TITLE:
High Resolution Study of $0^{-}$ states in $^{16}\text{O}$

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RUNNING TIME:
Test running time for experiment 2 days
Data runs 8 days

BEAM LINE: WS (WS beam line + Grand Raiden)

BEAM REQUIREMENTS:
Type of particle Polarized Protons
Beam energy 392 MeV
Beam intensity 10 nA on target
Energy resolution $< 100$ keV (FWHM)
Beam polarization $> 0.7$
Injection mode High Resolution Mode
WS transport mode Dispersive/Achromatic Modes

BUDGET:
Summary of budget request 1,450,000
Experimental expenses 950,000
Travel plan 500,000
**SUMMARY OF THE PROPOSAL**

Isovector $J^\pi = 0^-$, $0^\pm \to 0^\mp$ excitations are of particular interest since they carry the simplest pion-like quantum number. At low momentum transfers, they have been investigated in beta decay and muon capture experiments [1–3]. Axial-vector and pseudoscalar currents are responsible for these first-forbidden transitions in nuclear weak processes. Gagliardi et al. [1] reported an enhancement of the decay rate by more than a factor 3 for the first-forbidden beta decay of the 120 keV, $0^-$ state in $^{16}$N. This enhancement can be explained by considering the meson-exchange effects [4].

The ($p, n$) and ($p, p'$) reactions are suited to study these transitions for a wide momentum-transfer range [5]. Orihara et al. [6] reported the angular distribution for the $^{16}$O($p, n$)$^{16}$N($0^-, 0.12$ MeV) reaction at $T_p = 35$ MeV. The discrepancy between the distorted wave Born approximation (DWBA) calculation and their data in the large momentum transfer region of $q = 1.4$–2.0 fm$^{-1}$ has been observed, which might be due to the effect of the enhancement of the pion probability in the nucleus [7–11]. However, in the proton inelastic scattering to the $0^-$, $T = 1$ state in $^{16}$O at $T_p = 65$ MeV, such an enhancement was not observed [12]. The differences between ($p, n$) and ($p, p'$) results might indicate the contribution from complicated reaction mechanisms in these low incident energies.

At intermediate energies of $T_p > 100$ MeV, where reaction mechanisms are expected to be simple, there are data only for the $0^-, T=0$ transition at $T_p = 135$ [13,14], 180 [14], 200 MeV [15], 318 MeV [16], and 400 MeV [17]. Most of these measurements were not performed with sufficient energy resolution to isolate the $0^-, T = 0$ state at $E_x = 10.96$ MeV from its strong neighboring doublet ($3^+$ and $4^+$) which is only about 140 keV away. It should be noted that there is no published experimental data for the $0^-, T = 1$ state at $E_x = 12.80$ MeV in this energy region.

In this experiment, we measure cross sections and analyzing powers for inelastic excitations of $0^-, T=0$ (10.96 MeV) and $0^-, T=1$ (12.80 MeV) unnatural-parity states in $^{16}$O in 392 MeV inelastic proton scattering from $^{16}$O. The results will be studied in a framework of DWIA with shell-model (SM) wave functions. Such a comparison will provide us information on tensor and spin-spin components of effective $NN$ interactions. Furthermore data will be compared with DWIA calculations employing RPA response functions in order to assess the pionic enhancement in a large momentum-transfer region.
1 Scientific motivation

Proton inelastic scatterings provide a potentially rich source of new nuclear structure information. Within a framework of a distorted wave impulse approximation (DWIA), the nucleon-nucleus transition matrix contains three types of nuclear response functions: the spin-scalar response function $R_0$, the spin-longitudinal response function $R_L$ (which varies as $\sigma \cdot q$), and the spin-transverse response function $R_T$ (which varies as $\sigma \times q$). The inelastic excitation of natural-parity transitions involves both $R_0$ and $R_T$, while the inelastic excitation of unnatural-parity transitions involves both $R_L$ and $R_T$ [5].

The dynamic structure function measured in the quasi-elastic electron scattering provides detailed information on $R_T$ because electrons can penetrate the entire nuclear volume with little distortion. However, it can not probe $R_L$ in a one-photon-exchange plane wave Born approximation (PWBA).

The $(\vec{p}, \vec{p}')$ and $(\vec{p}, \vec{n})$ reactions can probe both $R_L$ and $R_T$, and a measurement of a complete set of polarization transfer coefficients allows us to extract them. One of the most interesting aspects in determining $R_L$ comes from the expectation that the pion field in the nucleus is sensitive to $R_L$ [7–11,18].

In the $\pi + \rho + g'$ model of the residual interaction, the pion field at moderate momentum transfers (1–2 fm$^{-1}$) produces an attractive spin-longitudinal interaction, while the rho-meson field produces a repulsive spin-transverse interaction (see Fig. 1). In 1982, Alberico et al.

![Figure 1: Spin-longitudinal ($V_L$) and spin-transverse ($V_T$) residual interaction as a function of momentum transfer $q$. The dashed vertical lines indicate the momentum transfers measured in E59 and E131.](image1)

![Figure 2: Spin-longitudinal $R_L$ (solid curve) and spin-transverse $R_T$ (dashed curve) response functions of the infinite nuclear matter in RPA at $q = 1.3$ fm$^{-1}$ as a function of energy transfer. The free Fermi-gas response function is also shown by the dotted curve.](image2)
Figure 3: The ratios $R_L/R_T$ for the $^6$Li, $^{12}$C, $^{40}$Ca, $^{208}$Pb($\vec{p},\vec{n}$) reactions at $T_p = 346$ MeV and $\theta_{\text{lab}} = 22^\circ$. The solid and dashed curves are the ratios of the RPA and free response functions, respectively.

[18] theoretically pointed out that the attractive spin-longitudinal interaction should induce an enhancement and a softening (shift toward lower energy transfer) of the spin-longitudinal response function $R_L$ with respect to the free response function in the quasi-elastic region for $q > 1$ fm$^{-1}$. On the contrary, the repulsive spin-transverse interaction should induce a quenching and a hardening (shift toward higher energy transfer) of the spin-transverse response function $R_T$ in the same region. The result of theoretical calculations by Alberico et al. is presented in Fig. 2. The enhancement of $R_L$ has attracted much interest in connection with both the precursor phenomena of the pion condensation [18] and the enhancement of the pion probability in the nucleus [7–11].

Recent measurements with ($\vec{p},\vec{n}$) reactions at 346 MeV [19] and 494 MeV [20–22] with momentum transfer of 1.7 fm$^{-1}$ reveal no enhancement of $R_L$ relative to $R_T$ (see Fig. 3). In our measurement, the observed $R_L$ is consistent with the pionic enhanced $R_L$ expected by random phase approximation (RPA) calculations [19] (see Fig. 4). On the contrary, a large excess of the observed $R_T$ is found in comparison with $R_T$ of the quasi-elastic electron scattering as well as of RPA calculations. This excess masks the effect of pionic correlations in $R_L/R_T$. The theoretical calculations are performed in a distorted wave impulse approximation with RPA correlations, which indicates that the nuclear absorption effect depends on the spin direction. This spin-direction dependence is responsible in part for the excess of $R_T$ [25].

There are two possible crucial steps in confirming the pionic correlations in $R_L$. One is the examination of the momentum-transfer dependence of $R_L$ and $R_T$ in the quasi-elastic ($\vec{p},\vec{n}$)
Figure 4: The experimental spin-longitudinal $R_L$ (left panels) and spin-transverse $R_T$ (right panels) response functions for the $^{12}\text{C}(\vec{p},\vec{n})$ (upper panels) and $^{40}\text{Ca}(\vec{p},\vec{n})$ (lower panels) reactions at $T_p = 346$ MeV and $\theta_{\text{lab}} = 22^\circ$ ($q_{\text{lab}} \approx 1.7$ fm$^{-1}$). The solid and dashed curves are the RPA and free response functions, respectively. The open circles represent the spin response functions from the LAMPF data [21,22].

reaction, which we have already done under program number of E131. Figure 5 compares preliminary results for the experimental $R_L$ and $R_T$ of the $^{12}\text{C}(p, n)$ reaction at 346 MeV. The reaction angles are $\theta_{\text{lab}} = 16^\circ, 22^\circ$, and $27^\circ$ which correspond to momentum transfers of 1.2, 1.7, and 2.0 fm$^{-1}$, respectively. The solid curves are the RPA response functions employing $(g'_{NN}, g'_{N\Delta}, g'_{\Delta\Delta}) = (0.6, 0.3, 0.5)$ and $m^*(0)=0.7m_N$, while the dashed curves are the free response functions employing $m^*(0) = m_N$. The RPA calculations could reproduce $R_L$ fairly well at the low energy-transfer region of $\omega_{\text{lab}} \leq 60$ MeV, while they fail to reproduce $R_L$ at the high energy-transfer region of $\omega_{\text{lab}} > 60$ MeV. The calculations underestimate $R_T$ by a factor of 2 or so in the quasi-elastic region. The disagreement between experimental and theoretical results at the high energy-transfer region might suggest the importance of the two-step contribution in this region [26].

The other is the investigation of $0^+ \rightarrow 0^-$ transitions via proton inelastic scattering described below. The excitation of the $0^-$ state with $T = 1$ is especially appreciated since it is characterized with the pure pion-like transfer.

Isovector $0^\pm \rightarrow 0^\mp$ transitions have been investigated in beta decay and muon capture experiments at low momentum transfers [1–3]. Axial-vector and pseudoscalar currents are responsible for these first-forbidden transitions in nuclear weak processes. Kubodera et al. [4] pointed out that the meson-exchange effects might enhance these beta decay rates by a factor of 4. The first-forbidden beta decay of the 120 keV, $0^-$ state in $^{16}\text{N}$ was measured by Gagliardi et al. [1]. They observed an enhancement of the decay rate by more than a factor 3 which is consistent with the theoretical prediction.

The $(p,n)$ and $(p,p')$ reactions are suited to study these transitions for a wide momentum-transfer range [5]. The angular distribution of the cross section for the $^{16}\text{O}(p,n)^{16}\text{N}(0^-, 0.12$ MeV) reaction at 35 MeV was reported by Orihara et al. [6]. There is the discrepancy between the distorted wave Born approximation (DWBA) calculation and their data in the large momentum transfer region of $q = 1.4$–2.0 fm$^{-1}$, which might be due to the effect of the pion
field (pionic enhancement) in nuclei. However, in the proton inelastic scattering to the $0^-$, $T = 1$ state in $^{16}$O with 65 MeV protons [12], such an enhancement was not observed. The differences between $(p, n)$ and $(p, p')$ results might indicate the contribution from complicated reaction mechanisms in these low incident energies.

At intermediate energies of $T_p > 100$ MeV, where reaction mechanisms are expected to be simple, there are data only for the $0^-, T=0$ transition at $T_p = 135$ [13,14], 180 [14], 200 MeV [15], 318 MeV [16], and 400 MeV [17]. Most of these measurements were not performed with sufficient energy resolution to separate the $0^-, T = 0$ state at $E_x = 10.96$ MeV from its strong neighboring doublet ($3^+$ and $4^+$) which is only about 140 keV away. It should be noted that there is no experimental data for the $0^-, T = 1$ state in $^{16}$O in this energy region. Thus out measurement will reveal the effect of the pion field in nuclei to this pure spin-longitudinal excitation in a large momentum-transfer region.

The most general form of the transition amplitude for these $0^+ \rightarrow 0^-$ excitations via a spin-1/2 proton inelastic scattering which respects rotation and parity invariance is given by

$$M = M_q(\sigma \cdot \hat{q}) + M_Q(\sigma \cdot \hat{Q}),$$

where $M_q$ and $M_Q$ are scalar functions of energy and momentum transfers, $\hat{q} = (k - k')/|k - k'|$, and $\hat{Q} = (k + k')/|k + k'|$. For this particular case of interest, as in elastic scattering, we can only measure three independent observables. They are the cross section ($\sigma$), the analyzing power ($A_y$), and the spin rotation parameter ($Q$). Unfortunately, excitations to these $0^-$ states in $^{16}$O are expected to be very small (see following DWIA calculations). Therefore, as a first step, we would like to propose to measure the cross section and the analyzing power of these reactions. Data of $\sigma$ and $A_y$ are not sufficient to determine $M$. However, as described below,
Figure 6: Differential cross sections for the $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=0)$ reaction at $T_p = 392$ MeV. See text for details.

Figure 7: Same as Fig. 6 but for the $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=1)$ reaction.

these data provide information not only on effective NN interactions but also SM structure of these $0^-$ states.

We performed the full microscopic distorted-wave impulse approximation (DWIA) calculations by using the computer code DW81 which treats the knock-on exchange amplitude exactly [27]. We used the effective NN t-matrix interactions parameterized by Franey and Love (FL) at 425 MeV [28]. The harmonic oscillator range parameter $b = 1.77$ fm was used for $^{16}\text{O}$ [29]. The optical potential parameters obtained from proton elastic scattering on $^{12}\text{C}$ at 398 MeV [30] were used. It should be noted that angular distributions of both $\sigma$ and $A_y$ are relatively insensitive to choice of optical potentials.

The general form of the wave function for these $0^-$ states in $^{16}\text{O}$ is given with a $1\hbar\omega$ model space by

$$\sqrt{1 - \alpha^2} |1p_{1/2}^{-1}2s_{1/2}> + \alpha |1p_{1/2}^{-1}1d_{3/2}>.$$ (2)

In the most simplest case of $\alpha = 0$, $0^-$ states are formed by a pure $(1p_{1/2}^{-1}2s_{1/2})$ configuration. However, van der Werf et al. [31] pointed out that a value of $\alpha = 0.125$ is needed in order to reproduce the experimental $ft$-value of the beta decay from the $0^-$ state in $^{16}\text{N}$ at $E_x = 0.12$ MeV. The cross section for the $0^-$, $T = 0$ state at $T_p = 200$ MeV can be reproduced by DWIA calculations by adopting this $\alpha$ value. It should be noted that a small admixture of the $(1p_{3/2}^{-1}1d_{3/2})$ configuration with $\alpha = 0.055$ improved the fit to the cross section for the $0^-$, $T = 1$ state at $T_p = 65$ MeV. Thus we have performed DWIA calculations for both $\alpha = 0$ and $\alpha = 0.125$ cases.

The single particle radial wave functions are generated in a Woods-Saxon (WS) well to calculate a transition density. Assuming the last nucleon in the $p_{1/2}$ orbit in $^{16}\text{O}$, we have obtained $-12.128$ MeV and $-15.664$ MeV for the binding energies of a proton and a neutron in the $p_{1/2}$ orbit, respectively. The depth of a WS potential with $r_0 = 1.25$ fm, $a = 0.65$ fm, and $V_{LS} = 6$ MeV was adjusted to give the binding energies of these last nucleons. It was about 58 MeV.
Then the single-particle wave functions were generated in this WS potential. For the unbound single particle states, a shallow binding energy was assumed to simplify the calculations.

Figures 6 and 7 show the angular distributions of the calculated cross sections for $0^-, T = 0$ and $T = 1$ states, respectively. The solid curves are the results for the pure $(1p_{1/2}1s_{1/2})$ configuration, and the dashes curves are the results taking into account for the admixture of the $(1p_{3/2}1d_{3/2})$ configuration with $\alpha = 0.125$. The magnitude of the cross sections depends on the admixture of the $(1p_{3/2}1d_{3/2})$ configuration, while their shapes are rather insensitive to this admixture. It should be noted that the cross sections at large momentum transfers ($q > 1.5$ fm$^{-1}$) relative to those at low momentum transfers ($q \approx 0$) depend on this admixture. Thus the effect of this admixture should be carefully taken into account since the effect of the pion field would be appear as an excess of the cross sections from DWIA calculations at large momentum transfers.

The angular distribution for the $T = 0$ state is relatively structureless compared with that for the $T = 1$ state. This difference can be understood by considering the relevant effective $NN$ interaction. Figure 8 shows the spin-longitudinal part $V_L(q)$ of the effective $NN$ interactions by Franey and Love at 425 MeV. It is found that the $V_L(q)$ values for $T = 0$ are rather flat as a function of $q$ while those for $T = 1$ are more structured. Thus the comparison with DWIA calculations will provide us information on spin-longitudinal (spin-spin and tensor) components of effective $NN$ interactions.

Figures 9 and 10 show the angular distributions of the calculated analyzing powers for $0^-, T = 0$ and $T = 1$ states, respectively. The calculations with $\alpha = 0$ and 0.125 are shown by the solid and dashes curves, respectively. For both $T = 0$ and 1 states, it is found that the calculated analyzing powers are insensitive to the admixture of the $(1p_{3/2}1d_{3/2})$ configuration.

2 Experimental procedures

We measure the cross section and the analyzing power for inelastic excitations of $0^-, T=0$ (10.96 MeV) and $0^-, T=1$ (12.80 MeV) unnatural-parity states in $^{16}$O in 392 MeV inelastic
Figure 9: Analyzing powers for the $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=0)$ reaction at $T_p = 392\text{ MeV}$. See text for details.

Figure 10: Same as Fig. 9 but for the $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=1)$ reaction. $T_p = 392\text{ MeV}$. See text for details.

proton scattering from $^{16}\text{O}$. The measurement will cover an angular range of $\theta_{\text{lab}} = 0-34^\circ$ ($q = 0-2.5\text{ fm}^{-1}$) in $2^\circ$ steps. The Grand-Raiden (GR) spectrometer will be used for the momentum analysis of scattered particles. The high quality polarized proton beam (halo-free with good emittance and good energy resolution) is required. The halo-free beam is essential especially for the $0^\circ$ measurement because the $S/N$ ratio strongly depends on the halo component of the beam. We will perform the lateral and angular dispersion matching between the WS beam line and the GR spectrometer in order to compensate the contribution from the energy spread of the beam to the final energy and angular resolutions. In the following, we present a brief description of experimental details.

2.1 WS beam line

The GR spectrometer is characterized by its high resolving power of $D/M_x = 37,000$ with the dispersion of $D = 15,451\text{ mm}$. 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 $x_0 = \pm 0.5\text{ mm}$, the momentum resolution becomes $2.7 \times 10^{-5}$ corresponding to an energy resolution of about

Figure 11: Beam envelopes with $\theta_0=0, \pm 2\text{ mr}$, and $\delta_0=\pm 0.015\%$ in the dispersive mode.
18 keV for 400 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

$$x = x_0(s_{11}b_{11}T+s_{12}b_{21})+\theta_0(s_{11}b_{12}T+s_{12}b_{22})+\delta_0(s_{11}b_{16}T+s_{12}b_{26}+s_{16}C)+\Theta(s_{12}+s_{16}K),$$  \hspace{1cm} (3)

$$\theta = x_0(s_{21}b_{11}T+s_{22}b_{21})+\theta_0(s_{21}b_{12}T+s_{22}b_{22})+\delta_0(s_{21}b_{16}T+s_{22}b_{26}+s_{26}C)+\Theta(s_{22}+s_{26}K),$$  \hspace{1cm} (4)

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 $b_{26}=s_{21}s_{16}-s_{11}s_{26}$. Details for lateral and angular dispersion matching conditions are described in Ref. [32].

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 11 shows horizontal beam envelopes from SP to the target position for the dispersive mode. In this mode, lateral and angular dispersion of WS-BL is $b_{16}=37.5$ m and $b_{26}=21.5$ rad necessary.
to satisfy dispersion matching conditions with GR. The magnifications of WS-BL are \((M_x, M_y) = (0.99, 0.87)\) 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.

The commissioning experiments of WS-BL were performed in April and June, 2000, by using 300 MeV and 400 MeV protons, respectively. In the dispersive mode, the WS-BL was tuned by using the faint beam method to satisfy the double-achromatic condition in the FP of GR. These conditions can be verified quickly using the focal plane detectors of GR and establish both lateral and angular dispersion matching on targets for \(K=0\). Then we measured the \(^{168}\text{Er}(p, p')\) reaction at \(\theta_{\text{lab}}=9^\circ\) (see Figs. 12 and 13). The first excited \(2^+\) state of \(E_x=79.8\) keV is clearly separated from the ground state with an energy resolution of \(\Delta E=13.0\pm0.3\) keV FWHM for 300 MeV and \(\Delta E=16.7\pm0.3\) keV FWHM for 400 MeV.

2.2 Zero-degree measurement

A procedure to perform the \(0^\circ\) measurement has been already established in E96, E108, and E137, and the setup is shown in Fig. 14. The proton beam will pass through the GR spectrometer and will be transported into the beam dump through holes of the focal plane counters (VDC’s) at the higher momentum side. The \(S/N\) value at \(0^\circ\) after the particle identification is estimated to be about 1/1 from the data of E137. The background subtraction will be performed by using the vertical position information deduced from the focal plane counters.

2.3 Measurements at finite angles

The Q1 Faraday cup installed in the Q1 magnet will be used up to \(4^\circ\) for monitoring the integrated beam current. At other angles larger than \(6^\circ\), the normal Faraday cup installed in the scattering chamber will be used.
2.4 Determination of the scattering angles

The ion-optical properties of the GR spectrometer makes it difficult to achieve a sufficient resolution for the vertical angle $\phi$. At finite angles, scattering angles are mainly determined by the horizontal scattering angle $\theta$ and the contribution from $\phi$ is small. However, at zero degrees, $\phi$ is identical with $\theta$ and an insufficient resolution of $\phi$ causes a serious problem. Thus we determine to define the vertical acceptance by a slit with an acceptance of $\phi = \pm 30 \text{ mr}$. The horizontal acceptance will be determined by software.

2.5 Ice target

A windowless and self-supporting ice target developed in E137 will be used as an oxygen target. Figure 15 shows the process to make an ice target. Pure water will be held within a hole of the middle polyester film. Three polyester films are stacked, and they are frozen in a refrigerator. Then the aluminum foil with an ice target will be mounted on a copper frame. The target thicknesses between 10 and 50 mg/cm$^2$ are available. However, it is very difficult to achieve a reasonable uniformity for the thin target of about 10 mg/cm$^2$. It should be noted that the energy-loss difference coming from the in-uniformity of the target will govern the final energy resolution under the dispersion matching condition. Thus we intend to use the target with a thickness of about 30 mg/cm$^2$. The in-uniformity of the target is estimated to be about $\pm 5\%$.

2.6 Cooling system

A cooling system using liquid nitrogen (LN$_2$) will be used to cool the ice target. Figure 16 shows the schematic view of the cooling system. LN$_2$ is fed from the top of the apparatus and stored in the reservoir. The target ladder made of copper is located below the reservoir, and it is cooled down to 77K.

3 Beam time and Beam requirements

In E137, the count rate (event rate accepted by the data acquisition (DAQ) system) was limited by the speed of the DAQ system. A reasonable live ratio was achieved by using the 30 mg/cm$^2$ H$_2$O target with the beam intensity of about 2 nA for all angles. The $S/N$ ratio after
the particle identification is about 1/1 for $0^\circ$ and $2.5^\circ$ and the contribution from the background is almost negligible for angles of $\theta_{\text{lab}} \geq 4^\circ$.

3.1 cross section and analyzing power

From the following conditions:

- Target Thickness: $30 \text{ mg/cm}^2 = 1.00 \times 10^{21} \ 1/\text{cm}^2$
- Acceptance: $\theta = \pm 17.5 \text{ mr (} \pm 1.0^\circ\text{)}, \phi = \pm 30 \text{ mr}$
- Solid Angle: $2.1 \text{ msr}$
- Beam intensity: $2 \text{ nA} = 1.25 \times 10^{10} \text{ s}^{-1}$
- Beam polarization: 0.70
- Live Ratio: 0.80

the yield from the $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T = 1)$ reaction is given by

$$Y = 20.9 \times \sigma_{\text{lab}} \ \text{cps}, \quad (5)$$

where $\sigma_{\text{lab}}$ is the laboratory-frame cross section in the unit of mb/sr.

The cross sections for the excitations of $0^-, T = 0$ ($E_x = 10.96 \text{ MeV}$) and $0^-, T = 1$ ($E_x = 12.80 \text{ MeV}$) in $392 \text{ MeV}$ proton inelastic scattering at $0^\circ$ ($\theta_{\text{c.m.}}^{\text{eff}} \simeq 1.5^\circ$) can be estimated by using the data in E137 as
Figure 17: Expected cross sections for inelastic excitations of $0^-$, $T=0$ (10.96 MeV) and $0^-$, $T=1$ (12.80 MeV) unnatural-parity states in 392 MeV inelastic proton scattering from $^{16}$O. DWIA calculations are normalized to reproduce the experimental data in E137 shown by solid and open circles.

$E_x = 10.96$ MeV, $0^-$, $T=0$  $\sigma_{lab} = 0.029 \pm 0.002$ mb/sr

$E_x = 12.80$ MeV, $0^-$, $T=1$  $\sigma_{lab} = 0.024 \pm 0.005$ mb/sr

The normalization factors required for DWIA calculations with $\alpha = 0.125$ to reproduce these results are 0.42 and 0.15 for $T=0$ and $T=1$, respectively. Figure 17 shows the expected cross sections for both $T=0$ and $T=1$ states.

Then each data point with the uncertainties for $\sigma$ and $A_y$ of about 2 and 5% will be obtained for the $T=1$ state as follows.

<table>
<thead>
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<th>$\theta$</th>
<th>$\sigma_{lab}$</th>
<th>$S/N$</th>
<th>$S$ (hour)</th>
<th>$\delta \sigma$</th>
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<tbody>
<tr>
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<td>1/1</td>
<td>7,500</td>
<td>5</td>
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<tr>
<td>2.5</td>
<td>$4.3 \times 10^{-2}$</td>
<td>1/1</td>
<td>7,500</td>
<td>3</td>
</tr>
<tr>
<td>4.0</td>
<td>$6.0 \times 10^{-2}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>1</td>
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<tr>
<td>6.0</td>
<td>$4.0 \times 10^{-3}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>1</td>
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<tr>
<td>8.0</td>
<td>$7.3 \times 10^{-3}$</td>
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<td>5</td>
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</tr>
<tr>
<td>12.0</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>3</td>
</tr>
<tr>
<td>14.0</td>
<td>$9.7 \times 10^{-3}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>4</td>
</tr>
<tr>
<td>16.0</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>14</td>
</tr>
<tr>
<td>18.0</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>215</td>
</tr>
<tr>
<td>20.0</td>
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<td>$N=0$</td>
<td>2,500</td>
<td>18</td>
</tr>
<tr>
<td>22.0</td>
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<td>2,500</td>
<td>10</td>
</tr>
<tr>
<td>24.0</td>
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<td>$N=0$</td>
<td>2,500</td>
<td>8</td>
</tr>
<tr>
<td>26.0</td>
<td>$4.0 \times 10^{-3}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>9</td>
</tr>
<tr>
<td>28.0</td>
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<td>$N=0$</td>
<td>2,500</td>
<td>11</td>
</tr>
<tr>
<td>30.0</td>
<td>$1.9 \times 10^{-3}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>18</td>
</tr>
<tr>
<td>32.0</td>
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<td>$N=0$</td>
<td>2,500</td>
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</tr>
<tr>
<td>34.0</td>
<td>$3.9 \times 10^{-4}$</td>
<td>$N=0$</td>
<td>2,500</td>
<td>85</td>
</tr>
</tbody>
</table>

| total    | 195 (~8 days) |

For $\theta_{lab} = 18^\circ$, 32$^\circ$, and 34$^\circ$, we need beam time more than 24 hours for the statistical uncertainty of 2%. Thus we will measure only 24 hours for these angles. Then the expected statistical uncertainties are about 6%, 3%, and 4% for $\theta_{lab} = 18^\circ$, 32$^\circ$, and 34$^\circ$, respectively.
3.2 Test running time for experiment

We require the halo-free beam with a good energy resolution of less than 100 keV. In order to achieve these conditions, the AVF and ring cycrotrons and the beam-transport system should be carefully tuned. The beam energy spread will be monitored with the GR spectrometer by using the $^{12}\text{C}(p,p')$ reaction. The background events coming from the beam halo will be also monitored by the GR spectrometer. The beam will be tuned in the achromatic mode, and it will take about 24 hours (1 day).

Then the transport in the WS beam line will be changed into the dispersive mode. The WS beam line will be tuned in order to achieve the lateral and angular dispersion matching conditions. It will take about 12 hours.

The proton beam will pass through the GR spectrometer and will be transported into the beam dump through holes of the focal plane counters (VDC’s) at the higher momentum side. This transport in the GR spectrometer should be carefully performed in order to achieve a reasonable background level. It will take about 12 hours.

Thus we need 2 days for test running time for experiment.

3.3 summary

In summary, requirements for the beam time are as follows.

<table>
<thead>
<tr>
<th>Test running time for experiment</th>
<th>2 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data runs</td>
<td>8 days</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10 days</td>
</tr>
</tbody>
</table>

3.4 beam requirement

The requirements for the beam are following:

- Type of particle: Polarized Protons
- Beam energy: 392 MeV
- Beam intensity: 10 nA on target
- Energy resolution: $< 100$ keV (FWHM)
- Beam polarization: $> 0.7$
- Injection Mode: High Resolution Mode
- WS transport mode: Dispersive/Achromatic Modes

4 Budget

The damaged parts of the cooling system should be replaced. We will use an additional trigger counter to reduce the background.

| Replacement of damaged parts of cooling system | 200,000 |
| Additional trigger counter                   | 300,000 |
| Data Storage (DLT)                           | 150,000 |
| Data Storage (HD)                            | 300,000 |
| **Total**                                    | 950,000 |
Travel expenses (500,000 yen) for all of the members for the beam time as well as for preparation are also required.

5 Schedule

We would like to have the beam time in the fall of 2000.

6 Other commitment of group members

Most of our group member has a commitment of our own experiments performed with WS beam line (the GR and/or LAS spectrometers).

7 References

Recent publications on the related works

1. T. Wakasa et al.
   Polarization Transfer and Spin Response Functions in Quasi-Elastic $(\vec{p}, \vec{n})$ Reactions at 346 MeV

2. A. Tamii et al.
   Polarization Transfer Observables for Proton Inelastic Scattering from $^{12}$C at 0°


Thin Ice Target for $^{16}$O($p, p'$) experiment