Abstract

We have designed and constructed a new beam line which can accomplish both lateral and angular dispersion matching with the Grand Raiden spectrometer. In dispersive mode, lateral and angular dispersions of the beam line are $b_{16}=37.1$ m and $b_{26}=-20.0$ rad, respectively, to satisfy matching conditions for Grand Raiden. In achromatic mode, the beam line satisfies the double achromatic condition of $b_{16}=b_{26}=0$. The magnifications of the beam line are $(M_x, M_y) = (-0.98, 0.89)$ and $(1.00, -0.99)$ for dispersive and achromatic modes, respectively. In the commissioning experiments, we have succeeded to separate the first excited $2^+$ state of $^{16}$Er with $E_x=79.8$ keV clearly from the ground state in the $(p,p')$ reaction. We achieved energy resolutions of $\Delta E=13.0\pm0.3$ keV and $16.7\pm0.3$ keV in full width at half maximum for 295 MeV and 392 MeV protons, respectively. These energy resolutions agree with the resolving power of Grand Raiden for an object size of about 1 mm.

1 INTRODUCTION

The magnetic spectrometer Grand Raiden (GR) is the heart of the RCNP ring cyclotron facility. It is characterized by its high resolving power of $D/M_x=37,000$ with the dispersion of $D=15,451$ mm, and can analyze particles with a maximum magnetic rigidity of $B\rho=5.4$ Tm. The intrinsic momentum resolution of GR is given by $\Delta p/p=(M_x/D)x_0$ with the monochromatic beam size $x_0$ on the target. Thus, for $x_0=1$ mm, the momentum resolution becomes $2.7 \times 10^{-5}$ corresponding to an energy resolution of about $14$ keV for $300$ MeV protons. However, the typical energy resolution achieved with GR is about $150$ keV which is mainly governed by the energy spread of the incident beam.

The energy resolution can be improved by lateral dispersion matching between beam line (BL) and GR to compensate for the energy spread of the beam. Following the notation of the computer code TRANSPORT, the position $x$ and the angle $\theta$ in the focal plane (FP) of GR can be described in first order by using $b_{ij}$ and $s_{kl}$ as matrix elements of BL and GR, respectively, as

$$x = x_0(s_{11}b_{11}T + s_{12}b_{21}) + \theta_0(s_{11}b_{12}T + s_{12}b_{22}) + \delta_0(s_{11}b_{16}T + s_{12}b_{26} + s_{16}C) + \Theta(s_{12} + s_{16}K)$$

$$\theta = \frac{x_0(s_{21}b_{21}T + s_{22}b_{21}) + \theta_0(s_{21}b_{12}T + s_{22}b_{22}) + \theta_0(s_{21}b_{16}T + s_{22}b_{26} + s_{26}C) + \Theta(s_{22} + s_{26}K)}{s_{11}b_{11} + s_{12}b_{21} + s_{16}b_{16} + s_{26}b_{26}}$$

where $x_0$, $\theta_0$, and $\delta_0$ are position, angle, and momentum deviations from the central ray at the exit of the ring cyclotron [source point (SP)], respectively. The angle $\Theta$ is the relative scattering angle, $T$ the target function, $C$ the dispersion matching factor, and $K$ the kinematical factor. In the simplest case of zero-degree elastic scattering ($T=1$, $K=0$, and $C=1$), $x$ becomes independent of $\theta_0$ and $\Theta$ if we require a geometrical focus for both BL and GR ($b_{12}=s_{12}=0$). The $\delta_0$ dependence of $x$ can be removed by requiring the dispersion of BL to be $b_{16}=-s_{16}/s_{11}$. Furthermore, $\theta$ can be independent of $\delta_0$ by setting the angular dispersion of BL to be $b_{26}=s_{21}b_{16} - s_{11}b_{26}$. Details for lateral and angular dispersion matching conditions are described in Ref. [1].

2 WS BEAM LINE AT RCNP

We have designed and constructed a new BL (WS-BL) which can accomplish both lateral and angular dispersion matching between BL and GR. The WS-BL can also deliver a double-achromatic beam with zero lateral and angular dispersion ($b_{16}=b_{26}=0$) on targets. Figure 1 shows beam envelopes from SP to the target position for the dispersive mode. In this mode, lateral and angular dispersion of WS-BL is $b_{16}=37.1$ m and $b_{26}=20.0$ rad necessary to satisfy dispersion matching conditions with GR. The magnifications of WS-BL are $(M_x, M_y) = (-0.98, 0.89)$ and $(-1.00, -0.99)$ for dispersive and achromatic modes, respectively. The WS-BL provides two double-focus points for beam line polarimeters (BLP1 and BLP2) in both modes. These two points are separated by a bending angle of $115^\circ$, which enables us to measure the longitudinal components of the polarization vector.
3 MEASUREMENT

3.1 $^{168}$Er$(p, p')$ scattering

Figure 2 shows the excitation energy spectrum for the $^{168}$Er$(p, p')$ scattering at $T_p = 295$ MeV and $\theta_{lab} = 9^\circ$. An enriched $^{168}$Er target with a thickness of 2 mg/cm$^2$ was used. The first excited $2^+$ state of $E_x = 79.8$ keV is clearly separated from the ground state with an energy resolution of $\Delta E = 13.0 \pm 0.3$ keV in FWHM. The ideal value of the energy resolution can be evaluated from the intrinsic momentum resolution given by $|M_x/D|b_{11}\Delta x_0$. Thus, for the typical $\Delta x_0$ value of 1 mm, this value becomes 14 keV for 295 MeV protons which is consistent with the observed value.

We have also measured a spectrum at $T_p = 392$ MeV and $\theta_{lab} = 9^\circ$. In this case the final energy resolution was $16.7 \pm 0.3$ keV in FWHM which is also consistent with the ideal value of 18 keV for 392 MeV protons given by the resolving power limit of the spectrometer.

3.2 $^{nat}$Si$(p, p')$ scattering

Figure 3 shows the excitation energy spectrum of the $^{nat}$Si$(p, p')$ reaction at $T_p = 295$ MeV and $\theta_{lab} = 14^\circ$. A natural silicon target with a thickness of 1.77 mg/cm$^2$ was used. The observed energy resolution is about 19.1 keV as shown in Fig. 3. This is significantly worse compared with the $^{168}$Er spectrum. This is mainly due to the mismatch in the focus in the focal plane and the increase of the effective magnification coming from the kinematical correction factor $K \neq 0$. The $K$ value is $-0.002$ for $^{168}$Er, while that for silicon is about $-0.012$. After the kinematical correction of $s_{12} = -s_{16}K$ realized by shifting the focal plane, $x$ in Eq. (2) depends on $\theta_0$ as $x = 0.19\theta_0$. Thus the beam emittance of $\Delta \theta_0 = 1.1$ mrad contributes to $\Delta x$ with 0.22 mm for $^{nat}$Si. Furthermore, the effective magnification of $s_{11}b_{11}T + s_{12}b_{21}$ becomes larger by a factor of 1.2. The contributions from these two effects to the energy resolu-
The WS beam line consists of six dipole magnets with a total bending angle of 270°. This beam line can be divided into five sections. The beam is focused in both the horizontal and vertical planes at the end of each section. The beamline polarimeter systems are positioned at the ends of first and second sections to measure all polarization components of the beam. They are separated by a bending angle of 115°, allowing the determination of horizontal components of the beam polarization. In dispersive mode, lateral and angular dispersions of the WS beam line are $b_{16}$ = $37.1$ m and $b_{26}$ = $-20.0$ rad, necessary to satisfy dispersion matching conditions for Grand Raiden. The magnifications of the beam line are $(M_x, M_y) = (-0.98, 0.89)$ and $(-1.00, -0.99)$ for dispersive and achromatic modes, respectively.

The performance of the WS beam line was studied by using the faint beam method for the $^{168}$Er($p, p'$) scattering. The WS beam line was successfully tuned to establish complete matching with Grand Raiden. We have succeeded to separate the first excited 2$^+$ state of $^{168}$Er at $E_x$ = $79.8$ keV clearly from the ground state in the ($p, p'$) scattering. The achieved energy resolutions are $\Delta E$ = $13.0 \pm 0.3$ keV and $16.7 \pm 0.3$ keV in FWHM for 295 MeV and 392 MeV protons, respectively. These energy resolutions agree well with the resolving power limit of the high-resolution Grand Raiden spectrometer.

### 5 REFERENCES