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Study of *M1* excitations by high-resolution proton inelastic scattering experiment at forward angles

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Experimental technique for measuring proton inelastic scattering with high-resolution at 295 MeV and at forward angles including zero degrees have been successfully developed. An excitation energy resolution of less than 20 keV, good scattering angle resolution, low background condition, and reasonable background subtraction have been achieved. The experimental technique have been applied for several sd and pf shell nuclei for systematic study $M1$ and $E1$ excitations in nuclei. The experimental method and preliminary spectra are reported.

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1. Introduction

Systematic studies of $M1$ strengths and their distributions are of much interest. We have been developing an experimental technique for measuring high-resolution proton inelastic scattering at forward angles including zero degrees. Our primary physics motivations are 1) systematic study of $M1$ strengths and their quenching properties, 2) study of fragmentation mechanism of one-particle one-hole states, 3) search for new and exotic excitation modes, and 4) determination of spin part of the $M1$ strength distribution for calculation of neutrino inelastic scattering cross section from astrophysical interest.

From study of Gamow-Teller (GT) strengths by (p, n) reactions, it was claimed that observed strengths were systematically smaller than predictions of the sum rule [1]. The phenomenon is known as the GT quenching problem. Two mechanisms were proposed to accounting for the GT quenching problem. One is coupling of one-particle one-hole (1p-1h) configuration to two-particle two-hole (2p-2h) and higher configurations, and the other is coupling of 1p-1h configurations to Δ-particle one-hole (Δ-h) configurations. Recent sophisticated measurement and analysis of (p, n) reactions have revealed that a large fraction of the missing strengths is located in the continuum energy region of up to 50 MeV [2–4]. It implies that the main part of the quenching is caused by mixing of 1p-1h configurations to 2p-2h and higher configurations.

Concerning the $M1$ strengths, there are two types of transitions from self-conjugate (N=Z) even-even nuclei, which are isoscalar (isospin transfer $\Delta T = 0$) and isovector ($\Delta T = 1$) transitions. The spin-part of the isovector $M1$ transitions are analogous to GT transitions on the assumption of the charge-symmetry. Thus quenching phenomena similar to the GT case are expected in the isovector transitions since both of the two quenching mechanisms are considered to take place in the same manner as the GT case. On the contrary Δ-h excitation cannot contribute to the isoscalar $M1$ excitation due to the isospin conservation. The amount of contribution of each mechanism can thus be studied by observing quenching phenomena of both isoscalar and isovector $M1$ excitations.

The spin-part of the $M1$ transition strengths $B(\sigma)$, are most-suitably studied by proton inelastic scattering at forward angles. Systematic measurements of $B(\sigma)$ strengths in sd-shell nuclei have been carried out at Orsay and at Saturne. They reported that quenching phenomena occur in both isoscalar and isovector $M1$ excitations in ^{28}Si [6], and later that almost no quenching was observed in sd-shell nuclei if the summed strengths of both transitions were considered [5]. The results were, however, not conclusive due to following reasons. Since a measurement of cross sections at zero degrees was not feasible, the data at finite forward angles, around 3° and larger angles, were extrapolated to the cross sections at zero degrees. This procedure introduced non-negligible systematic uncertainty. In addition, the data at finite forward angles still suffered much instrumental background. Thus determination of the cross section and assignment of spin-parity and isospin of each state was not satisfactory. Thanks to the recent development of experimental technique, now measurements at zero degrees with much lower background condition with higher energy resolution are possible.

Another concern is distribution of fragmented $M1$ strengths. The $M1$ strength in ^{48}Ca mainly consists of a simple shell model configuration of $(\nu(f_{7/2})^{-1}\nu(f_{5/2}))$. Actually most of the $M1$ strength concentrates on a prominent excited state located at 10.22 MeV. It has however been claimed from studies using (e, e') and (p, p') reactions that considerable amount of the strength is possibly fragmenting into many tiny states around 10 MeV [7,8]. Conversely, a simple shell-model does not predict $M1$ strengths in ^{16}O and ^{40}Ca but in reality $M1$ strengths are observed in both nuclei. Ground state correlation plays one of key rolls in the mechanism. Precise determination of the $M1$ strength distributions provides a good test ground for studying fragmentation mechanism of 1p-1h strengths.

The first step of this project was to establish the experimental method of high-resolution proton inelastic scattering at forward angles including zero-degrees. Tuning technique of high-resolution halo-free beams and experimental methods of measuring proton inelastic scattering at zero degrees with high energy resolution and with good scattering angle resolution have been successfully developed. Development of high-quality beams is reported elsewhere [9]. In this paper, we report the experimental method and recent preliminary results.

2. Experimental Method

2.1. Experimental Setup

Figure 1 shows a schematic view of the experimental setup for the proton inelastic scattering measurement at zero degrees. A proton beam was accelerated up to 295 MeV by AVF and RING cyclotrons and bombarded a target placed in the scattering chamber. We have used unpolarized beams up to now but polarized proton beams are also available. The primary beam which passed through the target was transported inside the high-resolution spectrometer Grand Raiden (GR), extracted at the focal plane, focused by a quadrupole doublet, and stopped in a Faraday cup located in the zero-degree beam dump [10–12]. Inelastically scattered protons were measured by the focal plane detectors which consisted of two multi-wire drift chambers (MWDC's) and two plastic scintillators.

In measurements at 2.5 and 4.5 degrees, a part of the beam duct between the quadrupole doublet and the beam dump was removed for rotating the spectrometer, and the primary beam was stopped at a Faraday cup (Q1-FC) located downstream of the first quadrupole. In measurements at larger angles, the beam was stopped by a Faraday cup placed in the scattering chamber.

Typical target thicknesses were 1-5 mg/cm^2.

2.2. Tuning of a high-quality beam

A high-quality beam was tuned by optimizing parameters of two accelerators for obtaining a small beam energy spread and a low beam-halo condition. This procedure typically requires two days. The beam energy spread was tuned to 37 keV in the best case and 40-60 keV in the typical case. After applying the dispersion matching technique [13,14], the final energy resolution was 17-20 keV. The beam spot width on the target was 3-5 mm in the case of dispersive transport mode. This small beam spot size is essential for measuring absolute cross sections as well as for low background data. The beam intensity was 3-8 nA.

2.3. Ion Optics and Scattering Angle Resolution

Ion-optical parameters of the GR spectrometer were optimized by compromise between good vertical scattering-angle resolution and high signal to noise (S/N) ratio in the back-

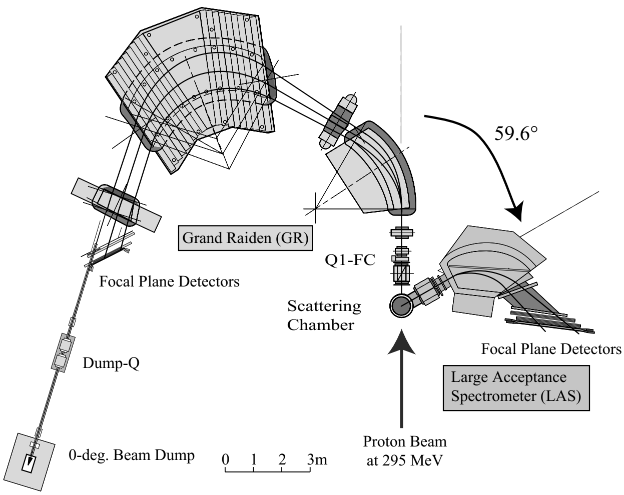

Figure 1. Experimental setup for proton inelastic scattering measurement at zero degrees. The primary beam was transported inside the spectrometer and was stopped at a Faraday cup after passing through holes of the focal plane detectors. The Large Acceptance Spectrometer (LAS) was used for monitoring the vertical beam position on the target. The Q1 Faraday cup (Q1-FC) was used for the measurements at 2.5 and 4.5 degrees.

ground subtraction procedure. We chose mildly under-focusing optics comparing with the standard focusing optics. The ion-optical parameters were calibrated by analysing the data with a sieve slit at the entrance of the spectrometer measured at 10 °. The horizontal scattering angle resolution was 0.15 °. The vertical scattering angle resolution was 0.5° (0.8°) at the lower (higher) excitation energy region. The ion optical parameters for the vertical scattering angle were very sensitive to the vertical beam position on the target. Thus we employed another spectrometer LAS for monitoring the vertical beam position continuously during the experiment by detecting protons mainly produced by quasi-free scattering. The beam spot position data were included in the off-line analysis of the vertical scattering angle.

2.4. Background Subtraction

Even in a measurement with a very clean beam, there still existed instrumental background. The background particles were mostly caused by multiple Coulomb scattering at the target followed by scattering at inner part of the spectrometer. The shape and height of the background events in a spectrum could be experimentally determined by the following method. Vertical trajectory of particles determined by MWDC's were projected onto the vertical focal plane as shown in the left panel of Fig. 2. Since true events focused around Y=0, the part of trapezium consisted of background events. In the right panel, the thick spectrum corresponds to the events located in the central hatched region

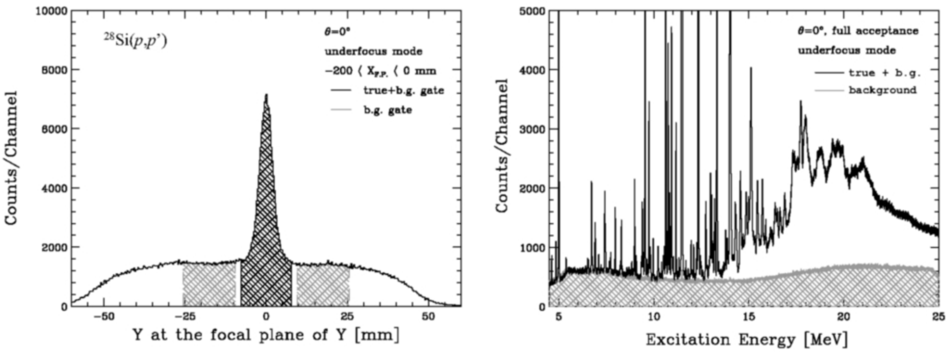

Figure 2. Vertical position histogram at the vertical focal plane (left panel). True and background regions were selected as shown by thick and thin hatched regions, respectively. Background events were averaged and subtracted from the spectrum obtained by the true gate as shown in the right panel.

around Y=0 in the left spectrum, while the gray spectrum is the averaged one for the events located in the other two gray-hatched regions. Thus by assuming a flat distribution of background events in the Y histogram, not only the shape but also the height of the background events in the excitation energy spectrum were determined. After subtracting the background spectrum, excitation energy spectra free from instrumental background were obtained.

3. Spectra and Results

We have succeeded in measuring very clean spectra at zero degrees. Excitation energy spectrum of the ^{26}Mg(p,p') reaction at 0.0-0.5° is shown in Fig. 3. The target thickness was 1.6 mg/cm^2. An energy resolution of 17 keV was achieved. Background subtraction procedure worked well as can be seen in the low-lying discrete state region. Many discrete peaks are clearly seen. At present, the level assignments of Ref. 5 are shown in the figure.

Excitation energy spectrum of the ^{48}Ca(p,p') reaction at 0.0-0.5° is shown in Fig. 4. The target thickness was 1.9 mg/cm^2. A very prominent peak at 10.22 MeV is observed with an energy resolution of 17 keV. At the foot of the peak, many tiny discrete states were observed as shown in the inset of Fig. 4. They consist of $M1$ and $E1$ excitations. Angular distribution is continuously measured up to large angles in 0.5° step. The $M1$, $E1$, and other excitations are to be identified from angular distribution of differential cross sections of each peak.

As examples, angular distributions of differential cross sections of the ^{12}C(p,p') reaction are shown in Fig. 5 for prominent two 1^+ states at 12.7 and 15.1 MeV. The solid curves are the results of distorted wave impulse approximation calculations using the Cohen and Kurath target wave functions [15] and the 325 MeV parameter set of the Franey and Love interaction [16]. The calculations surprisingly well reproduce the experimental data without any normalization.

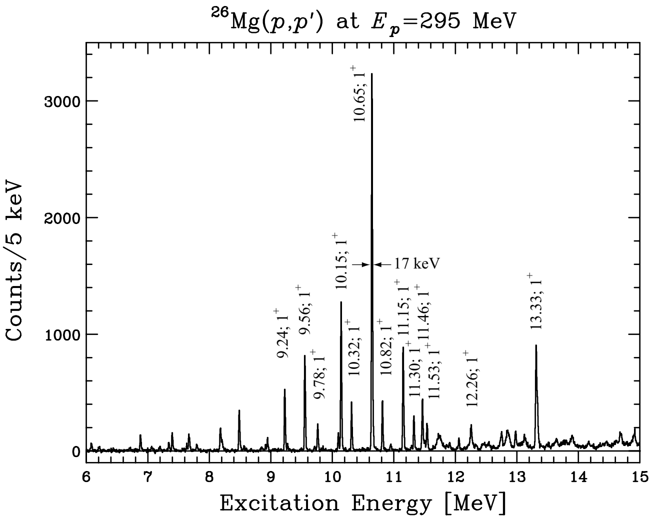

Figure 3. Excitation energy spectrum of the ^{26}Mg(p, p') reaction at 0.0-0.5°. Level assignments are taken from Ref. 5.

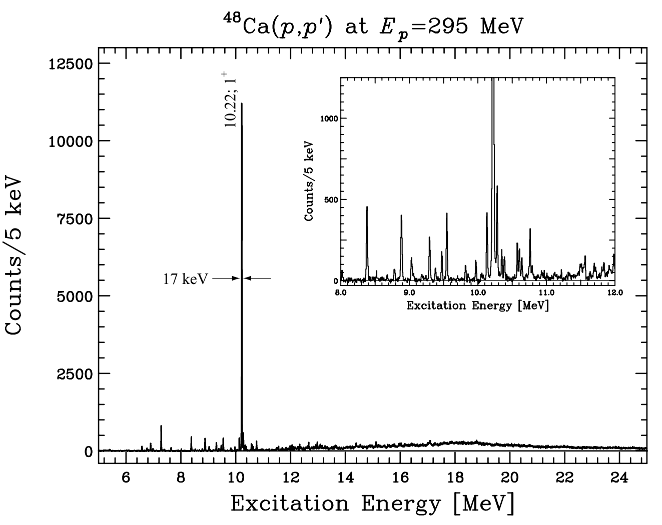

Figure 4. Excitation energy spectrum of the ^{48}Ca(p, p') reaction at 0.0-0.5°. An enlarged spectrum is shown in the inset.

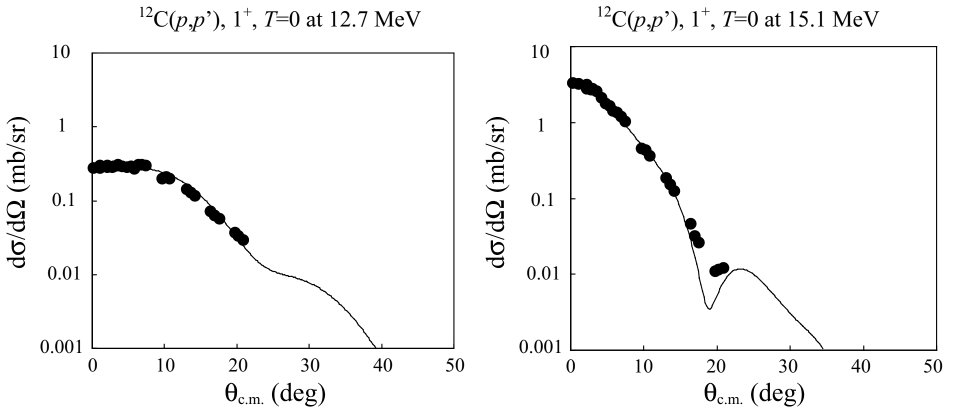

Figure 5. Angular distribution of differential cross sections of the ^{12}C(p, p') reaction for 1^+,T=0 state at 12.7 MeV (left panel) and 1^+,T=1 state at 15.1 MeV (right panel). The solid curves are the results of distorted wave impulse approximation calculations. See text for details.

Extraction of differential cross sections of each peak is in progress for target nuclei ^{12}C, ^{26}Mg, ^{28}Si, ^{48}Ca, and ^{58}Ni.

4. Summary and Outlook

Experimental technique for measuring proton inelastic scattering with high-resolution at 295 MeV and at forward angles including zero degrees have been successfully developed. We have achieved an excitation energy resolution of less than 20 keV, good scattering angle resolution, low background condition, and reasonable background subtraction. Absolute cross sections can be measured continuously from zero degrees to large angles. The experimental technique is very useful for the systematic study of $M1$ and $E1$ excitations in nuclei.

Up to now measurements were performed for several sd and pf shell nuclei. Feasibility of measuring inelastic scattering from ^{208}Pb was confirmed in a test measurement. A measurement of the ^{208}Pb(p, p') reaction including spin-transfer observables at zero-degrees is scheduled in year 2006 for studying distribution of $M1$ and $E1$ strengths and for searching exotic excitation modes.

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