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Proposal for a Spin Physics Research at HIAF-BRing

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Abstract: The construction of the future scientific facility High Intensity heavy-ion Accelerator Facility (HIAF) in China has started. Once established, HIAF will provide excellent conditions for fundamental investigations on both matter structure and heavy-ion applications. The booster ring (BRing) of HIAF is designed to accelerate high-intensity protons with the maximum momentum of 11.9 GeV/c. Therefore it will bring new opportunities for the nuclear and hadron physics in the GeV region. Polarized experiments have been proved as a powerful tool in the explorations of the building blocks of matter. We propose to initiate a pre-investigation for the related physics and polarization techniques, which will lay the foundation of the spin physics at the HIAF-BRing.

Key words: polarized internal target; HIAF-BRing; spin physics

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1 Introduction

The new scientific complex High Intensity Heavy-ion Accelerator Facility (HIAF)[1], which was proposed by the Chinese nuclear community, has been approved by the National Development and Reform Commission. The conceptual design of HIAF is depicted in Fig. 1. Highly-charged ions are produced by a superconduct-

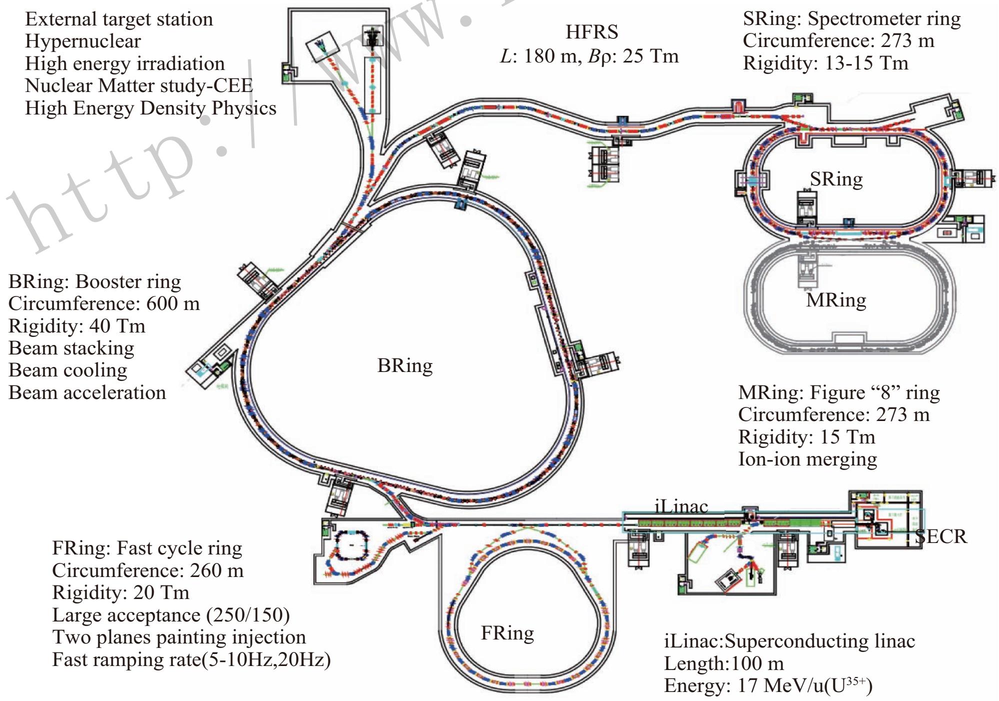

Fig. 1 (color online) Schematic drawing of HIAF.

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ing electron cyclotron resonance source (SECR); the pre-accelerated particles from the linear accelerator iLinac and the fast cycle ring (FRing) are injected into the booster ring (BRing), where the beam is further accelerated, cooled and accumulated. With the secondary beam line HIAF FRagment Separator (HFRS), high intensity radioactive beams can be available in the spectrometer ring (SRing). Thus properties, such as atomic masses, structures and dynamics of various exotic isotopes, can be investigated. The Figure "8" ring, composed of SRing and MRing, allows the coasting beam to be merged with itself at the the intersection point. This unique feature will enable studies of the highly-charged atomic physics. With the maximum rigidity of $B\rho = 40$ Tm the BRing is able to provide a proton beam with a momentum up to 11.9 GeV/c, which bears great potential for nuclear and hadron physics in the GeV region. In particular, much more abundant research programmes could be expected if the target and/or beam at the BRing are polarized. In this paper we propose to build a polarized internal gas target for a spin-physics research at the HIAF-BRing.

In the following, some possible physics programs which can be carried out with polarized reactants at HIAF-BRing are discussed first. The principle of the internal polarized gas target is presented in section 3. The possibility of developing a polarized ion source based on a polarized target is discussed briefly afterwards. A summary and an outlook is given in the last part.

2 Physics significance

Spin is an intrinsic property of subatomic particles as mass and charge, which plays a significant rule in generating the dynamics that drive the microscopic processes. Consequently, most experimental spectra contain the spin information and, therefore, one can investigate the spin itself and how it influences the dynamics underlying via spectroscopic studies of experimental data. For instance, the spin of a resonance in a two-body scattering can be determined from the characteristic structure (*i.e.*, the number of the dips) of the differential cross section. However, much more information on spin dynamics are difficult (even impossible) to learn merely from the unpolarized cross section since the contributions from different spin states are mixed. To disentangle the mixture one needs to perform polarized experiments, where the initial states are prepared in definite spin states, or/and the polarizations of the final states are measured.

One good example that highlights the significance of the polarized experiment is the nucleon-nucleon (NN) scattering. The main purpose of the NN scattering experiment is to study the nuclear force, which is encoded in terms of the scattering amplitudes[2]. Starting from a particular theoretic model, a set of amplitudes can be calculated; on the other hand, the amplitudes are extracted from the experimental data by the phase-shift analyses (PSA). In this sense, the amplitudes connect theory and experiment. They are the testing ground of our understanding of the nuclear force. In addition, the NN amplitudes are the key input quantities in describing the nuclear many-body system and the meson production in the NN collision. Through decades of efforts by many laboratories, a wealth of NN data have been accumulated. Databases such as NN-Online[3] and SAID[4] were set up to maintain and analyse these data. Fig. 2 shows the abundance plots of the existing NN data in terms of the beam kinetic energy and the scattering angle in

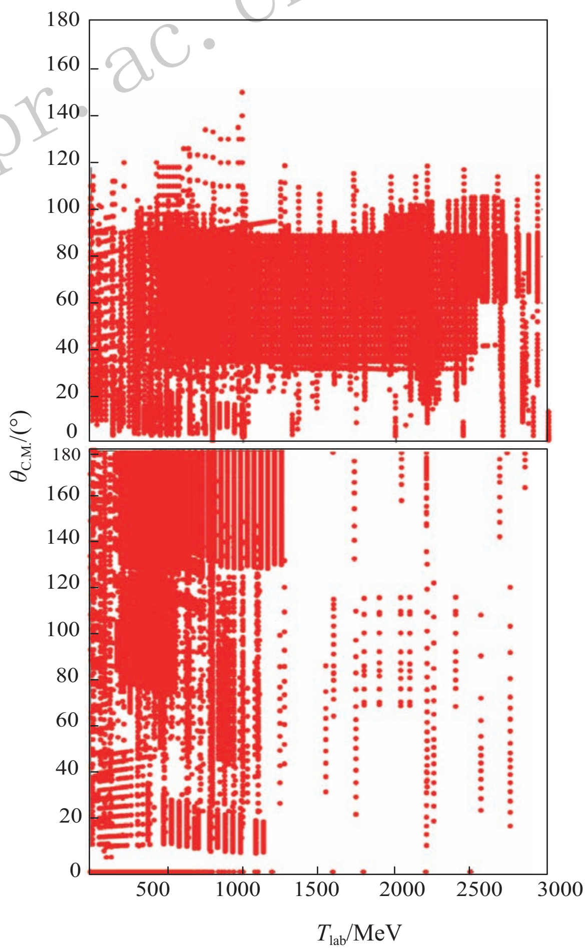

Fig. 2　(color online) Abundance plots of the experimental data on pp (upper) and np (lower) scattering, in terms of the nucleon kinetic energy $T_{\rm lab}$ in laboratory reference and the scattering angle θ. Both polarized and unpolarized observables are plotted.

the center-of-mass reference. Currently, the pp data have been measured up to about 2.8 GeV, which is far from sufficient. Due to the difficulties in preparing neutron beams and targets, the data of neutron-proton (np) scattering are even more rare. If an internal-target experiment setup is developed with polarized target and beam at the BRing, the NN scattering data can be measured up to 11 GeV, which will dramatically advance the study of the nuclear force. Besides, the baryon spectrum and the dibaryon states can be investigated as well at BRing via polarized NN collisions.

The polarized experiment is an effective tool in the symmetry studies. For example, the parity violation was experimentally verified in the beta decay of polarized ^{60}Co[5].

A nonnegligible advantage of the polarized experiment associates with the spin dynamics of the polarized beams[6]. The correlation between the energy and the frequency of the spin precession of a particle in a storage ring allows to determine the beam energy with extremely high accuracy. This application has been proven to be very successful at both electron[7−10] and hadron[11] accelerators.

We emphasis that the physics at the HIAF-BRing should not be limited to these presented in this paper. For instance the charm physics might be accessible if the rigidity of the BRing can be increased to 40.6 Tm. A concrete physics-program list is expected as a result of an in-depth pre-research.

3 Principle of the polarized internal target

A comprehensive review of the polarized internal target has been given by E. Steffens and H. Haeberli[12]. In this section the basic principle is introduced briefly for hydrogen and can be generalized to deuterium.

Polarization is a matter of spin manipulation by means of the electromagnetic fields. In order to take advantages of the large magnetic moment associated with the electron spin, the hydrogen molecules are first dissociated into atoms through radio-frequency (rf) discharge[13]. A hydrogen atom is a bound system of one proton and one electron, whose spins are aligned either parallel ($F=1$) or antiparallel ($F=0$). Corresponding to these spin alignments the hydrogen atom can be found in two different hyperfine states, whose energy difference is $\Delta E=1\,420$ MHz. In the presence of an external magnetic field $\boldsymbol{B}$ the hyperfine states are further split into four energy eigen states due to the Zeeman effect. In the so-called Breit-Rabi representation $|m_\mathrm{e}, m_\mathrm{I}\rangle$ defined in terms of the spin projections of the electron (m_e) and the proton (m_I) along the magnetic field, the Zeeman states are expressed as

$$\begin{aligned}
|1\rangle &= \left|\frac{1}{2},\frac{1}{2}\right\rangle,\\
|2\rangle &= \cos\theta\left|\frac{1}{2},-\frac{1}{2}\right\rangle+\sin\theta\left|-\frac{1}{2},\frac{1}{2}\right\rangle,\\
|3\rangle &= \left|-\frac{1}{2},-\frac{1}{2}\right\rangle,\\
|4\rangle &= -\sin\theta\left|\frac{1}{2},-\frac{1}{2}\right\rangle+\cos\theta\left|-\frac{1}{2},\frac{1}{2}\right\rangle,
\end{aligned} \tag{1}$$

where the mixing angle between the energy representation and the Breit-Rabi representation is determined by the external magnetic field as $\theta=\frac{1}{2}\operatorname{arccot}(B/B_\mathrm{crit})$, with $B_\mathrm{crit}=50.7$ mT being the critical magnetic field for the hydrogen atom. In Fig. 3 the energies of the Zeeman states are plotted as functions of the magnetic field. The states $|1\rangle$, $|2\rangle$ and $|3\rangle$ belong to the triplet ($F=1$) and the state $|4\rangle$ belongs to the singlet ($F=0$) in a weak field ($B \ll B_\mathrm{crit}$), where the spins of the electron and the proton are coupled together hence the total spin F is a good quantum number. With increasing external magnetic field, the coupling will be destroyed.

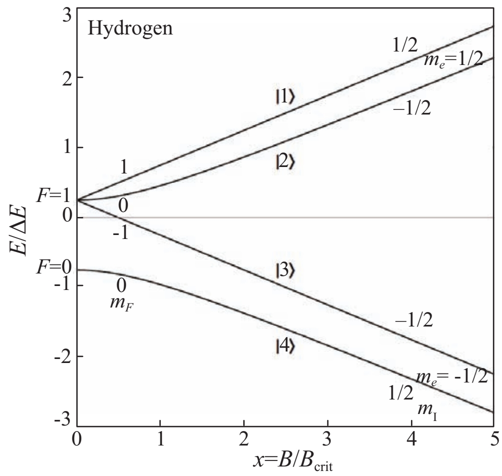

Fig. 3 The Breit-Rabi diagram of the hydrogen atom. The magnetic field and the energy are normalized by the critic field $B_\mathrm{crit}=50.7$ mT and the hyperfine splitting energy $\Delta E=5.87\times10^{-6}$ eV.

Fig. 4 shows the dependence of the nuclear polarization on the external magnetic field for each Zeeman state. Note for the two superposed states $|2\rangle$ and $|4\rangle$, the polarization varies with the external field. To polarize an ensemble of hydrogen atoms one needs to manipulate the spins of the atoms so that the four Zeeman states are not equally populated. Two techniques are employed for the spin manipulation in the polarized gas target, namely Stern-Gerlach spin separation and rf-induced spin transition.

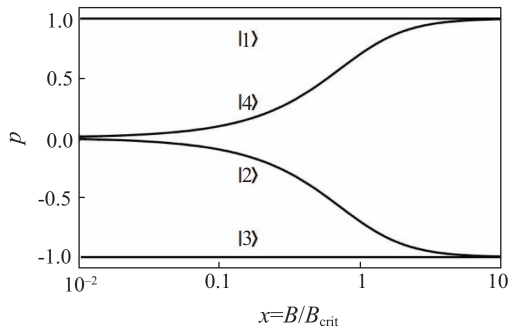

Fig. 4 The nuclear polarization $\left(p=\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}\right)$ of each Zeeman state. Here $n_\uparrow$ and $n_\downarrow$ denote the number of particles with spin up and down.

The Stern-Gerlach type spin separator is a set of sextuple magnets, whose magnetic fields are cylindrically symmetric but inhomogeneous with respect to the radius. As shown in Fig. 5, in an inhomogeneous magnetic field, a force $\boldsymbol{F}=-\nabla E$ will influence a particle with a magnetic moment. Therefore, when passing through the sextuple magnets, the atoms in the states $|3\rangle$ and $|4\rangle$ will be deflected out of the beam axis, while those at states $|1\rangle$ and $|2\rangle$ are focused on the axis.

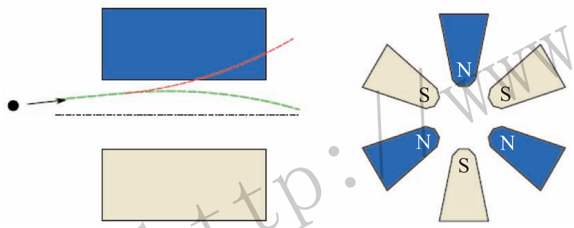

Fig. 5 (color online) The principle of the Stern-Gerlach type spin separation. The magnetic field within the aperture distributes as $B = kr^2$, where r is the radius and k is constant. The force on a magnetic moment $\boldsymbol{u}$, *i.e.* $\boldsymbol{F}=-\nabla E=-\nabla \boldsymbol{\mu}\cdot\boldsymbol{B}$, is dominated by the alignment of $\boldsymbol{u}$ with respect to $\boldsymbol{B}$.

Transitions between different Zeeman states are realized by the adiabatic passage method[14], where one rf magnetic field B_{rf} and one static gradient magnetic field B_{grad} varying from $B_0+\delta B$ to $B_0-\delta B$ are employed. Although the whole process is described exactly by a quantum solution[15–17], it is more intuitive to be explained in a classic scenario[18]. As illustrated in Fig. 6, the rf magnetic field B_{rf} oscillating with a frequency ω can be viewed as one counterclockwise rotating field B_+ and one clockwise rotating field B_-, both with the angular velocity ω. In the reference frame, which co-rotates with B_+, B_+ becomes a static homogeneous field B_{hom}, and B_- rotates clockwise with an angular velocity 2ω. B_- can be ignored because it is far beyond the resonance. The static gradient field B_{grad} varies along the beam direction from $+\delta B$ to $-\delta B$. If the maximum value of the gradient field δB is much larger than the homogeneous field B_{hom}, the combined field (indicated in green) gets reversed. Suppose a particle with spin travelling through the magnetic field. If the combined field varies with an angular velocity much smaller than the spin precession angular velocity, the spin will follow the external field thus gets flipped. By adjusting the parameters ω, δB, B, interchange between different Zeeman states can be realized. According the strength of the magnetic field B_0 the rf transitions can be classified into three types:

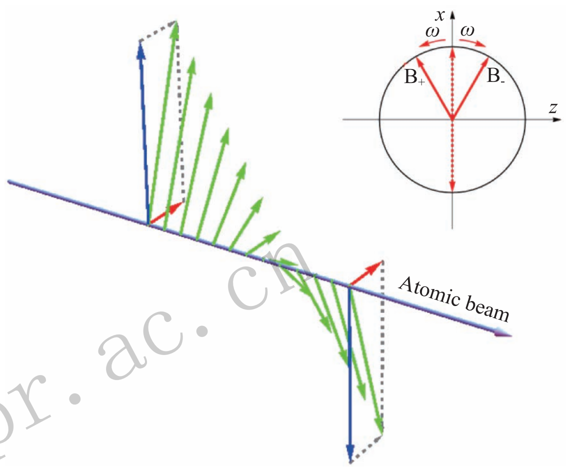

Fig. 6 (color online) Classical explanation of the adiabatic passage method.

(1) WFT (Weak-field transition, $B_0 \ll B_{crit}$): in very weak fields the Zeeman states within one triplet are nearly equidistant on the Breit-Rabi diagram (refer Fig. 3). The rf frequency is adjusted to match the energy split between the neighboring Zeeman states, so that transitions between all the pairs of neighboring states take place simultaneously. In this way, the transitions between non-neighboring states are realized. Via WFT, the interchange between Zeeman states $|1\rangle$ and $|3\rangle$, *i.e.* $1 \leftrightarrow 3$, occurs for hydrogen.

(2) MFT (Medium-field transition, $B_0 < B_{crit}$): the MFTs are operated in magnetic fields where the energy splits of different neighboring pairs are well distinguished, therefore transitions between neighboring Zeeman components are induced. Typical transitions are $1 \leftrightarrow 2$ and $2 \leftrightarrow 3$ for hydrogen.

(3) SFT (Strong-field transition, $B_0 \geqslant B_{crit}$): since the electron-proton spin coupling is broken in this case, the SFTs are able to induce transitions between the states of different multiplets. The most commonly used strong-field transition is $1 \leftrightarrow 4$ for hydrogen.

By means of proper combinations of sextuple magnets and rf transitions, various polarization modes can be prepared. Fig. 7 illustrates a configuration which is widely adopted in the existing polarized atomic beam sources[19–22]. By switching off and on the weak-field transition (WFT) polarized atomic beams of Zeeman states 1 and 3, which correspond respectively to nuclear polarizations +1 and −1, are produced. Note the states 1 and 3 are pure states thus their polarization does not depend on external fileds. Besides, the rf transitions do not affect the beam intensity. Therefore, fast polarization switches between different target modes with identical target thickness can be achieved. These features are crucial for in-beam experiments.

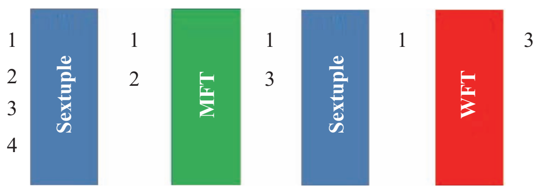

Fig. 7 (color online) An illustrative diagram for the production of the polarized hydrogen atomic beams. Two sets of sextuple magnets are used to filter out the Zeeman states $|3\rangle$ and $|4\rangle$ with negative electron spin. The rf transitions MFT and WFT are adjusted to induce interchanges $2 \leftrightarrow 3$ and $1 \leftrightarrow 3$. Nuclear polarizations +1 and −1 can be selected by switching the WFT.

For reactions with sufficiently large cross sections the free atomic jet can be used as a target directly[23]. However in most cases a storage cell[24] has to be used to increase the effective target thickness. To optimize the settings of the rf transitions, a polarimeter is needed to monitor the polarizations when tuning the atomic beam source. The Lamb-shift type[25] and the Breit-Rabi type[26] polarimeters are usual options.

4 From polarized target to polarized ion-source

Double polarized experiments are favourable since more options will be available with various beam-target combinations. By ionizing the polarized atoms nuclearly-polarized ions will be produced for acceleration. To preserve the nuclear polarization the ionization has to be performed in a magnetic field which is strong enough to decouple the spins of the electron and the proton ($B > 200$ mT for hydrogen). Positively charged particles can be produced by removing the orbit electrons via impact with free electrons or the quasi-neutral electrons in plasma[27]. For beam stacking in high-energy storage rings like the HIAF-BRing a striping injection is advantageous, because it is able to overcome the limitation on the beam intensity imposed by the Liouville′s theorem[28] and, therefore, negatively-charged ion sources are preferred. Negatively-charged ions (H^-) can be obtained through resonant charge-exchange collisions between neutral atoms (H^0) and certain particles. Commonly used particles for such charge-exchange collisions are D^- in the deuterium plasma[29] and Cs^0, an atomic cesium beam[30].

For the polarized beam acceleration, special care needs to be taken to avoid any depolarization as well as to achieve various polarization modes[6].

5 Summary and outlook

The future facility HIAF will provide new opportunities for atomic, nuclear and hadronic physics. Its boost ring (BRing) is an ideal machine to host internal-target experiments. We propose to build a polarized internal target at the HIAF-BRing for spin physics. A pre-research, which aims to investigate the possible physics studies and to set up a solid procedure to build a polarized internal target, has been supported by the CAS “Light of West China” program. Both international and domestic collaborations are demanded to promote the program.

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References:

[1] ZHAO H W, YANG J C. Status and Challenges of High Intensity heavy-ion Accelerator Facility (HIAF) in China, talk presented at HB2016, https://hb2016.esss.se/prepress/talks/mopm2p90_talk.pdf
[2] MACGREGOR M H, MORAVCSIK M J, STAPP H P. Annu Rev Nucl Sci, 1960, **10**: 291.
[3] http://nn-online.org
[4] ARNDT R A, STRAKOVSKV I I, WORKMAN R L. Phys Rev C, 2000, **62**: 034005, http://gwdac.phys.gwu.edu
[5] WU C S, AMBLER E, HAYWARD R W, *et al.* Phys Rev, 1957, **105**: 1413.
[6] LEE S Y. Spin Dynamics and Snakes in Synchrotrons[M]. Singapore: World Scientific, 1997.
[7] AULCHENKO V M, BALASHOV S A, BALDIN E M, *et al.* Phys Lett B, 2003, **573**: 63.
[8] BARBER D P, BREMER H D, KEWISCH J, *et al.* Phys Lett B, 1984, **135**: 498.
[9] MACKAY W W, HASSARD J F, GILES R T, *et al.* Phys Rev D, 1984, **29**: 2483.
[10] ARNAUDON L, KNUDSEN L, KOUTCHOUK J P, *et al.* Phys Lett B, 1992, **284**: 431.
[11] GOSLAWSKI P, KHOUKAZ A, GEBEL R, *et al.* Phys Rev ST-AB, 2010, **13**: 022803.

[12] STEFFENS E, HAEBERLI W. Rep Prog Phys, 2003, **66**: 1887.
[13] KOCH N, STEFFENS E. Rev Sci Instr, 1999, **70**: 1631.
[14] ABRAGAM A, WINTER J M. Phys Rev Lett, 1958, **1**: 374.
[15] OH S. Nucl Instr Meth, 1970, **82**: 189.
[16] BEIJERS J P M. Nucl Instr Meth A, 2005, **536**: 282.
[17] SCHIECK H PAETZ GEN. Nucl Instr Meth A, 2008, **587**: 213.
[18] HAEBERLI W. Annu Rev Nucl Sci, 1967, **17**: 373.
[19] WISE T, ROBERTS A D, HAEBERLI W. Nucl Instr Meth A, 1993, **336**: 410.
[20] BYUG M V, ISAEVA L G, LAZARENKO B A, *et al.* Nucl Instr Meth A, 2002, **495**: 8.
[21] NASS A, BAUMGARTEN C, BRAUN B, *et al.* Nucl Instr Meth A, 2003, **505**: 633.
[22] MIKIRTYCHYANTS M, ENGELS R, GRIGORYEV K, *et al.* Nucl Instr Meth A, 2013, **721**: 83.
[23] ALTMEIER M, BAUER F, BISPLINGHOFF J, *et al.* Phys Rev Lett, 2000, **85**: 1819.
[24] GRIGORYEV K, RATHMANN F, ENGELS R, *et al.* Nucl Instr Meth A, 2009, **599**: 130.
[25] ENGELS R, EMMERICH R, LEY J, *et al.* Rev Sci Instr, 2003, **74**: 4607.
[26] BAUMGARTEN C, BRAUN B, COURT G, *et al.* Nucl Instr Meth A, 2002, **482**: 606.
[27] SCHMELZBACH P A. KEK Report, 1990, **90-15**: 329.
[28] WEIDMANN R, GLOMBIK A, MEYER H, *et al.* Rev Sci Instr, 1996, **67**: 1357.
[29] BELOV A S. AIP Conf Proc, 2008, **980**: 209.
[30] EGGERT M, SCHIECK H PAETZ GEN. Nucl Instr Meth A, 2000, **453**: 514.

关于在 HIAF-BRing 上开展自旋物理研究的提议

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摘要: 国家重大科技基础设施“强流重离子加速器装置”(High Intensity heavy-ion Accelerator Facility，HIAF) 已由国家发改委批准立项并开始建设。建成之后，HIAF将为微观物质结构和重离子应用等研究提供很好的实验平台。HIAF 的加速储存环 (Booster Ring，BRing) 设计可以加速最高动量为 11.9 GeV/c 的高流强质子束流。因此，HIAF-BRing 将为 GeV 能区的核物理和强子物理研究带来新的机遇。另一方面，极化实验是研究微观物质及其相互作用的有力工具。我们提议启动相关物理和极化技术的预研工作，为在 HIAF-BRing 上开展自旋物理研究打下基础。

关键词: 极化内靶；HIAF-BRing；自旋物理

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