T :
- Measure in $0.4 < T < 0.9 \text{ MeV}$;
 relative A_N from pC/H-jet ratio
 sensitive to ^{12}C energy scale:
 $\Delta T = 25 \text{ keV} \Rightarrow \delta A_N = 5\% \text{ relative}$

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energy scale of scattered ^{12}C major source of A_N , P uncertainty

- 1st point: the energy scale uncertainty of the Si detectors introduces uncertainty on A_N , P
- e.g. estimated dead layer in Si $\sim 60 \mu\text{g}/\text{cm}^2$; ^{12}C in T range lose $\sim 200 \text{ keV}$
- uncertainty of $\sim 10\%$ on dead layer $\Rightarrow 5\%$ uncertainty on A_N

^{12}C energy loss in target

- Scattered ^{12}C nuclei lose energy in ^{12}C target en route to Si detectors
- Measured T_{meas} down-shifted from scattered T_{scat}

measure over a fixed T_{meas} range

changes path length changes

given T_{meas} corresponds to different T_{scat} , A_N

$t/(2 \cdot \sin \theta) \Rightarrow$ steep change A_N as $\theta \rightarrow 0^\circ$

in #'s for C-C dE/dz , $A_N(T)$,

relative variation (%) of A_N with θ :

^{12}C multiple scattering in target

- The recoil ^{12}C also undergo multiple Coulomb scattering, RMS angle $\theta_{\text{RMS}} \propto \sqrt{L/T}$ (L=path length, T=kinetic E)

nult. scat. ~all perpendicular to beam
 detector 18cm from target
 ore material $\Rightarrow$ more events larger θ , Z:

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- er energy $\Rightarrow$ larger scattering angles
- Mean energy drops at larger θ , Z:
- On top of this is the energy loss in target (previous slide)
- Consider all effects $\Rightarrow$ simple simulation $\searrow$ (already used for these plots)

Z = direction along beam
 Z = 0 perpendicular to target

Simple simulation

A_N/A_{N0} vs. Z-det, various $L_{\max}$:

Z = detector center along beam
Z = 0 perpendicular to target

- 0=no material
 - Rotate target about vert. axis:
 - }. 1,4,9 = nominal target $90^\circ, 15^\circ, 5^\circ$
 - 4,9 = 2x thick. target $30^\circ, 15^\circ$
 - 4,9 = 4x thick. target $90^\circ, 45^\circ$
- target rotates, thickness varies
can change by >15%
- target sways longitudinally
(Z-det varies), few % shifts if
target-detector ~centered;
much worse if misaligned

⇒ Target orientation, alignment significant effect on A_N

that was just a simulation, we have some data ↘

^3He and Proton Polarimetry for RHIC

Yousef I. Makdisi

Brookhaven National Laboratory

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Polarimetry utilizing the Coulomb Nuclear Interference process has served us well in proton polarimetry. The analyzing power was measured to be fairly constant from RHIC injection to the highest energy reached. We propose to extend this to ^3He polarimetry beams. ^3He – Carbon polarimeters will be used for fast measurements, but these have to be calibrated using either a ^3He jet or possibly a storage cell to increase target density. The ^3He beam calibration will rely on ^3He - ^3He elastic scattering and two identical particles process where the analyzing power is the same whether the target or the beam is polarized. Of course the jet or cell polarization will be measured using a separate process. The recoil scattering Kinematics are similar to what we are using in proton polarimetry that the same equipment could be used interchangeably between proton and ^3He beams.

Opportunities for Polarized He-3 in RHIC and EIC
September 28-30, 2011

Analyzing power in pp-Hjet and p-Carbon CNI

24 GeV: PRD 79, 094014(2009)

31 GeV: Preliminary

100 GeV: PLB 638 (2006) 450

250 GeV: Preliminary

BROOKHAVEN
NATIONAL LABORATORY

Possibly an unpolarized hydrogen Jet for higher intensity?

The Polarimetry Requirements for RHIC

- The polarimeters should operate over a very wide range
Protons: 24 to 250 GeV, 3He: 10 to 160 GeV
- The physics program requires precision polarimetry $< 5\%$
- Polarimeter calibration is required at each energy
- Beam polarization profile(s)
- Polarization lifetime or decay during a store
- Polarization measurement on the ramp
- Bunch to bunch emittance measurements

We need a system for calibration

- Use a polarized Helium 3 target the polarization of which is measured through a different process
- Use the calibrated polarized proton beam to measure A_N vs t in p- ^3He elastic Scattering (see L. Trueman's presentation)
- But if one can calculate the Analyzing power in $^3\text{He} - ^3\text{He}$ elastic scattering
- No breakup as the CNI process with momentum transfer < 1 MeV well below The nuclear binding energy
- Use a polarized ^3He Jet and utilize the identical “entities” principle in $^3\text{He} - ^3\text{He}$ elastic scattering and simultaneously measured A_N using the Jet polarization and then turn around and measure the beam polarization.

The HERMES Target (proof of principle)

- ^3He gas
- Polarized using metastability- exchange optical pumping
- Helium polarization in the cell measured at 54% (higher later?)
 - Just learned the Mainz target reached 90%
- Target thickness (cell) 1×10^{15} nucleons/ cm^2 if jet only a factor of 100 lower intensity with longitudinal and transverse polarization
- The target polarization was measured using the positron beam scattering. We need to find a different way
- Significant differential pumping was employed for beam vacuum

What Next?

- A theoretical estimate of the analyzing power of $^3\text{He} - ^3\text{He}$ elastic scattering in the CNI region
- Experimentally measure A_N in $p-^3\text{He}$ and $^3\text{He} - ^3\text{He}$ elastic scattering at various energies
 - The AGS is good start and the sweet energy is for injection into RHIC
- The selection of the recoil particle is similar to what has been employed in our current systems
- If successful, then employ at RHIC
 - We need to find a suitable location if the polarized hydrogen jet is to remain in place.
- Lots of work ahead....

Discussion:

Open questions and possible solutions for ^3He gravimetry

Online Polarimeter display

Jun 28, 2009 2:22:18 AM

Carbon rate 50 - 100 kHz/ strip

Prompts background to signal $\sim 1/1$ with an energy threshold cut at 125 keV.

Shaper pulse rise time 20 nsec and fall time 50 nsec

The RHIC Carbon CNI polarimeters

- Can we use ^3He – Carbon CNI?

Pro:

We can do polarization profiles

Use an existing system

Con:

Impact on the beam

Will the helium breakup?

The Local Polarimeters

Needed for setting up the spin rotators

- The ZDCs measure a significant forward neutron asymmetry should we expect a similar analyzing power from Helium scattering?
- Do we need to measure the spectator proton?
- Roman Pots?
- We need theoretical guidance

The Local Polarimeters Cont'd

The BBC polarimeters

- Measure inclusive charged hadron production in the forward direction. A small analyzing power but with high rate. I suspect similar results from Helium scattering.
- We need theoretical guidance
- Should we think of some other schemes?

Needed measurements

AGS

Do we need to measure beam polarization near injection?

The CNI targets do not allow this

Shall we employ a different process at low energy?

The CNI polarimeter is well poised for pol. ^3He -Carbon measurements at AGS extraction energies

Polarized He-3 in MEIC

Ya. Derbenev, Jefferson Laboratory

*Workshop on Opportunities for Polarized ^3He
in RHIC and EIC
BNL, September 28-30, 2011*

Outline

- Ion Polarization Requirements
- Source
- Figure-8-based design
- Proton and ^3He transverse and longitudinal polarization schemes
- Deuteron transverse and longitudinal polarization schemes
- Polarized ions acceleration and maintenance in figure 8 rings
- Flipping ion spin
- Conclusions

Ion Polarization Requirements

- High polarization degree of stored high-current ion beams
- Ion polarization preservation during acceleration and storage
- Capability to provide both longitudinal and transverse *proton and $^3\text{He}^{++}$* polarization in both straights
- Capability to provide both longitudinal and transverse *deuteron* polarization
- Ability to accommodate highly polarized $^6\text{Li}^{+++}$ ion beam

Physics with polarized ^3He and D

- *"Having both polarized ^3He and D... will greatly enhance the study of both binding energy effects on nucleon structure (the EMC effect in ^3He and D) and the spin structure functions of quasi-free neutrons."*
- *"Experiments with polarized deuterium where the proton is tagged in the final state are important to study the free neutron properties."*
- *"...the deuteron is natural one for extracting the polarized gluon information."*

MEIC Layout

Summary

- **Figure-8 design provides spin preservation and control at acceleration in boosters for polarized p, d and $^3\text{He}^{++}$**
/With reference to BNL experience with polarized protons in AGS and RHIC/
- **Proton , $^3\text{He}^{++}$ and deuteron longitudinal and transverse polarization schemes in twisted collider ring conceptually established. Tracking and studying limits of long term polarization maintenance underway.**
- **Stacking of high current polarized $^3\text{He}^{++}$ by use of electron cooling in pre-booster is proposed. Design and study underway.**
- **Study of the proposed single-turn and many-turn Spin Flipping systems is underwa**

TRANSPORT OF POLARIZED $^3\text{He}^{2+}$ IN BOOSTER AND AGS**F. Méot****Brookhaven National Laboratory, C-AD/AP****SUMMARY**

Various aspects of the acceleration of $^3\text{He}^{2+}$ through Booster and AGS are reviewed. Booster and AGS with the two partial snakes should allow polarization transmission comparable to protons' or better.

Further possibilities of bringing extraction rigidity from booster and from AGS closer to proton ones are explored. That could bring possibilities of easing spin transmission in AGS at the low energy end of the cycle. That would improve beam optics at AGS injection as well, being the snakes used in a better working range. Extraction towards RHIC beyond $G\gamma=51$ would require crossing the strong AGS resonance 60-Qy.

LAYOUT

INCREASED EXTRACTION ENERGY FROM BOOSTER

- Extract in $G\gamma = -10.5$ region or even beyond, for AGS snakes purpose.
- For instance, below booster's 6+ Q_y resonance (needs $Q_y > 4.5$) if -10.5 ($B\rho = 10.8$ T.m). Will in addition escape AGS 0+.
- If, further, $B\rho \rightarrow 15$ T.m ($G\gamma \rightarrow -14$) then will get closer to better behaved region in snake optics.
- Note : still below transition γ ($|G\gamma|_{tr} > 16$), and below max. $B\rho = 17$ T.m.

Strengths ($Q_x/Q_y=4.73/4.82$) :

$G\gamma$	0+	12-	6+	18-
N_n at 2.5π	0.011	0.0006	0.010	0.012

interest :

$\gamma = -7.5$ is $B\rho = 6.97$ T.m, even lower than proton $G\gamma = 4.5$, $B\rho = 7.21$;

is low-rigidity region is less favorable as to snake optics : perturbed ring focusing, coupling.

OVERCOMING IMPERFECTION RESONANCES BEYOND $G\gamma = 60 - Q_y$ IN AGS WITH $^3\text{He}^{2+}$

	Warm snake	Cold snake	Comments
B max (T)		3	
B nominal (T)	1.5	2.1	Case of tracking below
snake angle (deg.) $\left\{ \begin{array}{l} \text{proton :} \\ ^3\text{He}^{2+} : \end{array} \right.$	$\left\{ \begin{array}{l} \approx 11 \\ 26 \end{array} \right.$	$\left\{ \begin{array}{l} \approx 21 \\ 44 \end{array} \right.$	$\left\{ \begin{array}{l} \\ \text{Discussed further on} \end{array} \right.$
"% snake" $\left\{ \begin{array}{l} \text{proton :} \\ ^3\text{He}^{2+} : \end{array} \right.$	$\left\{ \begin{array}{l} 6 \\ 15 \end{array} \right.$	$\left\{ \begin{array}{l} 12 \\ 25 \end{array} \right.$	

Example :

ipping across imperfection resonances, $G\gamma : 43.5 \rightarrow 60$, rigidities : $\left\{ \begin{array}{l} \text{proton : } 75.9 \rightarrow 104.7 \text{ T.m} \\ ^3\text{He}^{2+} : 48.47 \rightarrow 67.0 \text{ T.m} \end{array} \right.$

ingle particle on vertical orbit : $\left\{ \begin{array}{l} \text{proton : } \hat{y}_{co} \approx 8 \text{ mm} \\ ^3\text{He}^{2+} : \hat{y}_{co} \approx 5 \text{ mm} \end{array} \right.$

I orbit < 1 mm, H and V invariants $\approx$ zero, $\delta p/p|_{synch.} < 10^{-4}$.

roton

$^3\text{He}^{2+}$, tentative, snakes unchanged : 15%+25%

TENTATIVE TRACKING OF $^3\text{He}^{2+}$ THROUGH 60-Qy

- Snakes have their nominal field, 2.1 T and 1.5 T,
- Optics : Qx/Qy 8.72 / 8.97. Orbits are $H \ll 1$ mm, $V \approx 1$ mm peak. Jump quads off,
- For reference : zero emittances case is that shown on slide 4.

Single particle, $^3\text{He}^{2+}$. $\epsilon_x \approx 0$,
 $\epsilon_y \approx 1.25 \pi \text{ mm.mrad norm.}$,
 $dp/p \in [-10^{-4}, +10^{-4}]$.

Proton, for comparison. $\epsilon_x \approx 15 \pi \text{ norm.}$,
 $\epsilon_y \approx 2 \pi \text{ norm.}$, $dp/p \in [-10^{-3}, +10^{-3}]$.

$^3\text{He}^{2+}$. $\epsilon_x \approx 1.25 \pi$, ϵ_y very small,
 $dp/p \in [-10^{-4}, +10^{-4}]$.

- Depolarization may result from betatron coupling [Ref.H.Huang et al, PAC97]. Need investigate with simulations including coupling correction.
- Worth exploring increased snake strength : cold snake is 70%, warm snake is 1.5 T with 2600 Amp in 0.5 Tesla/kAmp working region.

$^3\text{He}^{2+}$ SPIN ROTATION IN AGS SNAKES

Proton

AGS COLD SNAKE, PROTON

AGS WARM SNAKE, PROTON

$^3\text{He}^{2+}$

AGS COLD SNAKE, ^3He

AGS WARM SNAKE, ^3He

- Note : Warm snake is operated at ~ 2600 Amp. [Ref.J.Takano,EPAC2004], a region of 0.5 Tesla/kA. Increasing the angle $\rightarrow$ matter of (i) power supply, (ii) saturation effects.

Accelerating Polarized He3 in RHIC

Mei Bai

Collider Accelerator Dept. BNL

Outline

- Introduction
 - accelerating polarized beams to high energy
- Possibility of polarized light ions in RHIC
 - Deuteron and others
 - He3
 - With current layout
 - Alternatives
 - Luminosity perspective
- Summary

Depolarizing mechanism in a synchrotron

- When perturbations on spin vector from horizontal field are coherently built up, a polarization loss can happen
- Imperfection resonance
 - From dipole errors, quadruple misalignments
 - $G\gamma = k$, k is an integer
 - Scales with the size of vertical closed orbit distortion
- Intrinsic resonance
 - From betatron oscillation
 - $G\gamma = kP \pm Q_y$, where P is the super periodicity of the accelerator, Q_y is the vertical betatron tune

III

Snake depolarization resonance

□ Condition

$$mQ_y = Q_s + k$$

□ even order resonance

- Disappears in the two snake case if the closed orbit is perfect

□ odd order resonance

- Driven by the intrinsic spin resonances

Summary

- Current RHIC dual snake configuration can accelerate He3 to its store energy if beam control can be improved by another factor of 2
 - Closed orbit distortion, spin tune shift/spread, betatron shift/tune spread
- Alternatively, another two pairs of snake for each ring will
 - Eliminate high order snake resonances and open up more room in the betatron tune space to accommodate acceleration as well as store
 - Relax the very tight requirements on beam control
 - And most importantly, there are still rooms in RHIC to accommodate them!!!

Open questions and necessary tests for polarized He-3 in RHIC/EIC

Thomas Roser

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Towards polarized He-3 in RHIC

- Polarized He-3 from EBIS
- Polarimeter after EBIS linac at 2 MeV/n (He-3, He-4 elastic scattering?)
- Unpolarized He-3 from EBIS:
 - Injection into Booster at low rigidity
 - Acceleration in Booster, AGS, RHIC?
 - Test carbon polarimeters
- Acceleration of polarized He-3 in Booster and transfer to AGS
 - Vertical tune in Booster < 4.19 !!
- Measure polarization at AGS injection energy, no depolarization?
- Accelerate He-3 in AGS and measure polarization on ramp and extraction energy
- Calibrate AN of carbon polarimeter at extraction energy with up/down ramp?
- Transfer to RHIC and calibrate carbon polarimeter in RHIC (which ring?)
- Absolute polarization measurement at RHIC injection with pol. He-3 jet/cell
- Accelerate in RHIC and measure polarization on ramp and at store energy
- Calibrate AN of carbon polarimeter at store energy with up/down ramp
- Absolute polarization measurement at RHIC store with pol. He-3 jet/cell

Number of snakes in RHIC

- Acceleration in RHIC will need more than 2 snakes (OK up to 56 GeV/n)
- Ideally six snakes but four may be enough:

6 Snakes
 $\Delta\alpha = 30^\circ, 90^\circ$

4 Snakes

- Built two additional snakes initially and test with polarized protons?

Other open questions

- Explore alternative polarimeter schemes
 - Elastic polarized electron on polarized He-3 scattering
 - ...
- Does DX magnet have to moved for p-He3 collisions?
 - Rigidity ratio: p-He3: 1.5; d-Au: 1.25
- Expect the luminosity of p-He3 to be similar to pp, will benefit from electron lenses in the same way as pp.
- Interesting processes (W production, Drell-Yan) could use even more luminosity
-> implement strong cooling and large crossing angle collisions

Collisions with large crossing angle

- Head-on collisions:
 - Luminosity loss from hour-glass effect requires shorter bunch length for smaller beta-star
 - Reducing bunch length limited by peak current and instabilities
 - Difficult to reduce beta-star without reducing emittance and momentum spread

Large crossing-angle collisions:

- To be beneficial needs low emittance beams (strong cooling: synchrotron rad. or CeC)
- Separate bunches outside high luminosity region to avoid beam-beam effect from low luminosity region.
- Reducing beam emittance back to beam-beam limit
- Smaller emittance and shorter overlap region allows for smaller beta-star
- For N_b/k particles colliding:

$$\frac{L}{\gamma} = \frac{1}{4\pi} k \frac{N_b/k}{\varepsilon_n} \frac{N_b/k}{\tau_b} \frac{R}{\beta^*} = \frac{1}{4\pi} \frac{N_b}{k\varepsilon_n} \frac{N_b}{\tau_b} \frac{R\gamma\sigma'^2}{\varepsilon_n} = \frac{1}{4\pi} \frac{N_b}{\varepsilon_n^0} \frac{N_b}{\tau_b} \frac{R\gamma\sigma'^2}{\varepsilon_n^0/k} = k \frac{L^0}{\gamma}$$

- RHIC: overlap length ~ 10 cm, ε_n (95%) $\sim 1 \pi \mu\text{m}$, $\beta^* \sim 10$ cm $\square$ luminosity $\sim \times 10$
- Effect of long range beam-beam?

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*Nuclei as heavy as bulls
Through collision
Generate new states of matter*

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Workshop on Opportunities for Polarized He-3 in RHIC and EIC -- sponsored by the RIKEN BNL Research Center

28-30 September
2011 *Universe*
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Wednesday 28 September 2011

September 28, 2011 Morning: Introduction - Brookhaven Center, Bldg. 30 (10:30-12:00)

time	[id]	title	presenter
10:30	[2]	Welcome	Dr. VIGDOR, Steve
10:40	[3]	Workshop goals and organization	Dr. FISCHER, Wolfram
11:00	[4]	Overview of plans for colliding polarized He-3 beams (45+15 min)	Dr. ASCHENAUER, Elke-Caroline

September 28, 2011 Afternoon: Polarized He-3 Source - Brookhaven Center, Bldg. 30 (13:00-17:00)

time	[id]	title	presenter
13:00	[5]	Polarized He-3 production, storage and transport (30+15 min)	Dr. KARPUK, Sergei
13:45	[6]	Metastability Exchange Optical Pumping of Helium-3 at high magnetic field for an in-situ polarizer (30+15 min)	Mr. COLLIER, Guilhem
14:15	[7]	Polarized He-3 source development at MIT (30+15 min)	Dr. MILNER, Richard
15:00		Coffee Break	
15:30	[8]	Polarized He-3 beams from EBIS (30+15 min)	Dr. ALESSI, James
16:15	[9]	Discussion: Implementation of a polarized He-3 source for RHIC	Dr. ZELENSKI, Anatoli

Thursday 29 September 2011

September 29, 2011-Morning : Physics with colliding polarized He-3 beams - Brookhaven Center,

Bldg. 30 (09:00-12:00)

time	[id] title	presenter
09:00	[10] Unraveling the helicity struct. of nucleons w/ p+He-3+He-3 collisions (30+15 min)	Dr. STRATMAN, M.
09:45	[11] Unraveling the transverse structure of nucleons w/ p+He-3 and e+He-3(30+15 min)	Dr. KANG, Zhong Bo
10:30	Coffee Break	
10:45	[12] Tagging back-scattered protons with pp2pp@STAR (30+15 min)	Dr. LEE, J.H.
11:30	[13] Discussion: Further physics topics with polarized He-3 (30+15 min)	SEIDL, Ralf

September 29, 2011 - Afternoon : Polarimetry at low and high energies - Brookhaven Center, Bldg.

30 (13:00-18:15)

time	[id] title	presenter
13:00	[14] He-3 polarization measurement at low energy (30+15 min)	Dr. ZELENSKI, Anatoli
13:45	[15] Theory of CNI polarimetry with He-3 (30+15 min)	Dr. TRUEMAN, Larry
14:30	[16] Experimental CNI polarimetry with He-3 (30+15 min)	Dr. HUANG, Haixin
15:15	Coffee Break	
15:30	[17] Systematic errors in polarization measurements (30+15 min)	Dr. SCHMIDKE, William
16:15	[18] He-3 polarization measurement with a jet target (30+15)	Dr. MAKDISI, Yousef
17:00	[20] Discussion: Open questions and possible solutions for He-3 polarization measurements	Dr. MAKDISI, Yousef

Friday 30 September 2011

September 30, 2011 - Morning: Polarized He-3 in Booster, AGS, RHIC and EIC - Brookhaven Center, Bldg. 30 (09:00-12:30)

time	[id] title	presenter
09:00	[21] Polarized He-3 in ELIC (30+15 min)	Dr. DERBENEV, Slava
09:45	[22] Polarized He-3 in Booster and AGS (30+15 min)	Dr. MEOT, Francois
10:30	Coffee Break	
10:45	[23] Polarized He-3 in RHIC (30+15 min)	Dr. BAI, Mei
11:30	[24] Discussion: Open questions and necessary tests for polarized He-3 in RHIC/EIC	Dr. ROSER, Thomas
12:15	[25] Adjourn	

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Link: PHENIXSpinfestSchool2009@BNL
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Opportunities for Polarized He-3 in RHIC and EIC

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*Nuclei as heavy as bulls
Through collision
Generate new states of matter.
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