PROPOSAL FOR EXPERIMENT AT RCNP

5 February 2007

TITLE:

Investigation of $M1$ quenching in sd-shell region

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RUNNING TIME:	Development of new gas target system	1.0 day
	Test running time for experiment	2.5 days
	Data runs	12.5 days

BEAM LINE:		Ring : WS course
BEAM REQUIREMENTS:	Type of particle	unpolarized / polarized p
	Beam energy	295 MeV
	Beam intensity	$\geq$ 3 nA (unpol.), $\geq$ 10 nA (pol.)
	Any other requirements	energy resolution $\leq$ 20keV
		high resolution, halo-free, small emittance
BUDGET:	Experimental expenses	2,550,000 yen
	Traveling and living expenses	600,000 yen

TITLE:
Investigation of $M1$ quenching in sd-shell region

SPOKESPERSON: Hiroaki Matsubara

SUMMARY OF THE PROPOSAL

Missing strength, called as quenching, in Gamow-Teller (GT) and $M1$ excitations has been one of interesting subjects in nuclear physics. Sophisticated experimental studies on GT resonances have revealed that a coupling with $2p$-$2h$ states is the main source of quenching phenomena, while a coupling with Δ-h states plays a minor role. As for the $M1$ strengths, comparison of the amount of quenching between isoscalar (T=0) and isovector (T=1) strengths is essential for understanding quenching mechanism owing to the following reason. The $M1$ isoscalar excitation has no contribution from the coupling with Δ-h states due to the isospin selection rule, while both couplings can occur in the isovector one. Recently we have performed a (p, p') measurement on ^{28}Si with high resolution to extract $M1$ strengths; the result is that the quenching factor of the isoscalar transition is smaller than that of the isovector one. Although it can be recognized that the coupling with Δ-h states does not play an important role in the $M1$ strengths, it is an unexpected result because the quenching factor of the isoscalar transitions should be equal or larger than that of the isovector ones. Lack of data on the isoscalar strength may bring such inconsistency because the isoscalar strength is small and therefore has been hard to be observed. Actually, few states are known as the isoscalar $M1$ states. Our realization of (p, p') experiments with high resolution at forward angles, however, has provided a reliable method to study it.

We propose to measure the (p, p') reactions on ^{16}O, ^{20}Ne, ^{24}Mg, ^{32}S, ^{36}Ar and ^{40}Ca at forward angles including zero-degrees at 295 MeV with high resolution for systematic study on $M1$ isoscalar strengths. Even-even N=Z nuclei are good targets to study $M1$ excitations because of their ground state property, 0^+, and good separation of isospin. We can test by a systematic study whether the unexpected trend of the quenching factor seen in ^{28}Si between the isoscalar and the isovector excitation is just a peculiar case or not. Furthermore, these data are valuable to test the isoscalar spin-flip component V_σ of the effective nucleon-nucleon interaction since we have only limited knowledge on the component from experiments.

1 Scientific motivation

1.1 $M1$ quenching in ^{28}Si

The Gamow-Teller (GT) and $M1$ transitions are one of the most basic excitation modes in nuclei since they carry quantum numbers of ΔJ^{π}=1^{+} (ΔS=1, ΔL=0) and are considered as the simplest spin-flip excitations. Since the discovery of GT giant resonances [1], they have been much studied by charge-exchange reactions, but the observed strengths were still smaller than the model independent sum-rule value [2]. This missing strength problem, called a quenching problem, has attracted much attention. Two mechanisms were proposed for the quenching problem. They are configuration mixings with Δ-h and $2p$-$2h$ states. Recent sophisticated and systematic studies on GT resonances have revealed that the coupling with $2p$-$2h$ states is the main source of the quenching phenomena because most of the missing strengths have been found in the continuum region of up to 50 MeV [3].

As for the $M1$ strengths, comparison of quenching between the isoscalar (T=0) and the isovector (T=1) strengths is unique for studying the quenching mechanism. The isoscalar excitations have no contribution from the coupling with Δ-h states due to the isospin selection rule, while both coupling with Δ-h and $2p$-$2h$ states can occur in the isovector ones. According to this selection rule, one can understand that difference in degree of quenching between the two types of excitations reflects the selective contribution between the Δ-h and $2p$-$2h$ admixtures in the $M1$ excitations. Therefore the quenching factor, which is defined as the ratio of the observed strength to the predicted one, of the isoscalar transitions is expected to be larger than, or at least equal to that of the isovector transition. Note that the quenching factor is defined as it takes a value of unity when there is no quenching. A (p, p') experiment on ^{28}Si at E_p=200 MeV was previously performed to extract $M1$ strengths [5]. The results suggested that the quenching factor of the isoscalar transition was smaller than that of the isovector one. This was an unexpected result. In their measurement, $M1$ strengths were obtained by extrapolation of the cross section data from $2-3°$ to $0°$, due to experimental difficulty on the zero-degrees measurement, although it was essential for $M1$ strength because of its ΔL=0 property. Actually, a large systematic uncertainty of $\pm$10% was originated form this extrapolation procedure [5]. Large background amount and poor energy resolution of their data brought additional difficulty on finding $M1$ states and extracting their strengths. Therefore, in order to derive a reliable conclusion, we have recently carried out a (p, p') measurement on ^{28}Si at zero-degrees with high resolution at RCNP

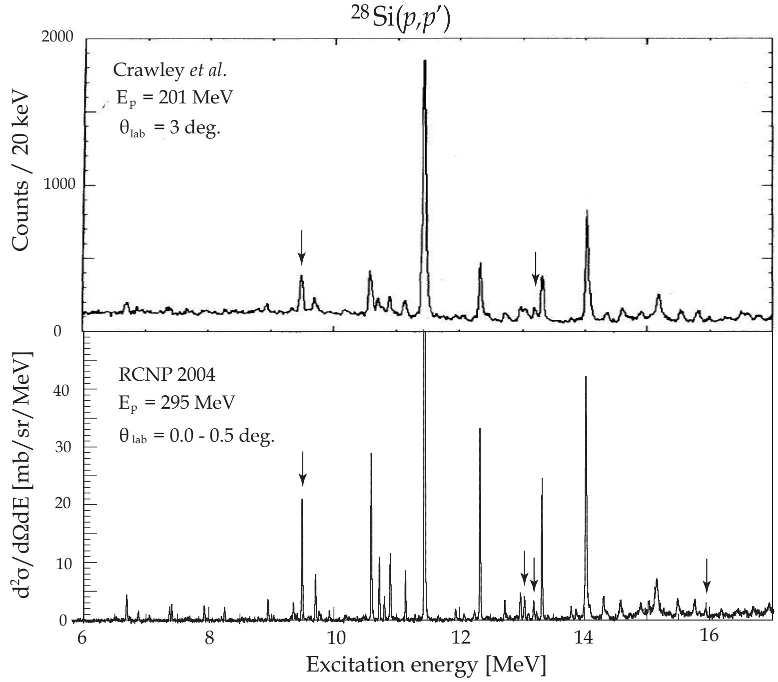

Figure 1: Spectra of the ^{28}Si(p, p') reactions. The top figure represents the data taken from Ref. [5]. The bottom shows our new data which was measured at 0° with high resolution at RCNP. Arrows in the figures indicate excited states assigned as $M1$ isoscalar (1^+ ; T=0).

(Fig. 1). Proton beam was accelerated up to 295 MeV, where distortion effects are minimum and $M1$ strengths are enhanced. The quenching factors of our data were determined from each cumulative sum of $M1$ isoscalar and isovector strengths up to an excitation energy of 16 MeV. Free g-factors were used for the calculated sums. The result was again that the isoscalar quenching factor was smaller than the isovector one. In order to include higher order configuration mixings and meson exchange current, effective g-factors are proposed to be used in a constrained model space calculation [6, 7, 8]. The isoscalar quenching was seen, while the isovector factor was not quenched but exceeded the unity, with using Brown-Wildenthal effective g-factors which were determined experimentally [6]. These results are not explained by theories. Although it suggests that Δ-h admixture is not the dominant quenching mechanism in ^{28}Si, we cannot fully understand the results.

1.2 Weak spin-flip isoscalar strength

The isoscalar spin-flip component V_σ is much smaller than the isovector $V_{\sigma\tau}$ owing to the destructive interference of the nucleon g-factor. Since tiny strength corresponds to a small cross section and difficulty in detecting it, only few isoscalar $M1$ states have been observed. In the case of ^{28}Si, since there are relatively large $M1$ strengths, the former experiments could extract the quenching factors of both isospin excitations. Although sd-shell nuclei were studied systematically by (p, p') reactions in Ref. [5], it was just from ^{32}S and ^{28}Si that isoscalar $M1$ strengths were extracted. It was due to large uncertainty from poor resolution and huge background events. Several new $M1$ isoscalar states have been found in our new ^{28}Si spectrum as shown in Fig. 1. Our realization of sophisticated (p, p') measurements at zero-degrees has opened new horizon to study the isoscalar excitations. The new powerful probe provides us systematic study on the quenching between the isoscalar and isovector transitions because it would detect both isospin strengths separately. Thus we can test whether the unexpected trend of the quenching seen in ^{28}Si is a peculiar case or not.

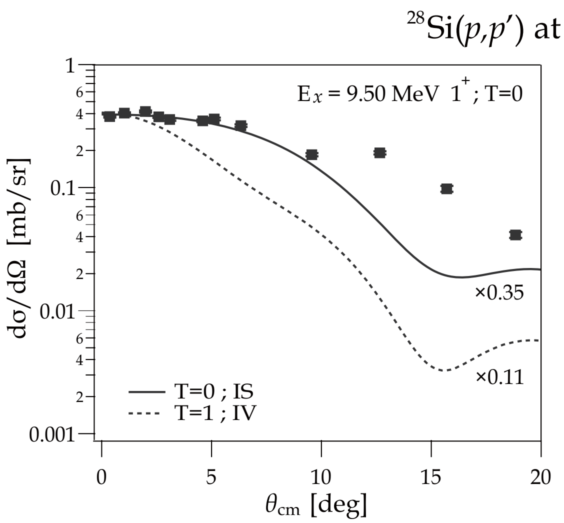

Figure 2: Measured angular distributions of the E_x=9.50 MeV (1$^+$; T=0) and 11.45 MeV (1$^+$; T=1) states in the ^{28}Si(p, p') reactions are compared with normalized DWBA curves. It is clear that the DWBA slopes at forward angles reproduce measured angular distributions well.

Angular distribution of $M1$ transition is forward peaked due to its ΔL=0 property. Distorted wave Born approximation (DWBA) calculation shows enough difference between the $M1$ isoscalar and the isovector distribution to identify its isospin as shown in Fig. 2. A flatter distribution of the isoscalar is explained by the contribution of tensor component of V_τ^T. Actually, the trend that the angular distribution of the isovector excitation is obviously steeper than that of the isoscalar one is commonly seen in calculated wave functions. Therefore comparison of angular distribution is enough to identify the isospin of $M1$ excitation without polarization transfer observables or another probe data, for example (d, d'), although they actually provide helpful information. Here we note that distribution of the isoscalar transition at $10° - 15°$ is flatter than that of the DWBA prediction. This reflects an uncertainty of the isoscalar excitation which is not fully established.

For a study on the weak isoscalar strength with (p, p') reactions, selection of the target nuclei is important. Since $M1$ strengths should be separately observed with respect to isospin, target nuclei need to have a 0^+, T=0 ground state. Therefore even-even N=Z nuclei in the *sd*-shell are ideal targets, where N and Z are neutron and proton number, respectively. The candidates are ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca. Nucleus in the *sd*-shell region provide a good test ground to shell-model calculations because sophisticated large-space shell model calculations are available. Another reason is that ^{40}Ca is the heaviest stable N=Z nuclei.

1.3 Ground state correlation and $M1$ strengths

There is another interesting subject concerning with double closed shell systems, like ^{16}O and ^{40}Ca. In the extreme single-particle model, these nuclei have no $M1$ strength because in their ground states both spin-orbit partners are filled. Experimentally, however, significant $M1$ isovector strengths were observed in both ^{16}O and ^{40}Ca [9, 10]. These phenomena are discussed with core-excited states due to mainly $2p2h$ configuration mixing. This is called as ground state correlation. A high quality measurement of (p,p') reactions can identify $M1$ isoscalar and isovector strengths distribution in those nuclei.

1.4 Summary of the purposes

We propose to measure the (p,p') reactions on ^{16}O, ^{20}Ne, ^{24}Mg, ^{32}S, ^{36}Ar and ^{40}Ca at forward angles including zero-degrees at 295 MeV with high resolution for systematic study on $M1$ strengths. Spin-parity and isospin of each state is determined from its angular distribution. By systematic study in *sd*-shell region, we study if the interesting result of the quenching factors seen in ^{28}Si is a common nature. A high quality measurement on double closed shell systems, ^{16}O and ^{40}Ca, provides a study of ground state correlation. Although experimental data on isoscalar $M1$ transitions have been much limited, now they are available. They are important also for reaction studies.

2 Experimental procedure

We have already established a procedure to perform (p,p') measurement at zero-degrees with high resolution in the previous experiment E249 [11]. Experimental procedure is briefly summarized below. We note that an energy resolution and beam intensity requested here are the numbers that have been achieved in E249.

2.1 Measurements procedure

An unpolarized proton beam from the Neomafios ion source is employed for forward angles measurements of cross sections. Polarized proton from the HIPIS is employed for elastic scattering measurements to obtain optical model parameters of the target nuclei.

Protons scattered by target nuclei are measured by the focal plane detectors of the Grand Raiden (GR) spectrometer. Quasi-free scattered protons are detected by the spectrometer LAS for monitoring beam spot in the vertical direction. The beam position is important information for a calibration of scattered angles and background subtraction. The LAS is fixed at 59.6° during the experiment, where is the most forward angle when the GR is set at 0°.

Medium under-focus mode of the GR is employed for achieving sufficiently good angle resolution in both horizontal and vertical components at very forward angles. Calibration runs with a sieve-slit are required to obtain an ion optics of the GR in each experiment.

(a) Measurements at zero-degrees

Typically two days are required for tuning a good beam to perform measurements at zero-degrees. At first a beam with an energy spread of 40 keV is achieved in the achromatic transport mode at the WS course. After performing lateral and angular dispersion matching [12], a beam is tuned to achieve an energy resolution of 12-15 keV with a faint beam without target. Our goal is to achieve an energy resolution of 20 keV in zero-degrees spectra with target.

The primal beam is transported in the GR and stopped at the 0° dump which locates at 12 m downstream of the focal plane as shown in Fig. 3. A beam intensity of 3 nA is required at least.

(b) Measurements at forward angles

The Q1 Faraday-cup as shown in Fig. 3 is used to stop the primal beam. The GR is placed at 2.5° and 4.5° with beam intensities of 4 nA and 8 nA, respectively. The beam ducts used between the Dump-Q and the 0° dump are taken off.

(c) Measurements at finite angles

The Faraday-cup in the scattering chamber as shown in Fig. 3 is used to stop the primal beam. The GR will be placed at 6°, 8°, 10°, 12°, 14° and 16°. A beam intensity of 10 nA is employed.

(d) Measurements of elastic scatterings

A polarized proton beam is used for measuring cross sections and analyzing powers to obtain optical model parameters. The data will be taken at $6^\circ-40^\circ$ in a step of 3°. At forward angles smaller than 25.5°, the primal beam is stopped at the Faraday-cup in the scattering chamber with a beam intensity of $10-15$ nA. At backward side angles more

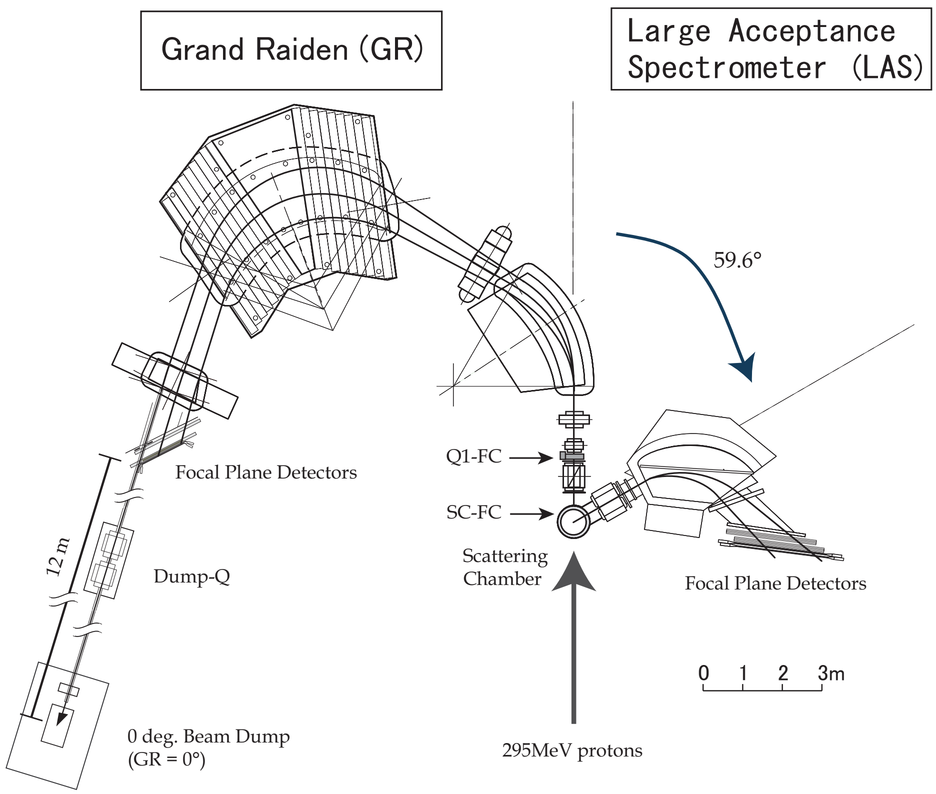

Figure 3: Set up of the Grand Raiden spectrometer and the LAS for the zero-degrees measurement. The primary beam is transported to 0° the dump through the GR and the focal plane. The location of Q1 Faraday-dup (Q1-FC) and scattering chamber Faraday-cup (SC-FC) are also shown.

than 25.5°, the primal beam is passed through the scattering chamber and stopped at the Faraday-cup in the wall of the experimental hall in order to obtain a large intensity beam of 40−50 nA. We need large intensity to reduce the time because the cross sections of elastic scattering at backward side angles are 10^1−10^5 times smaller than those at forward angles.

We do not take the ^{16}O and ^{40}Ca data because they have already been measured by Kyoto university group.

2.2 Target preparation

Because our goal is to achieve an energy resolution of 20 keV, a target thickness of 2−3 mg/cm^2 is optimum for 295 MeV proton beams. This corresponds to 10 μm for a solid target. ^{24}Mg and ^{40}Ca are relatively easily prepared because they are metal foils. ^{16}O and ^{32}S are prepared with a cooling system by using LN_2 which was made by Kawabata *et al.* [13]. Ice is good target for ^{16}O. Cooling of a solid ^{32}S target is for preventing it from sublimation. This manner cooled ^{32}S target was successfully used in (α,α') experiments [14]. Reduction of the target thickness and improvement of the uniformity is required. Reference 10 reports that minimum of the ice sheet thickness was 10 mg/cm^2, which is too thick to achieve 20 keV resolution. Nevertheless since the system provides windowless and self-supporting target which realizes background-free measurement, it is an ideal for the high resolution experiment. We also survey possibility of using SiO_2 or gas O_2 target system to find the optimum condition.

The rare gas targets, ^{20}Ne and ^{36}Ar, will be stored in a gas cell with foils as windows. Based on the fact that the thickness of 2−3 mg/cm^2 is optimum for our experiment, a thickness of 10 mm is enough to match the condition at room temperature. In this case, the target thicknesses of ^{20}Ne and ^{36}Ar are 0.90 and 1.78 mg/cm^2, respectively. A few atm pressure is favorable than 1 atm. The 10 mm thickness allows us to realize the dispersive matching condition within 20 keV at scattering angles from 0° to 6°. Uncertainty of the scattering angle is negligible. If 6 μm aramid foils are used as windows of the entrance and the exit, the estimated signal to noise (S/N) ratios are 1/6 and 1 in ^{20}Ne and ^{36}Ar for the most strong isovector state, respectively. Suitable window shapes and its material will be chosen to satisfy the physical requirements. A gas recycle system is required since expensive isotope targets are used. Once the new gas cell system is developed, it can be used in a variety of zero-degrees experiments including (^{3}He,t) reactions.

3 Beam time requirement

According to the calculations using shell-model code OXBASH for each target, three or four $M1$ isoscalar states are predicted which cross section at $0°$ is larger than 40 μb/sr. (An exception is 20 μb/sr for ^{20}Ne.) Here OXBASH code predicts B(σ) strengths and a conversion constant from a B(σ) strength to a differential cross section is taken from the previous ^{28}Si result [11]. In order to obtain a statistical accuracy of 5% for a 40 μb/sr isoscalar cross section in the scattering angle of $0°-0.85°$, 2500 counts is required at 0°-shot. This corresponds to 50% of an acceptance at the 0°-shot. To be accumulated this statistics, 14 hours is required with a beam intensity of 3 nA on target and with a target thickness of 2.0 mg/cm^2. The S/N ratio is estimated to be 2/3. ^{20}Ne target, however, needs almost twice hours at each setting owing to particular small cross section which was predicted in calculations.

Table 1: Beam time estimation for each target

Measurement at zero-degrees	14 hours
Measurement at forward angles	5+3 hours
Measurement at finite angles	2×6 hours
total (inelastic)	1.4 days for each target
	2.8 days for ^{20}Ne
Measurement of elastic scattering	6×4 hours
total (elastic)	1.0 days for all targets

We would like to request 1 day as a development beam time of a new gas cell system. We need to check that the window shape of the cell is wide enough to prevent background events from increasing due to scatterings of a beam halo at the window frame. We also check the resolution and the S/N ratio. We will use seven targets including an empty gas cell for background subtraction. 2.5 days is required for beam tuning, calibration of excitation energy and ion optics, and exchanging the target system during the beam time.

Table 2: Total beam time estimation

Development of new gas target system	1.0 day
Beam tuning	2.5 days
Measurements (inelastic)	1.4 days×6 (^{16}O, ^{24}Mg, ^{32}S, ^{36}Ar, ^{40}Ca, empty)
	2.8 days (^{20}Ne)
Measurements (elastic)	1.0 days
total	16 days

4 Budget request

We need to purchase new thin foil targets of ^{24}Mg and ^{40}Ca, and enriched gases. ^{20}Ar and ^{36}Ar gas cost 50,000 and 1,100,000 yen per one litter, respectively. We need a development expense for the gas target system and the improvement of the cooling system. The gas target system consists of driving the cell, monitoring the pressure and the temperature, and a circulation system for a gas reuse.
We also request travel and living expense for collaborators.

Table 3: Budget request

Foil targets	400,000 yen
Target gas	1,150,000 yen
Development of new gas target system	1,000,000 yen
total	2,550,000 yen
travel and living expense	600,000 yen

5 Schedule

We would like to have the beam time in the autumn of 2007. H. Matsubara will manage the development, experiment and analysis for his doctoral dissertation.

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