

Breakup corrections to spin asymmetries in the ^3He beam polarization measurements with the Polarized Atomic Hydrogen Gas Jet Target

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The requirements for hadron polarimetry at the future Electron-Ion Collider (EIC) include measurements of the absolute helion (^3He , h) beam polarization with systematic uncertainties better than $\sigma_p^{\text{sys}}/P \leq 1\%$. Recently, it was proposed that the Polarized Atomic Hydrogen Gas Jet Target (HJET) be utilized for the precision measurement of the polarization of the ≈ 100 GeV/ n helion beam. At the Relativistic Heavy Ion Collider, HJET serves to determine the absolute proton beam polarization with low systematic uncertainties of about $\delta^{\text{sys}}P/P \lesssim 0.5\%$. To adapt the HJET method for the EIC helion beam, the experimentally determined ratio of the beam and target (jet) spin-correlated asymmetries should be adjusted by the ratio of $p^\uparrow h$ and $h^\uparrow p$ analyzing powers. A potential problem with the suggested method is that the breakup of ^3He in polarization measurements could drastically affect the analyzing power ratio. However, an analysis of the breakup corrections, presented in this paper, reveals that while these corrections can be as substantial as $\approx 4\%$, the effect cancels out to a negligible level in the measured beam polarization.

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I. INTRODUCTION

The physics program requirements [1] for hadron polarimetry at the Electron-Ion Collider (EIC) [2] include the precise determination of the ^3He ($A_h = 3$, $Z_h = 2$) beam polarization,

$$\sigma_p^{\text{sys}}/P \lesssim 1\%. \quad (1)$$

It has been advocated [3,4] that the Atomic Polarized Hydrogen Gas Jet Target (HJET) [5] can be used for this purpose.

In the Relativistic Heavy Ion Collider, HJET is employed to measure the absolute transverse (vertical) polarization of the proton beams with a low systematic uncertainty of about $\sigma_p^{\text{sys}}/P \lesssim 0.5\%$ [6]. Recoil protons from the RHIC beam scattering off the jet target are counted in left-right symmetric Si strip detectors. The HJET geometry predetermines the detection of the recoil protons only in the Coulomb-nuclear interference (CNI) scattering constrained by

$$0.0013 < -t < 0.018 \text{ GeV}^2. \quad (2)$$

The Lorentz-invariant momentum transfer t can be simply related to the recoil proton energy T_R ,

$$-t = 2m_p T_R, \quad (3)$$

where m_p is the recoil particle (proton) mass.

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The ^3He beam polarization P_h can be related [3] to the precisely known jet target polarization, $P_{\text{jet}} \approx 0.96 \pm 0.001$ [5], as

$$P_{\text{meas}}(T_R) = P_{\text{jet}} \frac{a_{\text{beam}}(T_R)}{a_{\text{jet}}(T_R)} \mathcal{R}_h(T_R), \quad (4)$$

where $a_{\text{beam}}(T_R)$ and $a_{\text{jet}}(T_R)$ are experimentally determined beam and target (jet) spin asymmetries [6], respectively. The ratio of the proton ($p^\uparrow h$) and helion ($h^\uparrow p$) spin analyzing powers [7] is denoted by

$$\mathcal{R}_h(T_R) = \frac{A_N^{ph}(T_R)}{A_N^{hp}(T_R)} = \frac{\kappa_p - 2I_5^{ph} - 2R_5^{ph} T_R/T_c}{\kappa_h - 2I_5^{hp} - 2R_5^{hp} T_R/T_c}, \quad (5)$$

where $\kappa_p = \mu_p - 1 = 1.793$ and $\kappa_h = \mu_h/Z_h - m_p/m_h = -1.398$ [8] are derived from the magnetic moments of the proton and helion, $T_c = 4\pi\alpha Z_h/m_p\sigma_{\text{tot}}^{ph} \approx 0.7$ MeV, and σ_{tot}^{ph} is the total ph cross section. The hadronic spin-flip amplitude parameters $r_5 = R_5 + iI_5$ for $p^\uparrow h$ and $h^\uparrow p$ can be calculated [4,9,10] with sufficient accuracy, $r_5^{ph} \approx r_5^{pp}$ and $r_5^{hp} \approx r_5^{pp}/3$, using the proton-proton value r_5^{pp} ($|r_5^{pp}| \approx 0.02$) measured at HJET [11].

For the calculated beam polarization P_h , the systematic errors due to possible uncertainties in values of R_5 and T_c can be eliminated if the measured polarization $P_{\text{meas}}(T_R)$ is extrapolated to $T_R \rightarrow 0$,

$$P_{\text{meas}}(T_R) = P_h[1 + \xi(T_R)], \quad (6)$$

$$\xi(T_R) = \xi_0 + \xi_1 T_R/T_c + \dots \quad (7)$$

The right-hand side of Eq. (5) displays only the leading-order approximation of the interference terms in the

numerator of the CNI elastic analyzing power expression [7]:

$$A_N(t) = \frac{-2 \operatorname{Im} [\phi_5^{\text{em}} \phi_+^{\text{had}*} + \phi_5^{\text{had}} \phi_+^{\text{em}*} + \phi_5^{\text{had}} \phi_+^{\text{had}*}]}{|\phi_+^{\text{had}} + \phi_+^{\text{em}}|^2}. \quad (8)$$

Here, ϕ_5 and ϕ_+ are spin-flip and nonflip helicity amplitudes, the hadronic and electromagnetic parts of which are denoted by “had” and “em.”

^3He breakup in the scattering can effectively alter the (elastic) interference terms

$$\{\operatorname{Im} \phi_5 \phi_+^*\}_I \rightarrow \{\operatorname{Im} \phi_5 \phi_+^*\}_I [1 + \omega_I(T_R)] \quad (9)$$

(schematically discriminated by index I) and, consequently, results in a systematic error in the measured P_h .

A breakup correction,

$$|\phi_+^{\text{had}}|^2 \rightarrow |\phi_+^{\text{had}}|^2 [1 + \omega(t)], \quad (10)$$

to the pd cross section was evaluated in Ref. [4], using experimental data obtained in the unpolarized deuteron d beam measurements in HJET. Extrapolating the result obtained to the ^3He beam scattering, the breakup related systematic error in measured P_h was found to be negligible.

However, it was underlined in Ref. [4] that an oversimplified and unjustified theoretical model was used to interpret the deuteron data and to make the extrapolation. Additionally, some assumptions used in the data analysis were not reliably verified.

Although the conclusion drawn in Ref. [4] was found to be stable against possible variations of the model used, a more comprehensive analysis is necessary for considering HJET in precision ^3He polarimetry at EIC.

In this paper, the breakup fraction estimated in Ref. [4] is compared with the dp and hp scattering study results in the hydrogen bubble-chamber experiment [12,13]. The HJET and bubble-chamber results were found to be in fair consistency within the experimental accuracy of the measurements. No evidence was found that the breakup fraction given in Ref. [4] was underestimated therein.

Following basic principles of the Glauber theory [14], it can be readily shown that for high-energy polarized proton scattering off a nucleus target, both elastic and breakup, the ratio of hadronic spin-flip and nonflip amplitudes is the same as for $p^\uparrow p$ scattering. It also was found that, for high-energy forward $p^\uparrow h$ and $h^\uparrow p$ scattering, breakup corrections $\omega_I(t)$ to the interference terms $\phi_5^{\text{em}} \phi_+^{\text{had}*}$, $\phi_5^{\text{had}} \phi_+^{\text{em}*}$, $\phi_5^{\text{had}} \phi_+^{\text{had}*}$ are the same, within a relative accuracy of about 10%–20%, as the correction $\omega(t)$ to the cross-section term $|\phi_+^{\text{had}}|^2$.

The analysis carried out here improves the confidence of the conclusion reached in Ref. [4] that the EIC ^3He beam polarization can be measured by HJET with low systematic uncertainty (1).

II. THE BREAKUP FRACTION IN THE HJET ^2H AND ^3He BEAM ELASTIC DATA

A. A model used to isolate the breakup events

Considering the breakup $A(p, p)X$ reaction as elastic scattering of a nucleon cluster in the nucleus off the jet proton, one can relate [4] the missing mass excess $\Delta = m_X - m_A$ to

the recoil proton energy:

$$\Delta = \left(1 - \frac{m^*}{m_A}\right) T_R + p_x \sqrt{\frac{2T_R}{m_p}}, \quad (11)$$

where m^* is the nucleon cluster mass and p_x is the internal motion’s transverse momentum of the cluster in the direction of the detector. Since only low-energy recoil protons ($T_R \lesssim 10 \text{ MeV}$) can be detected at HJET, Δ is much less than m_A . This indicates that the breakup event rate for this process would be strongly suppressed by the phase-space factor.

Obviously, for the deuteron beam, $m^* = m_p$. Assuming that the p_x distribution in a deuteron is given by a unity integral normalized Breit–Wigner function

$$f_{\text{BW}}(p_x, \sigma_p) = \frac{\pi^{-1} \sqrt{2} \sigma_p}{p_x^2 + 2\sigma_p^2}, \quad (12)$$

the $d \rightarrow pn$ breakup fraction $\omega(T_R, \Delta)$ can be found [4] as a convolution of the Δ distribution, calculated in accordance with Eq. (11), and the phase-space integral (calculated as a function of Δ),

$$\begin{aligned} \omega(T_R, \Delta) &= \frac{d^2 \sigma_{\text{brk}}(T_R, \Delta)}{d\sigma_{\text{el}}(T_R) d\Delta} \\ &= \frac{\sqrt{2m_p m_n}}{4\pi m_d} |\bar{\psi}(T_R, \Delta)|^2 f_{\text{BW}} \\ &\quad \times (\Delta - \Delta_0, \sigma_\Delta) \sqrt{\frac{\Delta - \Delta_{\text{thr}}^d}{m_d}}, \end{aligned} \quad (13)$$

$$\Delta_0 = (1 - m_p/m_d) T_R, \quad \sigma_\Delta^2 = 2\sigma_p^2 T_R/m_p. \quad (14)$$

Since the key dependence of the breakup amplitude on T_R and Δ is allocated in the function f_{BW} , $\bar{\psi}(T_R, \Delta)$ should be interpreted as a reduced ratio of the breakup to elastic amplitudes. Therefore, for HJET measurements, i.e., for low T_R and Δ , $\bar{\psi}(T_R, \Delta)$ can be substituted by a constant $\bar{\psi} \equiv \bar{\psi}(0, 0)$. For the $d \rightarrow pn$ breakup, the threshold is $\Delta_{\text{thr}}^d = m_p + m_n - m_d = 2.2 \text{ MeV}$.

Integrating over Δ , one can calculate the breakup fraction $\omega(T_R)$ as a function of the recoil proton energy in the elastic data.

B. The deuteron beam breakup in HJET

In RHIC run 16 deuteron–gold collisions were studied at several beam energies. Since HJET operated in this unpolarized ion run, the deuteron beam breakup fraction was experimentally evaluated. The measurements had been done in the recoil proton kinetic-energy range $2.8 < T_R < 4.2 \text{ MeV}$, and in the data fit, it was estimated [4]:

$$\sigma_p \approx 35 \text{ MeV}, \quad |\bar{\psi}| \approx 5.7. \quad (15)$$

The value of σ_p leads, within the model used, to the following slope of the diffraction cone in the elastic pd scattering:

$$B^{pd} = (1 - m_p/m_d)^2 / 8\sigma_p^2 + B = 37 \text{ GeV}^{-2}, \quad (16)$$

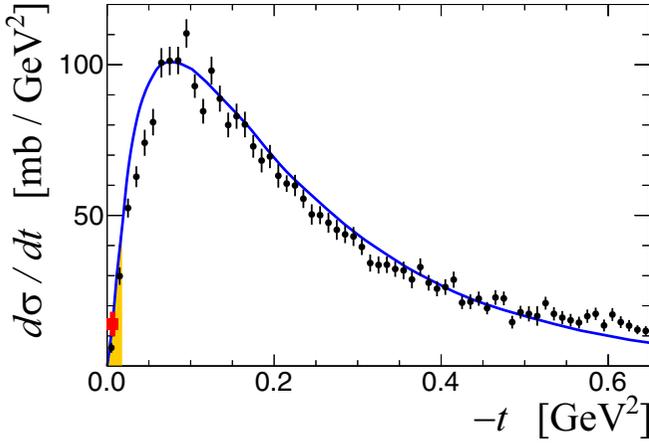


FIG. 1. Differential cross section for the $pd \rightarrow ppn$ breakup scattering. The experimental data (\bullet) and theoretical calculation (solid line) are taken from Ref. [12]. The result evaluated in the HJET measurement [4] is marked \blacksquare . The filled area indicates part of the distribution available for measurement at HJET.

where $B = 11 \text{ GeV}^{-2}$ [15] is the elastic pp slope. The calculation is in reasonable agreement with the experimental values for B^{pd} [16,17].

In the HJET measurements, the breakup fraction in the elastic pd data was estimated [4] as

$$\langle \omega_d(T_R) \rangle_{2.8-4.2 \text{ MeV}} = 5.0 \pm 1.4\%. \quad (17)$$

The value found can be compared with the $pd \rightarrow ppn$ differential cross-section (Fig. 1) measured in 1.8 GeV/nucleon deuteron beam scattering in a hydrogen bubble chamber [12]. Using, for normalization, elastic pd differential cross section [16], Eq. (17) can be rewritten as

$$d\sigma/dt|_{-t=0.0066 \text{ GeV}^2} = 14 \pm 4 \text{ mb/GeV}^2. \quad (18)$$

The result is in good agreement with the final-state interaction model calculation [12], $\approx 15 \text{ mb/GeV}^2$, and in fair consistency with the value, $8 \pm 2 \text{ mb/GeV}^2$, interpolated from experimental points in Fig. 1. It should also be pointed out that only a small fraction, $\approx 1.5\%$, of all $pd \rightarrow ppn$ events can be detected in HJET.

C. The helion beam breakup in HJET

Applying the breakup model and using parametrization (15) for the ${}^3\text{He}$ beam, one can evaluate [4] the breakup fraction for the HJET momentum transfer range

$$\langle \omega(T_R) \rangle_{1-10 \text{ MeV}} = 2.4 \pm 0.4\%, \quad (19)$$

while disregarding the detector acceptance and assuming that, for low t , only two-body breakup $h \rightarrow pd$ is taken into account, as the three-body breakup $h \rightarrow ppn$ is strongly suppressed by a phase-space factor. This result was obtained by substituting $m_d \rightarrow m_h$, $m_n \rightarrow m_d$, and $\Delta_{\text{thr}}^d \rightarrow \Delta_{\text{thr}}^h = 5.5 \text{ MeV}$ in Eqs. (13) and (14).

The breakup fraction $\omega_m(T_R)$, calculated for the 100 GeV/nucleon helion beam and $m^* = m_p$, is depicted in Fig. 2. The nonsmooth dependence of the calculated points on T_R

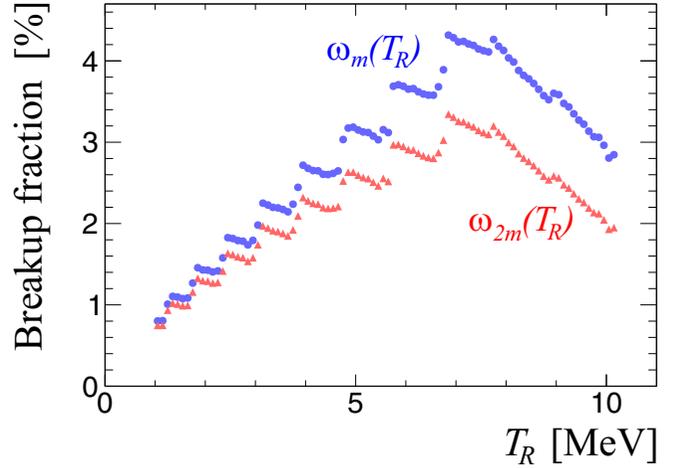


FIG. 2. An estimate of the breakup fractions $\omega(T_R)$, corresponding to $m^* = m_p$ and $m^* = 2m_p$, for 100 GeV/nucleon ${}^3\text{He}$ beam polarization measurement with HJET. For calculations, the function f_{BW} parametrization (15) found in the deuteron beam data analysis [4] was used.

reflects the discrete changes in the event selection efficiency attributed to the Si strip width. Near 7 MeV, the linear dependence on T_R is broken due to the finite size of the detector.

Since, for forward $h \rightarrow pd$ breakup scattering, the ${}^3\text{He}$ approximation by a bound state of proton and deuteron cannot be excluded *a priori*, the breakup fraction $\omega_{2m}(T_R)$ (corresponding to a coherent scattering off two nucleons) should also be considered. Furthermore, the $m^* = 2m_p$ approximation may be relevant, due to the long-distance nature of the Coulomb interaction, for the ϕ_+^{em} breakup amplitudes.

In further analysis, it will be assumed that all of the ${}^3\text{He}$ functions $\omega(T_R)$ and $\omega_I(T_R)$ are constrained by $\omega_m(T_R)$ and $\omega_{2m}(T_R)$. To tolerate a possible discrepancy between ${}^3\text{He}$ breakup corrections, the following function:

$$\Delta\omega(T_R) = \omega_m(T_R) - \omega_{2m}(T_R), \quad (20)$$

will be used.

For a 4.6 GeV/nucleon hp scattering, the elastic, $\sigma_{h \rightarrow h} = 24.2 \pm 1.0 \text{ mb}$, and breakup, $\sigma_{h \rightarrow pd} = 7.29 \pm 0.14 \text{ mb}$ and $\sigma_{h \rightarrow ppn} = 6.90 \pm 0.14 \text{ mb}$, cross sections were determined in the hydrogen bubble-chamber measurements [13]. For the HJET momentum transfer range (2), the effective elastic cross section can be derived from the measured $\sigma_{h \rightarrow h}$:

$$\sigma_{h \rightarrow h}^{\text{HJET}} \approx 11 \text{ mb}. \quad (21)$$

The scattered mass M_X versus momentum transfer t plots (see Fig. 3) for the breakup scattering were presented in Ref. [18]. It may be pointed out that the correlation seen is in a *qualitative* agreement with Eq. (11). It was underlined [18] that the breakup events band is spread around the line

$$M_X^2 = m_h^2 - 2t, \quad (22)$$

which is the same as that followed from Eq. (11) if $m^* = m_p$ and $p_x = 0$.

Each event in Fig. 3 plots contributes nearly 0.003 mb to the corresponding cross section. For $h \rightarrow ppn$, the breakup

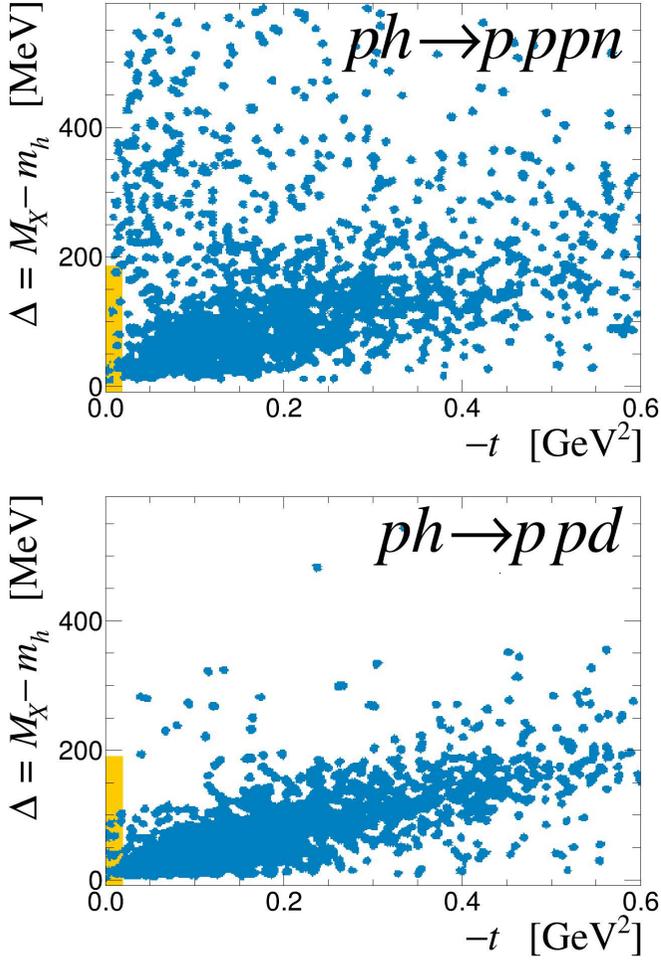


FIG. 3. Scattered mass excess Δ versus momentum transfer plots for helion 4.6 GeV/nucleon charge-retention breakup scattering, $ph \rightarrow pppn$ and $ph \rightarrow ppd$, measured in the hydrogen bubble-chamber experiment [18]. The filled areas indicate part of the distribution that can be studied at HJET.

band events can be counted in the HJET momentum transfer range. After applying corrections due to the recoil proton detection efficiency at low t [19], one arrives at

$$\sigma_{h \rightarrow pppn}^{\text{HJET}} < 0.02 \text{ mb.} \quad (23)$$

Since it is not unreasonable that mainly background events were counted, the result obtained should be interpreted as an upper limit.

Assuming that $h \rightarrow pd$ breakup has a flat $d\sigma/dt$ distribution in the $0 < -t < 0.45 \text{ GeV}^2$ momentum transfer range, one immediately finds $\sigma_{h \rightarrow pd}^{\text{HJET}}/\sigma_{h \rightarrow pd} \approx 0.04$. However, since $\omega(t) \rightarrow 0$ if $t \rightarrow 0$, a correction is needed. Guessing that the correction is the same as for the $h \rightarrow pd$ distribution in Fig. 1, the effective cross-section can be estimated as

$$\sigma_{h \rightarrow pd}^{\text{HJET}} \sim 0.15 \text{ mb.} \quad (24)$$

For comparison, the result displayed in Eq. (19) corresponds to 0.22–0.25 mb depending of value of m^* used.

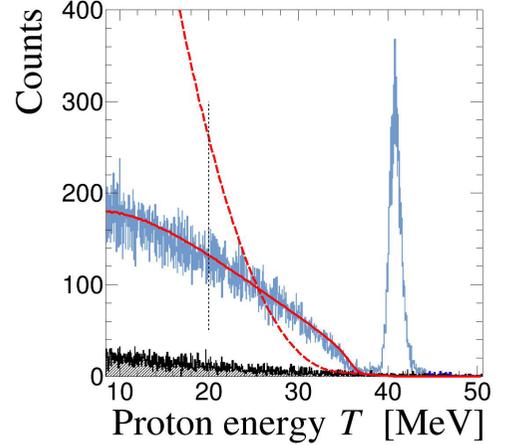


FIG. 4. Light output spectrum of scattered protons obtained by the NaI(Tl) scintillator at $\theta_{\text{lab}} = 70^\circ$ in the 65 MeV $p^3\text{He}$ elastic-scattering study [20]. The hatched region indicates the background contribution. Estimates (done here) for the $h \rightarrow pd$ and $h \rightarrow pppn$ breakup components are shown by solid and dashed red lines, respectively. The calculations were normalized by the total number of the breakup protons with energy above 20 MeV ($\Delta < 24$ MeV).

Thus, the following conclusion comes after Ref. [18]:

- (i) the helion beam breakup events which can be detected at HJET are mostly $h \rightarrow pd$;
- (ii) $\omega_m(T_R)$ depicted in Fig. 2 should be interpreted as an upper limit for the helion beam breakup in HJET.

Another piece of evidence of the $h \rightarrow pppn$ breakup suppression for low Δ follows from the scattered proton energy spectrum (Fig. 4) measured in the 65 MeV proton scattering off the ^3He target [20]. The elastic events are centered at $T_{\text{el}} = 40.8$ MeV. Since energy measured in the breakup scattering can be roughly approached by $T_{\text{brk}} \approx T_{\text{el}} - \Delta$, an evident square root dependence on T at the breakup endpoint should be attributed to the phase space integral, $\propto (\Delta - \Delta_{\text{thr}}^h)^{1/2}$, in the two-body breakup event rate in Eq. (13).

Applying Eqs. (13) and (14) to the $h \rightarrow pd$ breakup and using $\sigma_p = 90$ MeV, one can fairly well approximate the experimental spectrum in Fig. 4. Since low energy, 65 MeV, scattering is considered, the effective values of σ_p and $|\psi|$ may differ from those (15) evaluated in the high energy, 10–31 GeV, pd scattering.

For the three-body breakup, $h \rightarrow pppn$, phase space integral dependence in the event rate (13) is proportional to $(\Delta - \Delta_{\text{thr}}^h)^2$ which makes the calculated spectrum inconsistent with the experimental one. So, there is no evidence of the $h \rightarrow pppn$ events in Fig. 4.

III. HADRONIC SPIN-FLIP AMPLITUDES IN HIGH-ENERGY PROTON-NUCLEUS SCATTERING

In Ref. [9], it was shown that, at high energy, to a very good approximation, the ratio of the spin-flip to the nonflip parts of the elastic proton-nucleus amplitude is the same as for proton-nucleon scattering. In terms of the hadronic spin-flip

amplitude parameter r_5 , the result can be written as

$$r_5^{pA} = \frac{i + \rho^{pA}}{i + \rho^{pp}} r_5 \approx r_5, \quad (25)$$

where ρ^{pA} and ρ^{pp} are the real-to-imaginary ratio for the elastic pA and pp scattering, respectively. This result can be readily derived considering the polarized proton scattering off an unpolarized nucleus in Glauber (diffraction) approximation [14].

In this approach, the elastic ($f = i$) and/or breakup ($f \neq i$) proton-nucleus amplitude can be presented [21] using the following integral over the impact vector \mathbf{b} :

$$F_{fi}(\mathbf{q}) = \frac{ik}{2\pi} \int d^2\mathbf{b} e^{i\mathbf{q}\mathbf{b}} \prod_{j=1}^A d^3\mathbf{r}_j \times \Psi_f^*(\{\mathbf{r}_j\}) \Gamma(\mathbf{b}, s_1 \dots s_A) \Psi_i(\{\mathbf{r}_j\}), \quad (26)$$

where \mathbf{k} is the momentum of the incident proton, Ψ_i and Ψ_f are the nucleus's initial- and final-state wave functions, and $\Gamma(\mathbf{b}, s_1 \dots s_A)$ is the profile function. The positions of the A nucleons in the nucleus were defined by the vectors \mathbf{r}_j , $j = 1, \dots, A$, and s_j are the projections of these vectors on the plane perpendicular to \mathbf{k} .

For a proton-deuteron small angle scattering, the elastic pd amplitude F_{ii} can be approximated [22] by combining the proton-proton f_p and proton-neutron f_n ones as

$$F_{ii}(\mathbf{q}) = S(\mathbf{q}/2) f_n(\mathbf{q}) + S(\mathbf{q}/2) f_p(\mathbf{q}) + \frac{i}{2\pi k} \int S(\mathbf{q}') f_n(\mathbf{q}/2 + \mathbf{q}') f_p(\mathbf{q}/2 - \mathbf{q}') d^2\mathbf{q}', \quad (27)$$

where $S(\mathbf{q})$ can be interpreted as a deuteron form factor.

To calculate the $p^\uparrow d$ spin-flip amplitude F_{ii}^{sf} , one can utilize the proton-nucleon one, $f_N^{\text{sf}}(\mathbf{q})$, which, according to the definition of r_5 [7], is

$$f_N^{\text{sf}}(\mathbf{q}) = \frac{qn}{m_p} \frac{r_5^{pp}}{i + \rho^{pp}} f_N(\mathbf{q}) = qn \hat{r}_5^{pp} f(\mathbf{q}). \quad (28)$$

Since $|r_5^{pp}|q/m_p \lesssim 0.003$ in the HJET measurements, only one nonflip amplitude f_N in each term of Eq. (27) should be replaced by its spin-flip counterpart f_N^{sf} . In particular,

$$f_p f_n \rightarrow [(q/2 + \mathbf{q}') \mathbf{n} f_p f_n + f_p (q/2 - \mathbf{q}') \mathbf{n} f_n] \hat{r}_5^{pp} = qn \hat{r}_5^{pp} f_p f_n. \quad (29)$$

Because each term on the right side of Eq. (27) acquired a factor $qn \hat{r}_5$, one can readily reach Eq. (25).

Generally, elastic pA amplitude can be displayed as

$$F_{ii}(\mathbf{q}) = \sum_i \{S_i f_i\} + \sum_{i,j} \{S_{ij} f_i f_j\} + \sum_{i,j,k} \{S_{ijk} f_i f_j f_k\} + \dots, \quad (30)$$

where, e.g., for the three-amplitude terms,

$$\{S_{ijk} f_i f_j f_k\} = \int S_{ijk}(\mathbf{q}'_i, \mathbf{q}'_j, \mathbf{q}'_k) f_i(\mathbf{q}'_i) f_j(\mathbf{q}'_j) f_k(\mathbf{q}'_k) \times \delta(\mathbf{q} - \mathbf{q}'_i - \mathbf{q}'_j - \mathbf{q}'_k) d^2\mathbf{q}'_i d^2\mathbf{q}'_j d^2\mathbf{q}'_k. \quad (31)$$

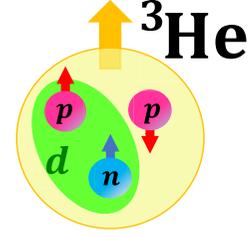


FIG. 5. A polarized ${}^3\text{He}$ spin structure in the ground 1S_0 state. Due to the Pauli principle, the protons are in a spin singlet state. A bound state of the neutron and proton with parallel spins can be approximated by a deuteron.

And similarly for other terms. Thus, no detailed knowledge of the form factor functions $S_{i\dots j}$ is needed to prove Eq. (25).

In the case of unpolarized proton scattering of a fully polarized nucleus with all nucleons having the same polarization P , one can easily find $r_5^{Ap} \cong r_5^{pp} P$. In the case of a space-symmetric distribution of the nucleons, the result is proportional to the average polarization of the nucleons, $r_5^{pA} \cong r_5 \sum P_i/A$. Assuming that ${}^3\text{He}$ nuclei are in a space-symmetric 1S_0 state (Fig. 5), in which the helion spin is carried by the neutron (i.e., $P_n = 1$ and $P_p = 0$), one can find $r_5^{hp} = r_5^{pp}/A_h$ [10]. Small corrections to $P_{n,p}$ due to the 3S_1 and 3D_1 partial waves were evaluated in Ref. [23].

Considering a breakup scattering, e.g., $hp \rightarrow dpp$, one can define the nonflip and spin-flip amplitudes as

$$F_{fi}(\mathbf{q}) = \psi_{fi}(\mathbf{q}) F_{ii}(\mathbf{q}), \quad \psi_{fi}(\mathbf{q}) = |\psi_{fi}(\mathbf{q})| e^{i\varphi_{fi}(\mathbf{q})}, \quad (32)$$

$$F_{fi}^{\text{sf}}(\mathbf{q}) = \frac{qn}{m_p} \frac{\tilde{r}_5}{i + \rho^{pA}} F_{fi}(\mathbf{q}). \quad (33)$$

Here, $F_{fi}(\mathbf{q})$ and $F_{fi}^{\text{sf}}(\mathbf{q})$ are effective breakup amplitudes (for a given value of \mathbf{q}), i.e., sums of all amplitudes over all internal states of the breakup. Therefore, the calculation of probabilities, such as $|F_{fi}|^2$, $|F_{fi}^{\text{sf}}|^2$, and $\text{Im}\{F_{fi}^{\text{sf}} F_{fi}^*\}$ assumes summation over these states.

Since the only difference between elastic and breakup scattering is given [see Eq. (26)] by the final-state wave function Ψ_f , the amplitude expansion (30) should be also valid (with some other set of functions $S_{i\dots j}$) for the breakup scattering. Thus,

$$\tilde{r}_5^{ph} = r_5^{pp} \frac{i + \rho^{ph}}{i + \rho^{pp}}, \quad \tilde{r}_5^{hp} = (1/3 + \delta_{pd}) r_5^{pp} \frac{i + \rho^{ph}}{i + \rho^{pp}}. \quad (34)$$

Considering a single nucleon scattering of an unpolarized proton from the fully polarized helion h^\uparrow in the ground state (see Fig. 5) and assuming that \mathbf{q} is sufficiently large to knock out the target nucleon, one should conclude that the $h \rightarrow pd$ helion breakup can occur only if the beam proton was scattered off the oppositely polarized proton p^\downarrow in ${}^3\text{He}$. Such a speculation suggests that $\tilde{r}_5^{hp} = -r_5^{pp}$ (or $1/3 + \delta_{pd} = -1$).

Even for the relatively large value of $|\delta_{pd}| = 4/3$, the breakup correction to the measured P_h is small [24]. Moreover, since the accordance between the $h \rightarrow pd$ breakup and the beam scattering off the p^\downarrow nucleon should be diluted at low \mathbf{q} , the effect must be much smaller in the HJET measurements.

Following discussion in the next section, one can find $\delta_{pd} = 0$ (if $t \rightarrow 0$) and

$$|\delta_{pd}/r_5^{hp}| \lesssim O(1\%) \quad (35)$$

in the momentum transfer range (2).

IV. EVALUATION OF BREAKUP CORRECTIONS IN HELION BEAM POLARIZATION MEASUREMENTS

A basic assumption of the Glauber theory approach that a high energy beam proton crosses a target nucleus before any changes in the nucleus structure caused by the proton occur, suggests that an electromagnetic interaction is the same for the elastic and breakup scattering. However, to compare the electromagnetic amplitudes for the elastic and breakup scattering, the interaction, in accordance with Eq. (26), should be projected to the final-state wave functions Ψ_h and Ψ_{pd} , respectively. Assuming that the helion disturbance, ${}^3\text{He} \rightarrow {}^3\text{He}^*(\mathbf{q})$, in the scatterings is small, one finds that the reduced breakup to the elastic ratio (13) is the same for the electromagnetic and hadronic as well as for the spin-flip and nonflip amplitudes.

$$\frac{\langle \bar{\Psi}_{pd} | {}^3\text{He}^*(\mathbf{q}) \rangle_{\text{em}}}{\langle \Psi_h | {}^3\text{He}^*(\mathbf{q}) \rangle_{\text{em}}} \approx \frac{\langle \bar{\Psi}_{pd} | {}^3\text{He} \rangle_{\text{em}}}{\langle \Psi_h | {}^3\text{He} \rangle_{\text{em}}} = \frac{\langle \bar{\Psi}_{pd} | {}^3\text{He} \rangle_{\text{had}}}{\langle \Psi_h | {}^3\text{He} \rangle_{\text{had}}} = \bar{\psi}. \quad (36)$$

For example, since function $f_{\text{BW}}(\Delta - \Delta_0, \sigma_\Delta)$ [Eq. (13)] must be the same for the $p^\uparrow h$ hadronic spin-flip and nonflip amplitudes, Eq. (36) immediately leads to $\tilde{r}_5^{ph} = r_5^{ph}$, in agreement with Eqs. (25) and (34).

Would $f_{\text{BW}}(\Delta - \Delta_0, \sigma_\Delta)$ be the same for all amplitudes considered in ratio (5), the breakup correction factors $1 + \omega_I(T_R)$ will cancel in each interference term I in $\mathcal{R}_h(T_R)$. In other words, the breakup corrections cannot affect the ${}^3\text{He}$ beam polarization measurements in such an approach.

In the more general case, the breakup corrections can be modified (diluted) using the median breakup fraction $\omega^*(T_R) = [\omega_m(T_R) + \omega_{2m}(T_R)]/2$:

$$1 + \omega_I(T_R) \rightarrow \frac{1 + \omega_I(T_R)}{1 + \omega^*(T_R)} = 1 + \omega'_I(T_R). \quad (37)$$

Since $\omega'_I(T_R)$ is small, of the order of 1%,

$$|\omega'_I(T_R)| \leq \Delta\omega(T_R)/2. \quad (38)$$

Replacing the real and imaginary parts of r_5^{pp} in Eq. (5) by the absolute value $|r_5^{pp}| \approx 0.02$ and using the above inequality (38), one can find *conservative* estimates for the breakup corrections $\xi(T_R)$ to the measured polarization separately for each interference term:

$$\phi_5^{\text{em}} \phi_+^{\text{had}} : \quad \xi^\kappa(T_R) < \Delta\omega(T_R) \quad (39)$$

$$\approx -0.11\% + 0.13\% \frac{T_R}{T_c}, \quad (40)$$

$$\phi_5^{\text{had}} \phi_+^{\text{em}} : \quad \xi^{ls}(T_R) < \left(\frac{1}{\kappa_p} - \frac{1}{3\kappa_h} \right) |r_5^{pp}| \Delta\omega(T_R) \quad (41)$$

$$\approx -0.002\% + 0.002\% \frac{T_R}{T_c}, \quad (42)$$

$$\phi_5^{\text{had}} \phi_+^{\text{had}} : \quad \xi^{R_5}(T_R) < \left(\frac{1}{\kappa_p} - \frac{1}{3\kappa_h} \right) |r_5^{pp}| \Delta\omega(T_R) \frac{T_R}{T_c} \quad (43)$$

$$\approx -0.08\% + 0.03\% \frac{T_R}{T_c}. \quad (44)$$

For numerical estimates, a linear fit was done in the recoil proton energy range $2 < T_R < 10$ MeV [25].

Relatively loose constraints, $|\xi_0^{R_5}| = 0.08\%$, on possible systematic errors in Eqs. (43), (44) can be explained by the essential nonlinearity of the $\Delta\omega(T_R)T_R/T_c$ function. To improve this, a parabolic function

$$\xi(T_R) \approx \xi_0 + \xi_1 T_R/T_c + \xi_2 (T_R/T_c)^2 \quad (45)$$

can be considered to fit (with $\xi_0 \equiv 0$) $P_{\text{beam}}(T_R)$ in the $2 < T_R < 7$ GeV energy range. In this case, $|\xi_0^{R_5}| \approx 0.02\%$.

V. SUMMARY

In this paper, possible ${}^3\text{He}$ breakup related corrections to the EIC ${}^3\text{He}$ beam polarization measurements with HJET were reviewed.

The breakup fraction in the HJET measurements, evaluated [4] using the deuteron data, was found to be consistent with a value obtained in the hydrogen bubble-chamber experiment [12]. This result proves that, within the experimental accuracy of the measurements [4], (i) the model used to describe the breakup event rate, $dN/dT_R d\Delta$, adequately simulates the experimental data and (ii) the breakup event fraction can be reliably monitored in the HJET measurements using 5–20 GeV ${}^3\text{He}$ beams.

In Ref. [4], the breakup fraction in the future ${}^3\text{He}$ beam polarization measurement at EIC was estimated by extrapolation of the $d \rightarrow pn$ results to the two-body $h \rightarrow pd$ breakup and neglecting the three-body $h \rightarrow ppn$ one. Analyzing experimental distributions displayed in Refs. [18,20], it was confirmed that the $h \rightarrow ppn$ rate is very small in the HJET measurements.

The evaluated [4] ${}^3\text{He}$ breakup rate was compared with the results of the ${}^3\text{He}$ beam scattering in the hydrogen bubble chamber [13,18]. It was found that the functions $\omega(T_R)$ displayed in Fig. 2 should be interpreted as an upper limit for the breakup fraction in the EIC ${}^3\text{He}$ beam scattering in HJET.

It was shown that, within the applicability of the Glauber theory, the ratio of the high-energy proton-nucleus $p^\uparrow A$ breakup spin-flip and nonflip amplitudes is the same as for elastic proton-proton scattering. Both for $p^\uparrow h$ and $h^\uparrow p$ scattering in the HJET momentum transfer range, the ratio of the spin-flip to nonflip amplitude is the same, with a percent accuracy, for the elastic and breakup amplitudes.

It was also found that the breakup corrections to the interference terms $\omega_I(T_R)$ and the cross section $\omega(T_R)$ are about the same within 10%–20% accuracy, which significantly limits possible alteration of the analyzing power ratio (5). Although the corrections $\omega_I(T_R)$ may be as large as 4% (relative), they do not exceed 1% in the analyzing power ratio $\mathcal{R}_h(T_R)$ and are reduced to a negligible level if $P_{\text{meas}}(T_R)$ is extrapolated to $T_R \rightarrow 0$.

Considering the breakup correction cancellation in Eq. (8), it should be concluded that the breakup corrections alter the

effective analyzing powers, $A_N^{ph}(t)$ and A_N^{hp} , in the HJET ^3He beam measurement by no more than 1%. This estimate is also expected to be applicable for the $p^\uparrow A$ analyzing power study [26] at HJET.

Estimates given in Eqs. (39)–(44) verify that the breakup corrections are negligible in the ^3He beam polarization measurements at HJET [4].

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