

Opportunities and challenges of transfer reaction at HIRFL-CSRe*

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Abstract: Opportunities and challenges of performing transfer reactions in inverse kinematics using the $^{16,18}\text{O}$ beams at the experimental Cooler Storage Ring (CSRe) of the Heavy Ion Research Facility in Lanzhou (HIRFL) with the internal gas-jet target are discussed. The kinematics, differential cross sections for various transfer reactions using the $^{16,18}\text{O}$ beam with incident energies of 30 and 100 MeV/nucleon and the H_2 - or D_2 -gas-jet targets are compared. The ^{16}O beam at 100 MeV/nucleon with an intensity of $\geq 10^6$ pps interacting with the H_2 -gas-jet target is recommended as the first transfer reaction at HIRFL-CSRe.

Keywords: transfer reaction, internal gas target, kinematics, differential cross sections

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I. INTRODUCTION

Single-nucleon transfer reactions serve as a powerful probe for studying single-particle structure of nuclei, providing access to extract spectroscopic factors (SFs), spin-parity(J^π), and effective single-particle energies (ESPEs) [1–4]. Additionally, cluster transfer reactions, such as (p, t), ($p, ^3\text{He}$), ($d, ^4\text{He}$), ($d, ^6\text{Li}$), are useful to investigate the nucleon-nucleon correlation and the $2n$ -, d -, and α -cluster structures [5]. We have completed several transfer reaction experiments in inverse kinematics [6–14] using radioactive beams (20–30 MeV/nucleon) impinging on the solid CH_2 and CD_2 targets at Radioactive Ion Beam Line in Lanzhou (RIBLL) [15] and Exotic Nuclei Beam Line (En-course) at Research Center for Nuclear Physics (RCNP), Osaka University [16, 17]. The evolution of intruder s - and d -wave intensities in the $N = 8$ isotones, refer to ^{12}Be , ^{13}B and ^{14}C , were deduced from the single-neutron transfer reactions [8, 9, 12]. Resonances in ^{12}Be and ^{13}B were first observed using the missing mass (MM) method [11, 13], which is a key technique for studying unbound states.

An internal gas-jet target [18] has been established at the experimental Cooler Storage Ring (CSRe) [19] of the Heavy Ion Research Facility in Lanzhou (HIRFL) [20],

enabling direct nuclear reaction experiments at CSRe. The maximum thickness achieved for the H_2 -gas-jet target is 6.6×10^{12} atoms/cm², with a background pressure of 10^{-11} mbar in CSRe. The target thickness is adjustable by controlling the nozzle temperature and inlet gas pressure. Using the H_2 -gas-jet target, the elastic scattering studies of medium-heavy nuclei on protons have been conducted by X.L.Tu's group [21–25]. However, transfer reactions have not been performed at HIRFL-CSRe.

This paper examines the opportunities and challenges of conducting transfer reactions at HIRFL-CSRe, focusing on kinematics, differential cross sections (DCSs), and Q -value resolution for various transfer reactions. The primary beams of ^{16}O and ^{18}O at incident energies of 30 and 100 MeV/nucleon are selected due to their widespread usage and high-intensity production capabilities. Thus, they are good choice for the first transfer reaction at HIRFL-CSRe. Additionally, the spectroscopic factors (SFs) of $^{16,18}\text{O}(p, d)$, (p, t), ($p, ^3\text{He}$) can be extracted by normalizing the experimental differential cross sections to the Distorted Wave Born Approximation (DWBA) calculations. The SFs provide crucial information for investigating the single-neutron strengths in the $^{16,18}\text{O}_{g.s.}$ and the quenching effect in transfer reactions [26], which are fundamentally connected to the nucleon-nucleon correla-

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tions [27]. Furthermore, the relative nn -pairing and np -pairing strengths in $^{16,18}\text{O}_{g.s.}$ can also be probed via the SF ratio between the (p, t) and $(p, ^3\text{He})$ reactions, which may provide insights into the unexpected findings in ^{12}C , referred to as the relative probabilities of pp and nn versus pn in ^{12}C [28].

II. EXPERIMENTAL SETUP AND KINEMATICS

Figure 1 shows the detailed structure of the internal gas-jet target at HIRFL-CSR [18]. To measure transfer reactions, a telescope comprised of a 300- μm double-sided silicon strip detector (DSSD) and two 1500- μm large surface silicon detectors (SSDs) is recommended to place at CF100, which centers at 35° relative to the beam line. Both the DSSD and SSDs share identical dimensions of $64 \times 64 \text{ mm}^2$. This telescope has been effectively utilized in the elastic scattering measurement [21–24]. The angular coverage is $14.5\text{--}55.6^\circ$, $19.2\text{--}50.8^\circ$, and $22.3\text{--}27.7^\circ$ when the telescope is placed 12, 16, and 20 cm from the center of the gas-jet target. The corresponding solid angles are estimated to be 0.28, 0.16, and 0.14 sr, assuming the beam is a point source. To measure the recoil light particles from transfer reaction after comprising the angular resolution and the coverage (acceptance), the distance of 12 cm between the target center and the DSSD center is adopted in the following text.

In principle, the D_2 -gas-jet target can be easily employed in future experiment. Thus, transfer reactions using the D_2 -gas-jet target are also discussed in this paper. For the H_2 - and D_2 -gas-jet targets, the telescope centering at approximately 35° can measure the target-like particles from potential transfer reactions of (p, d) , (p, t) ,

$(p, ^3\text{He})$, (d, t) , $(d, ^3\text{He})$, $(d, ^4\text{He})$ with the $^{16,18}\text{O}$ beam in inverse kinematics. The corresponding kinematics of recoil target-like particles from these reactions are displayed in Figs. 2 and Figs. 3. Shadows in Figs. 2 and Figs. 3 represent the detection ranges when the telescope is placed 12 cm from the gas-jet target center. This detector is incapable of measuring charged particles with energies above 100 MeV/nucleon, as their energy deposition falls below its detection threshold of 0.4 MeV [24]. Kinematics at a higher beam energy of 100 MeV/nucleon (solid curves), currently achievable at CSR, are compared with those at a lower energy of 30 MeV/nucleon (dashed curves), which is planned for future implementation. Although lower-energy beams are easily produced at RIBLL and En-course, these facilities lack pure H_2/D_2 gas targets and 10^6 Hz beam revolution frequency. We found that only part of the transfer reaction events will be measured (shadows), which can be clearly seen in both Figs. 2 and Figs. 3. In most cases only the low-energy branch of recoil particles can be measured with sufficient statistics (typically with statistical error $\leq 10\%$) within a limited beam time after considering the DCSs. Nearly all the low-energy branch events (except the events at angles less than 14°) are in the detection ranges no matter whether the incident energy is 100 or 30 MeV/nucleon.

For the H_2 -jet-gas target, as shown in Fig. 2, the beam energy of 100 MeV/nucleon (solid curves) provides a larger detection range compared to 30 MeV/nucleon (dashed curves) for most reaction channels, particularly for all ^{16}O -induced reactions and the $^{18}\text{O}(p, ^3\text{He})^{16}\text{N}$ reaction. However, the beam energy has little influence on the detection range for the D_2 -jet-gas target, see solid curves comparing to the corresponding dashed curves in Fig. 3.

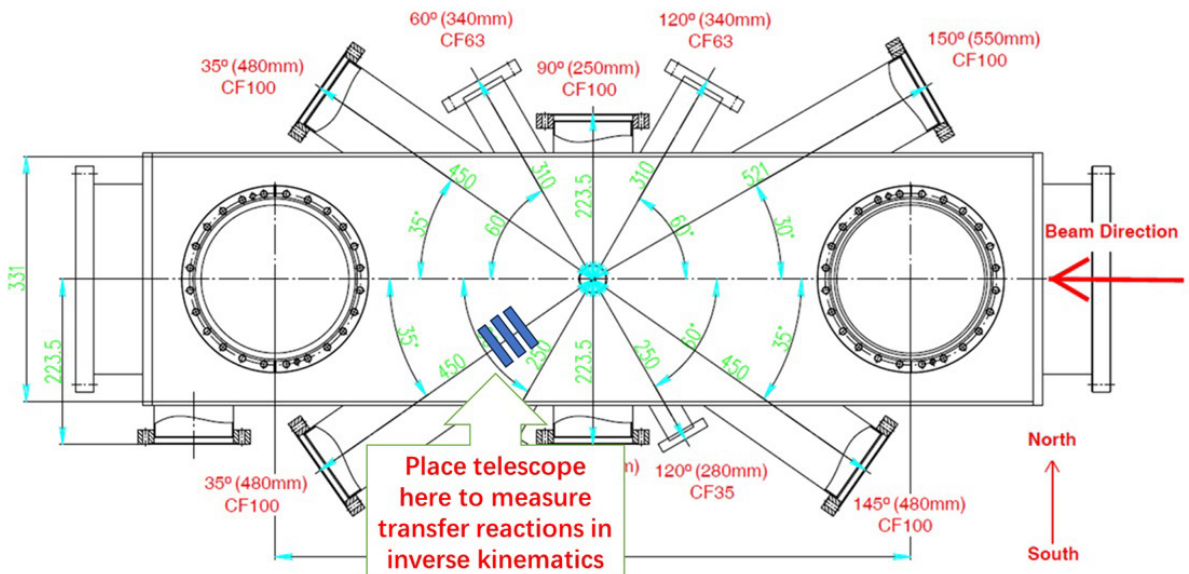


Fig. 1. (color online) Schematic view of the internal gas-jet target at HIRFL-CSR [18]. To measure transfer reactions, a telescope comprised of one DSSD and two SSDs (three blue frames) is installed at CF100 with a centering angle of 35° .

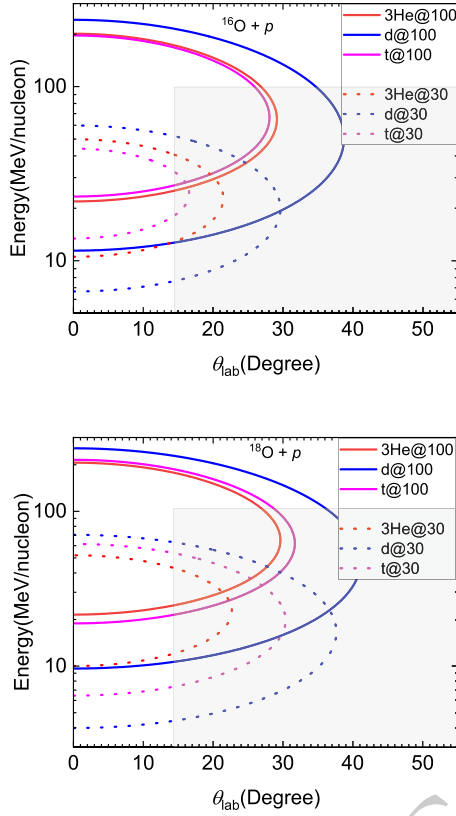


Fig. 2. (color online) Kinematics of the target-like particles emitting from the transfer reactions of $^{16}\text{O} + p$ and $^{18}\text{O} + p$. Shadows represent the detection range of the telescope. The solid and dashed curves stand for the kinematics with beams at incident energies of 100 and 30 MeV/nucleon, respectively.

It may be attributed to the very negative Q -values of $^{16}\text{O}(p, t)^{14}\text{O}$ ($Q = -20.41$ MeV), $^{16}\text{O}(p, ^3\text{He})^{14}\text{N}$ ($Q = -15.24$ MeV), $^{16}\text{O}(p, d)^{15}\text{O}$ ($Q = -13.44$ MeV), $^{18}\text{O}(p, ^3\text{He})^{16}\text{N}$ ($Q = -14.11$ MeV), compared to $^{18}\text{O}(p, t)^{16}\text{O}$ ($Q = -3.71$ MeV) and $^{18}\text{O}(p, d)^{17}\text{O}$ ($Q = -5.82$ MeV), as well as to the relatively lower center-of-mass energy with the proton target in comparison to the deuteron target.

III. DIFFERENTIAL CROSS SECTIONS

Various transfer reaction DCSs of $^{16,18}\text{O}$ on protons and deuterons were calculated in the framework of distorted wave Born approximation (DWBA) with the code of TWOFNR [29]. The global optical potential parameters deduced from the elastic scattering DCSs of a large number of stable nuclei on protons, deuterons, and $A = 3$ nuclei including tritons and ^3He were adopted for the calculations. CH89 [30] and Daehnick [31] were adopted for the entrance channels of transfer reactions on the proton and deuteron targets, respectively. Daehnick [31] was also employed for the exit channel of (p, d) , while GDP08 [32] was applied for the exit channels of (p, t) , $(p, ^3\text{He})$ and $(d, ^3\text{He})$.

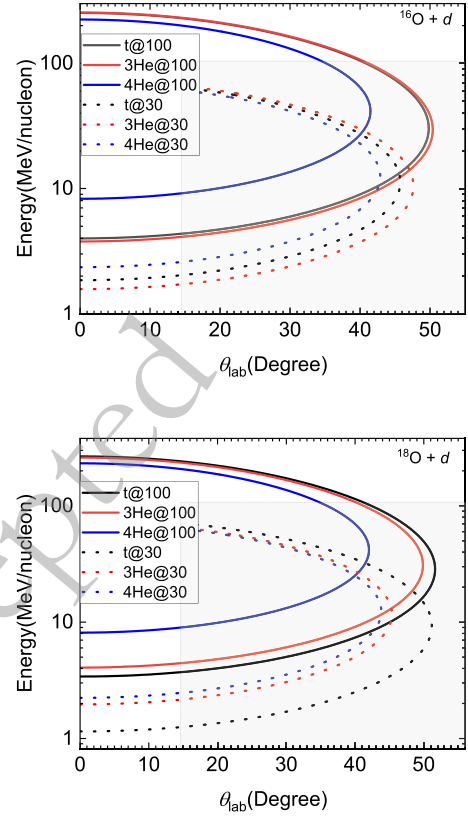


Fig. 3. (color online) Same as Fig. 2, but for the deuteron target.

Only the ground states of the residual nuclei were considered in the calculations of DCSs. For example, only the DCSs of $^{16}\text{O}(p, ^3\text{He})$ to the ground state of ^{14}N ($J^\pi = 1^+$) was calculated. For the single-neutron transfer reactions, referred to as (p, d) and (d, t) , the neutron with angular momentum of $l = 1$ and $l = 2$ was transferred from ^{16}O and ^{18}O to produce ^{15}O ($J^\pi = 1/2^-$) and ^{17}O ($J^\pi = 5/2^+$), respectively. The single proton with the same angular momentum of $l = 1$ was transferred from ^{16}O and ^{18}O to populate the ground state of ^{15}N ($J^\pi = 1/2^-$) and ^{17}N ($J^\pi = 1/2^-$), respectively. For the two-nucleon transfer reactions, both the $2n$ in the (p, t) reaction and the np in the $(p, ^3\text{He})$ reaction were assumed to be a cluster and only the one-step transfer was considered in calculations. The binding potentials of $1n$, $1p$, as well as $2n$ - and np -cluster in $^{16,18}\text{O}$ were assumed to be a Woods-Saxon potential. The geometric parameters of $a = 0.65$ fm and $r = 1.25$ fm were fixed, while the depth of Woods-Saxon potential was adjusted automatically to reproduce the experimental data of binding energies.

The calculation results for various transfer reactions of $^{16,18}\text{O} + p$ and $^{16,18}\text{O} + d$ are displayed in Figs. 4 and Figs. 5, respectively. Note that the DCSs in the laboratory frame for the low-energy branch of recoil target-like particles are depicted. The shaded regions in Figs. 4 and Figs. 5 represent the accepted angular coverage of the

telescope. The laboratory-frame angles are used for following reasons. First, it simplifies the visualization of the detection range for different reaction channels. Second, it is easy to compare the statistics of various reaction channels under identical beam time, target, and solid angles. Third, the maximum angle of each channel (in Figs. 4 and Figs. 5) which is kinematically constrained, is clearly visible.

For the H_2 -gas-jet target, refer to Figs. 4, the DCSs at 100 MeV/nucleon (dashed curves) for both the ^{16}O and the ^{18}O beam are obviously smaller than the corresponding ones at 30 MeV/nucleon (solid curves). However, the maximum angles of target-like particles increase significantly from 30 to 100 MeV/nucleon, resulting in larger angular coverage for transfer reactions. Despite the incident energy is 100 MeV/nucleon, the DCSs at most accepted angles exceed 1 mb/sr, which is required based on the statistical estimations within a limited beam time. For both ^{16}O and ^{18}O , the DCSs of two-nucleon transfer reactions (thick curves), including $(p, {}^3\text{He})$ and (p, t) , are larger than single-nucleon transfer reactions (thin curves) at the same angles. It indicates that protons, deuterons, tritons as well as He isotopes will be measured by the telescope simultaneously. Therefore, particle identification

(PID) is important to discriminate different reaction channels. We also found that, the DCSs of identical reaction channel, such as $(p, {}^3\text{He})$ (red curves), with ^{16}O beam are obviously different from these with ^{18}O beam, which may be due to the transferred cluster occupying different orbitals and having different node numbers.

For the D_2 -gas-jet target, only the DCSs of single-nucleon transfer reactions (d, t) and $(d, {}^3\text{He})$ are plotted in Figs. 5. The DCS shapes for $^{16}\text{O}(d, t)$ and $^{16}\text{O}(d, {}^3\text{He})$ are nearly identical, due to the similar quantum numbers and binding energies of the transferred neutron and proton in ^{16}O . In contrast, the DCS shapes for $^{18}\text{O}(d, t)$ and $^{18}\text{O}(d, {}^3\text{He})$ differ significantly, demonstrating the resolution power of different angular momentum of transfer reaction. Note that the solid and dashed curves in Fig. 5(b) represent the incident energies of 30 and 100 MeV/nucleon, respectively. It seems that angular momentum resolution power at these higher beam energies is comparable to the traditional low-energy measurements in the case of this proposed experiment. Comparing Figs. 5 to Figs. 4, we found that the DCSs are several magnitude lower than those with the H_2 -gas-jet target. Thus, the deuteron target is not recommended for initial transfer reaction experiments at HIRFL-CSRe. If we intend to use it in the future, the incident energy of 30 MeV/nucleon is more preferable than 100 MeV/nucleon, as shown in Figs. 5,

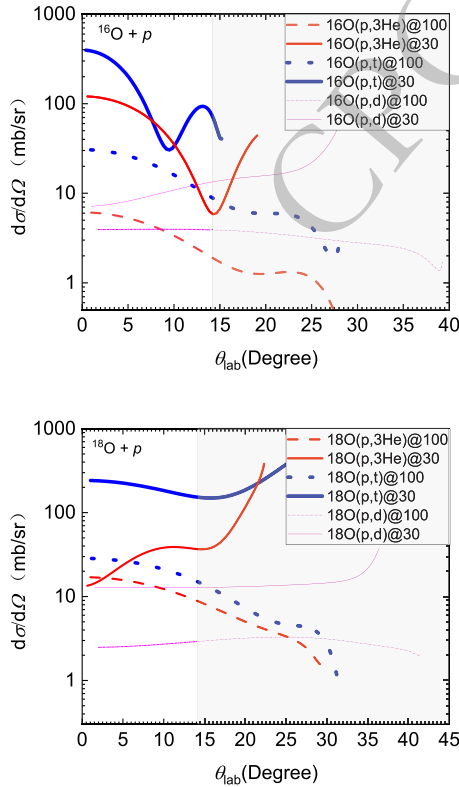


Fig. 4. (color online) The calculated differential cross sections in the laboratory frame for the low-energy branch of the target-like particles recoiling from various transfer reactions. Solid and dashed curves respectively represent two incident energies 30 and 100 MeV/nucleon for both ^{16}O and ^{18}O .

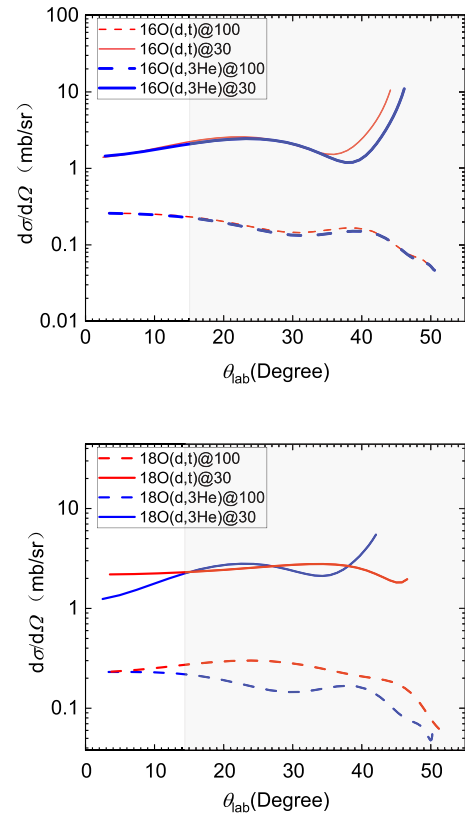


Fig. 5. (color online) Same as Fig. 4, but for the deuteron target.

because the DCSs at most angles exceed 1 mb/sr, which is required by the statistics in a limited beam time.

IV. DISCUSSION

A. Advantages and Feasibility

The primary advantages of performing transfer reaction at HIRFL-CSRe are good resolution of Q -value spectrum and 10^6 Hz revolution frequency of the stored beam ions. According to previous experimental results, the target thickness, the beam energy spread, as well as the energy and angular resolution of detectors contribute the resolution of Q -value spectrum reconstructed from the MM method. The thickness of the internal H_2 -gas-jet target (6.6×10^{12} atom/cm²) is equivalent to the 5.1×10^{-8} -mg/cm² solid CH_2 target. This thickness is eight orders of magnitude lower than the typical CH_2 targets (several mg/cm²) used in our previous experiments, reducing energy losses of recoil target-like particles to the meV level and making their contribution to Q -value resolution negligible. Additionally, the angular dispersion and energy loss of the stored beam ions can be compensated by the electron cooler, allowing the ions to continue circulating in the ring for multi-pass experiments. Therefore, the contribution from the beam ions to the Q -value spectrum can also be ignored. Finally, the detector properties, including energy and angular resolution, are the primary contributors. The simulated Q -value resolutions are listed in Table 1, which are worse than that from elastic scattering [24]. This difference may result from the worse angular resolution of the DSSD and the higher energy of both beam and recoil light charged particles. For instance, a reduction in the incident energy from 100 to 20(30) MeV/nucleon leads to a corresponding decrease in the energy of the recoil charged particle, thereby significantly improving the Q -value resolution for the $^{16}O(p, d)^{15}O$ reaction from 0.67 to 0.14(0.29) MeV. However, these resolutions are sufficient to discriminate the ground states from the first excited states of residual nuclei ^{15}O , ^{14}O and ^{14}N . Moreover, the 10^6 Hz revolution frequency of the stored ions enhances the beam intensity by a factor 10^6 .

Table 2 compares the $^{16}O(p, d)^{15}O$ experiment planned to be performed at HIRFL-CSRe to our previous $^{13}B(p, d)^{12}B$ experiment [12]. Several data points are required to determine the angular distributions, so we intend to integrate the events within 4° as a data point. Under the assumptions of a solid angle of 0.02 sr (4° interval), an average DCS of 1 mb/sr, and a beam intensity of 10^6 pps, one $^{16}O(p, d)^{15}O$ event per hour is expected for each data point. Therefore, 100 hours beam time are required to accumulate 100 events with a statistic error of 10% for each data point. More events can be measured for the $^{16}O(p, t)^{14}O$ and $^{16}O(p, ^3He)^{14}N$ reactions due to the larger DCSs, as shown in Fig. 4. These calculations demonstrate the

Table 1. The simulated resolutions of Q -value spectra reconstructed from the MM method. We assumed that the telescope is placed 12 cm away from the target center, the energy resolution of silicon detector is 1%, and angular resolution of the telescope is deduced from the strip width of 2 mm. The incident energy of ^{16}O is 100 MeV/nucleon.

reaction channels	σ
$^{16}O(p, d)^{15}O$ 100 MeV/nucleon	0.67 MeV
$^{16}O(p, t)^{14}O$ 100 MeV/nucleon	1.05 MeV
$^{16}O(p, ^3He)^{14}N$ 100 MeV/nucleon	1.04 MeV
Elastic scattering[24]	≤ 0.50 MeV

Table 2. Comparing the $^{16}O(p, d)^{15}O$ experiment planned to be performed at HIRFL-CSRe to our previous $^{13}B(p, d)^{12}B$ experiment [12].

	$^{16}O(p, d)^{15}O$	$^{13}B(p, d)^{12}B$ [12]
beam energy(MeV/nucleon)	100	23
beam intensity (pps)	$\geq 10^6 \times 10^6$	2×10^4
target thickness (atomic/cm ²)	6.6×10^{12}	8.71×10^{20}
average DCS (mb/sr)	1.0	1.0
statistic of each point(counts/h)	1.0	2.5

feasibility of transfer reactions using the ^{16}O beam and the ultra-thin internal gas-jet target at HIRFL-CSRe.

B. Challenges

Comparing to our previous experiment, several new challenges must be considered before conducting experiment. First, how to install the telescope closer to the beam line to enhance the angular coverage, such as 12 cm from the gas-jet center? Second, how to determine the emitting angles of target-like particles in the absence of tracking information (no position information of beam ions impinging on the gas-jet target), which will largely affect the Q -value resolution and the solid angles. Third, the CsI(Tl) detector commonly used to measure the residual energy, cannot be employed at HIRFL-CSRe to keep the ultra-high vacuum of storage ring. Thus, higher-energy target-like particles will punch through the silicon detector, complicating the total energy measurement without unambiguous PID. Finally, how to count the beam ions without beam monitor as well as how to measure the thickness of gas-jet target? These two numbers are important for extracting the experimental DCSs of transfer reactions.

To deal with these challenges, the telescope and its frame described in Sec.2 should be improved. We suggest adding a 1500- μ m DSSD behind the 300- μ m DSSD. Two DSSDs in a telescope can track target-like particles to determine their emitting angles. For particles penetrating the telescope, the ΔE - ΔE method will distinguish

$Z = 1$ particles from $Z = 2$ particles. Then, with different particle assumption, we deduce the total energy using the energy losses in the silicon detector and its actual thickness. Finally, particle type will be determined using the χ^2 minimum method, comparing total energy versus angle to the kinematics in Figs. 2 and Figs. 3. Additionally, we need to develop the stopping detectors that can function in the ultra-high vacuum of CSRe. A Schottky pickup is typically employed in storage rings to monitor beam ions. However, determining the luminosity for in-ring reaction measurements remains challenging, owing not only to temporal variations in beam intensity and gas-target density but also to uncertainties in the beam–target overlap [37]. To address this, a dual-measurement approach is often adopted, wherein experimental cross sections are normalized to well-established reference cross sections. In our case, the product of beam ions $\times$ target thickness can be calibrated using either simultaneously measured elastic scattering data [25] or the spectroscopic

factor derived from the single-neutron transfer reaction of ^{16}O via the summing rule [1].

V. SUMMARY

In summary, we have evaluated the feasibility, advantages, and challenges of measuring transfer reactions using the $^{16,18}\text{O}$ beams and the existing internal gas-jet target at HIRFL-CSRe. Key considerations include the target structure, reaction kinematics, differential cross sections, Q -value resolution, and statistical requirements. Based on the above discussion, incident energies of 100 MeV/nucleon for the H_2 target and 30 MeV/nucleon for the D_2 target are recommended to optimize transfer reaction measurements within limited beam time. Considering current experimental conditions, the ^{16}O beam at 100 MeV/nucleon with an intensity larger than 10^6 pps impinging on the H_2 -gas-jet target can be considered as the first attempt of transfer reactions.

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