HIGH RESOLUTION WS BEAM LINE AT RCNP

T. Wakasa, K. Hatanaka, H. Fujimura, J. Kamiya, T. Kawabata, K. Nagayama, and M. Uraki
Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan
Y. Fujita, H. Fujita, and Y. Shimbara
Department of Physics, Osaka University, Osaka 560-0043, Japan
M. Itoh, H. Sakaguchi, H. Takeda, M. Uchida, and M. Yosoi
Department of Physics, Kyoto University, Kyoto 606-8502, Japan
G. P. A. Berg, Indiana University Cyclotron Facility, Indiana 47405, USA
T. Noro, Department of Physics, Kyushu University, Fukuoka 812-8581, Japan
K. Tamura, Department of Physics, Fukui Medical University, Fukui 910-1193, Japan
H. Ueno, The Institute of Physical and Chemical Research, Saitama 351-0198, Japan

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 ^{168}Er with E_x=79.8 keV clearly from the ground state in the (p, p') reaction. We achieved energy resolutions of ΔE=13.0±0.3 keV and 16.7±0.3 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 2.7×10^{-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 θ 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

$$x = x_0(s_{11}b_{11}T + s_{12}b_{21}) + \theta_0(s_{11}b_{12}T + s_{12}b_{22}) + \delta_0(s_{11}b_{16}T + s_{12}b_{26} + s_{16}C) + \Theta(s_{12} + s_{16}K) \quad (1)$$

$$\theta = x_0(s_{21}b_{11}T + s_{22}b_{21}) + \theta_0(s_{21}b_{12}T + s_{22}b_{22}) + \delta_0(s_{21}b_{16}T + s_{22}b_{26} + s_{26}C) + \Theta(s_{22} + s_{26}K) \quad (2)$$

where x_0, θ_0, and δ_0 are position, angle, and momentum deviations from the central ray at the exit of the ring cyclotron [source point (SP)], respectively. The angle Θ 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 θ_0 and Θ if we require a geometrical focus for both BL and GR (b_{12}=s_{12}=0). The δ_0 dependence of x can be removed by requiring the dispersion of BL to be b_{16}=$-s_{16}/s_{11}$. Furthermore, θ can be independent of δ_0 by setting the angular dispersion of BL to be b_{26}=$s_{21}s_{16} - s_{11}s_{26}$. 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°, which enables us to measure the longitudinal components of the polarization vector.

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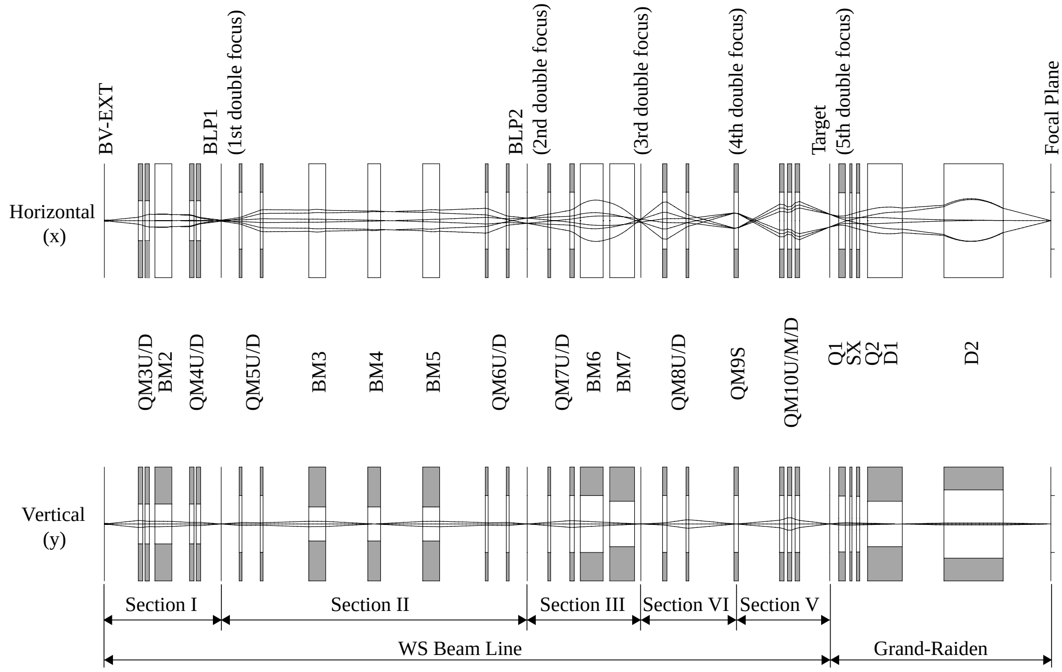

Figure 1: Envelopes of dispersive beam in the horizontal and vertical planes from the object point at the exit of the Ring Cyclotron (BV-EXT) via the target location to the focal plane of the Grand Raiden spectrometer. Trajectories are shown for particles with $\Delta p/p$ = $\pm 0.03\%$, $\Delta\theta$ = ± 2 mrad, and $\Delta\phi$ = ± 2 mrad. The transverse scale is increased for illustration purposes.

3 MEASUREMENT

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

Figure 2 shows the excitation energy spectrum for the $^{168}\mathrm{Er}(p,p')$ scattering at T_p = 295 MeV and $\theta_{\rm lab}$ = 9°. An enriched $^{168}\mathrm{Er}$ target with a thickness of 2 $\mathrm{mg/cm^2}$ 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 ΔE = 13.0±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 Δx_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 $\theta_{\rm lab}$ = 9°. In this case the final energy resolution was 16.7±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.

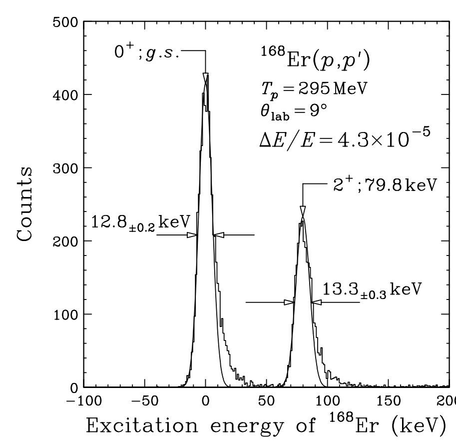

Figure 2: A typical excitation energy spectrum of the $^{168}\mathrm{Er}(p,p')$ scattering at T_p = 295 MeV and $\theta_{\rm lab}$ = 9° measured with the Grand Raiden spectrometer after employing the dispersion matching method.

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

Figure 3 shows the excitation energy spectrum of the $^{\rm nat}\mathrm{Si}(p,p')$ reaction at T_p = 295 MeV and $\theta_{\rm lab}$ = 14°. A natural silicon target with a thickness of 1.77 $\mathrm{mg/cm^2}$ was used. The observed energy resolution is about 19.1 keV as shown in Fig. 3. This is significantly worse compared with the $^{168}\mathrm{Er}$ 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 $^{168}\mathrm{Er}$, 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 θ_0 as x = 0.19θ_0. Thus the beam emittance of $\Delta\theta_0$ = 1.1 mrad contributes to Δx with 0.22 mm for $^{\rm nat}$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-

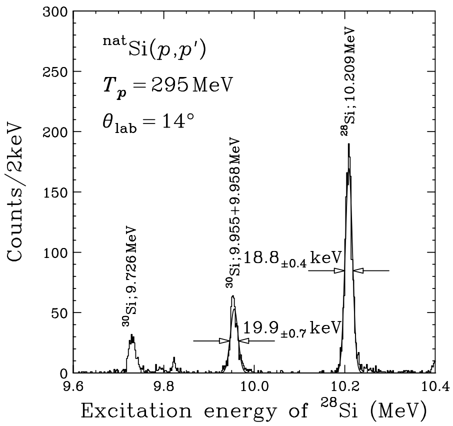

Figure 3: Excitation energy spectrum of the ${}^{\rm nat}{\rm Si}(p,p')$ scattering at T_p = 295 MeV and $\theta_{\rm lab}$ = $14°$ measured with the Grand Raiden spectrometer after employing the dispersion matching method. The overall energy resolution is 19.1 keV FWHM.

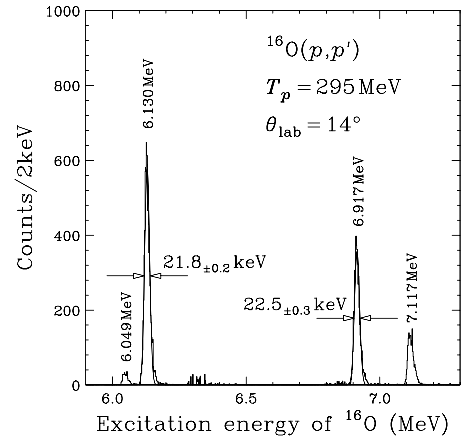

Figure 4: Excitation energy spectrum of the ${}^{16}{\rm O}(p,p')$ scattering at T_p = 295 MeV and $\theta_{\rm lab}$ = $14°$ measured with the Grand Raiden spectrometer after employing the dispersion matching method. The overall energy resolution is 22.0 keV FWHM.

tion are estimated to be about 17 keV which reasonably agrees with the experimental result of 19.1 keV. It should be noted that the dispersion matching is still possible for K $\neq$ 0 by using the single-slit method [4] instead of the faint-beam method employed here which works only for K = 0.

3.3 ${}^{16}{\rm O}(p,p')$ scattering

Figure 4 shows the excitation energy spectrum of the ${}^{16}{\rm O}(p,p')$ scattering at T_p = 295 MeV and $\theta_{\rm lab}$ = $14°$. The spectrum for the ${}^{16}{\rm O}(p,p')$ scattering was extracted by means of a subtraction of the ${}^{\rm nat}{\rm Si}(p,p')$ spectrum from the ${}^{\rm nat}{\rm SiO_2}(p,p')$ one. A natural ${\rm SiO_2}$ target with a thickness of 1.77 ${\rm mg/cm^2}$ was used.

Since the mass number of ^{16}O is only about one half of ${}^{\rm nat}$Si, the energy resolution for ^{16}O is expected to be worse compared with that for ${}^{\rm nat}$Si because of the K-dependence of dispersion matching which was not corrected as in the ${}^{\rm nat}$Si case. The observed energy resolution is about 22.0 keV (see Fig. 4). The K value for ^{16}O is about -0.020, and x in Eq. (2) depends on θ_0 as x = 0.32θ_0 after the kinematical correction of s_{12} = $-s_{16}K$. This means that the beam emittance of $\Delta\theta_0$ = 1.1 mrad contributes to Δx with 0.36 mm for ^{16}O. Furthermore, the effective magnification of $s_{11}b_{11}T + s_{12}b_{21}$ becomes larger by a factor of 1.3. These contributions to the energy resolution become about 20 keV which agrees fairly well with the experimental result of 22.0 keV.

4 SUMMARY

The high resolution WS beam line has been designed and constructed to accomplish complete matching including both lateral and angular dispersion and focus matching with the high-resolution Grand Raiden spectrometer at RCNP. 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 beam line 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 ${}^{168}{\rm Er}(p,p')$ 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 ΔE=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

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