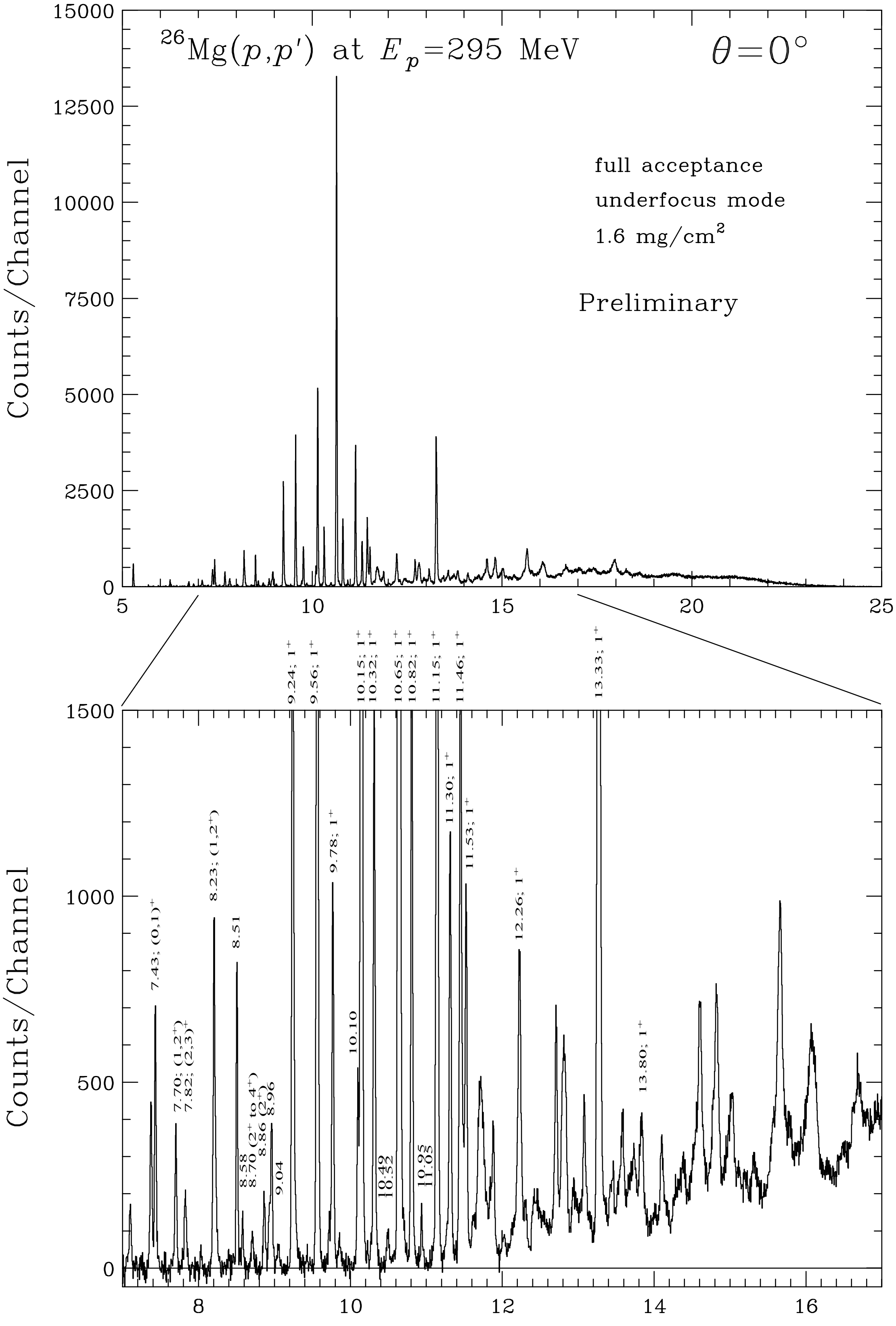
^{26}Mg(p,p') at E_p=295 MeV
θ=0°
full acceptance
underfocus mode
1.6 mg/cm^2
Preliminary
Counts/Channel
15000
12500
10000
7500
5000
2500
0
5
10
15
20
25
9.24; 1$^+$
9.56; 1$^+$
10.15; 1$^+$
10.32; 1$^+$
10.65; 1$^+$
10.82; 1$^+$
11.15; 1$^+$
11.46; 1$^+$
13.33; 1$^+$
11.30; 1$^+$
11.53; 1$^+$
9.78; 1$^+$
8.23; (1,2$^+$)
7.43; (0,1)$^+$
8.51
12.26; 1$^+$
7.70; (1,2$^+$)
7.82; (2,3)$^+$
10.10
8.58
8.70 (2$^+$ to 4$^+$)
8.86 (2$^+$)
8.96
9.04
10.49
10.52
10.95
11.05
13.80; 1$^+$
Counts/Channel
1500
1000
500
0
8
10
12
14
16
Excitation Energy [MeV]

Development of High Quality Beams and High Resolution Measurements of Proton Inelastic Scattering at Forward Angles Including Zero Degrees

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1 Introduction

High resolution study of nuclear structures by hadronic reactions has a potential to open a new era of nuclear physics. High resolution measurements have been done from an earlier time for decay particles from excited states, such as gamma rays and protons, at the level of keV, since the energy of the measured particle was low ($\leq$10 MeV). As different probes, missing mass measurements like inelastic scattering and charge exchange reactions can be used for systematic studies of nuclear excitation strengths since states can be excited independently of their decay channels including neutron decays. In fact, decay particle measurements and missing mass measurements are complementary tools and are often combined to be a more powerful probe.

In the case of missing mass measurements by hadronic reactions, it is essential to use beams at intermediate energies (100-400 MeV/U), where single step reactions become dominant and distortion effects are smallest. As a consequence, excitation cross sections become nearly proportional to the reduced matrix element which is relevant to the excitation. At the Research Center for Nuclear Physics, high resolution study of $(^3\mathrm{He}, t)$ reactions has been intensively performed [1]. In the study it has been demonstrated that giant Gamow-Teller resonances are not a single peak but consist of many excited states, each of which has a relatively narrow width even at excitation energies above particle decay threshold [1]. The fragmentation mechanism of the Gamow-Teller strength is one of the topics to be studied in a near future.

The physics motivation of this work is to do systematic studies of $M1$ strengths and their distributions in various targets by using high-resolution inelastic scattering measurements at forward angles including zero degrees. From the study of Gamow-Teller strengths by (p, n) reactions, it had been claimed that the observed strengths were systematically smaller [2] than the sum rule value. It is so-called Gamow-Teller quenching problem. Recent sophisticated measurements and analyses of (p, n) reactions have shown that a large fraction of the missing strength is located in the continuum of up to 50 MeV [3]. It indicates that the main part of the "quenching" is caused by mixing of one-particle-one-hole strengths to two-particle-two-hole and higher configurations. As for $M1$ strengths, systematic measurements of (p, p') reactions have been performed at forward angles at Orsay and Saturne. They reported that quenching phenomena also occurred for both isoscalar (ΔT=0) and isovector (ΔT=1) $M1$ strengths of ^{28}Si, and later that almost no quenching was observed in *sd*-shell nuclei if the summed strengths for ΔT=0 and 1 were considered [4]. However, since measurements at the scattering angle of zero degrees were not feasible, the strengths were extrapolated from the data at finite forward angles, and even those forward angle data suffered from much instrumental background. Thus spin-parity and isospin assignment of each state was not satisfactory. Systematic errors were large and the results were not conclusive. Therefore high quality data of $M1$ strengths are required for systematic studies.

Another concern is the distribution of fragmented $M1$ strengths. The $M1$ strengths of ^{48}Ca are considered to have a simple one-particle-one-hole configuration in the shell model. Actually most of the $M1$ strength is believed to be concentrating on a state at 10.22 MeV. From a recent measurement of the $^{48}\mathrm{Ca}(p, p')$ reaction it has been claimed that a considerable fraction of the strength is possibly fragmenting into many tiny states at the foot of the 10.22 MeV state. The shape of the distribution is not explained by simple theoretical calculations. One of our purposes is to obtain high quality data at forward angles for identifying the spin-parity of each state and accurate strength distribution of the fragmented strengths.

The first step of this study was to establish a tuning technique and instrumentation for accelerating high-resolution halo-free beams, and experimental methods for measuring proton inelastic scattering at zero degrees, very forward angles, and other angles. A halo-free beam was essential for the inelastic scattering measurements at zero degrees since huge background events come to the detector system from the beam halo. In this paper we will report on the successful development on the high-quality beams and preliminary results of proton inelastic scattering measurements. The achievements of the beam tuning technique has been already applied in many experiments not only for proton and ^{3}He beams but also for other high quality beams.

2 Development of High Quality Beams

Basic developments of the tuning technique of accelerating high quality beams are proposed and performed by a combined team of experimental group and accelerator group under the program number E214. One of the key point was considered to establish a stable condition of single turn extraction from the injector AVF cyclotron, while those of the RING cyclotron were at a level of satisfaction [5].

The issues of improvements were as follows.

1. Magnetic field distribution in the AVF cyclotron was re-calculated based on information on the phase of turns measured by phase probes. The trim coil currents were optimized for realizing an isochronous field.
2. Two phase probes were newly added at the outer orbit side.
3. The position of the movable phase slit in the Dee electrode was shifted to the outer side by 4 mm for optimizing the tuning range.
4. The acceleration voltage was increased from 40 kV to 56 kV for larger turn separation.

Tuning of a high-quality ^{3}He beam at 420 MeV was challenged in October 2003. The beam was selected since we had much experience of accelerating high-resolution beams, the expected turn separation was large comparing with other beams, and the beam can be easily stopped or cut by slits comparing with a proton beam. After efforts, turn patterns in the AVF cyclotron became clearly observed by a beam probe (Fig. 1), which showed the good quality of the established isochronous field comparing with previous ones. The energy width of the beam measured by the elastic scattering on ^{197}Au in an achromatic transport mode was as small as 67 keV by full width at half maximum. By applying the dispersion matching method [6] for the high resolution WS beam line [7], we have achieved an excitation energy resolution of 22 keV for the $^{54}\mathrm{Fe}(^3\mathrm{He}, t)$ reaction.

Tuning of a high-quality proton beam at 295 MeV was tested in April 2004. The energy was selected since we had much experience of acceleration. After applying essentially the same tuning processes, we have achieved an energy resolution of 37 keV in the achromatic transport mode. The energy width corresponded to a spot size of 3 mm on the target in the dispersive direction in the dispersive transport mode. The small beam spot size helped much for reducing the uncertainty of the solid angle of the spectrometer system.

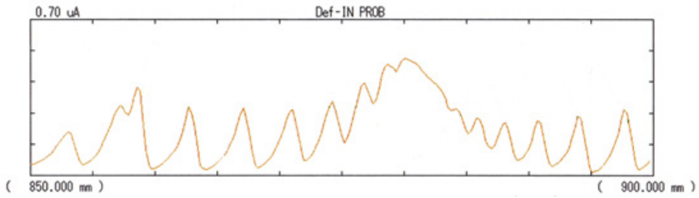

Figure 1: Beam profile in the AVF cyclotron measured by a beam probe. The extraction radius is located around the right edge of the histogram.

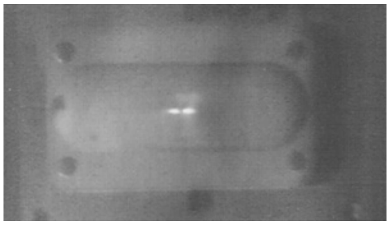

Figure 2: Beam spot on the target in the dispersive transport mode.

A halo-free beam has been tuned, which was indispensable for measurements of inelastic scattering at zero degrees. In the tuning process, it has been confirmed that establishing the condition of single-turn extraction from the AVF cyclotron was also essential for accelerating a halo-free beam. Finally we have succeeded in tuning a halo-free beam to measure proton inelastic scattering at zero degrees in the dispersion matching mode. A resolution of 20 keV has been achieved.

3 Measurement of Proton Inelastic Scattering at Forward Angles

Based on the successful development of the beam tuning technique, measurements of proton inelastic scattering for nuclei up to nickel have been proposed and performed as a physics run under the program number E249.

The experimental setup is shown in Fig. 3. An unpolarized proton beam at E_p=295 MeV bombarded a target placed in the scattering chamber. In the measurements at zero degrees, the primary beam was transported inside the spectrometer Grand Raiden (GR) and was stopped in a Faraday cup after passing through the focal plane detectors and being focused by a quadrupole doublet [8]. In the measurements at 2.5 and 4.5 degrees, a part of the beam duct to the zero-degree beam dump has been removed for rotating the spectrometer, and the primary beam was stopped at the Q1 Faraday cup (Q1-FC). In measurements at larger angles, the beam was stopped by a standard Faraday cup placed in the scattering chamber. The typical beam intensity was 3-8 nA. Target thicknesses were 1-5 mg/cm^2.

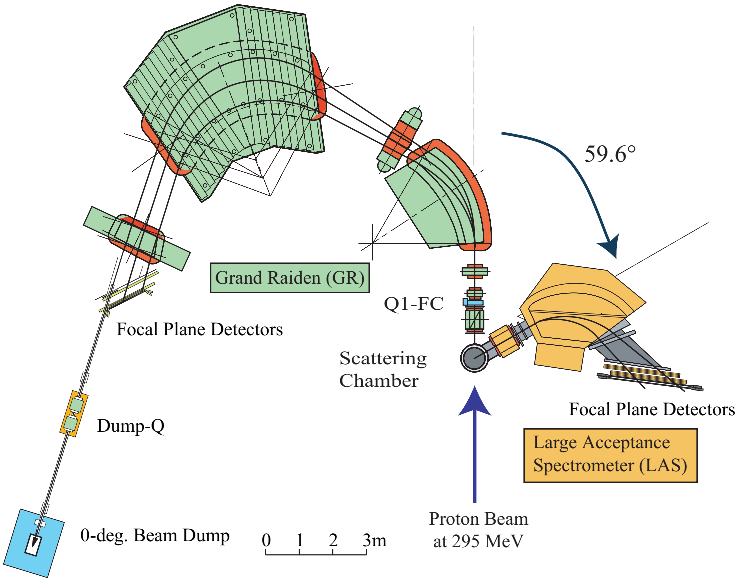

Figure 3: Experimental setup for proton inelastic scattering at zero degrees. The Large Acceptance Spectrometer (LAS) was used for monitoring the vertical beam position on the target. The Q1 Faraday cup (Q1-FC) was used for the measurements at 2.5 and 4.5 degrees.

Ion-optical parameters of the GR spectrometer have been optimized by a compromise between vertical scattering angle resolution and signal to noise ratio of the background subtraction technique as explained below. The vertical scattering angle resolution became better as the optics in the vertical direction was defocused at the detector position. However, the image size at the detector position became larger by the defocusing, which deteriorated the signal to noise ratio of background subtraction technique since background events were determined by assuming their flat distribution on the vertical position while true events were focused [8]. We chose mildly under-focused optics comparing with the standard one. Over-focused optics had larger correlation between the vertical and horizontal scattering angles and, therefore, were not used.

The ion optics have been calibrated by the analysis of the data taken with a sieve slit at the entrance of the GR spectrometer. Figure 4 shows the sieve slit data before and after the calibration at the low excitation energy region. We could obtain a sufficient vertical scattering angle resolution of 0.5° (0.8°) at the low (high) excitation energy region.

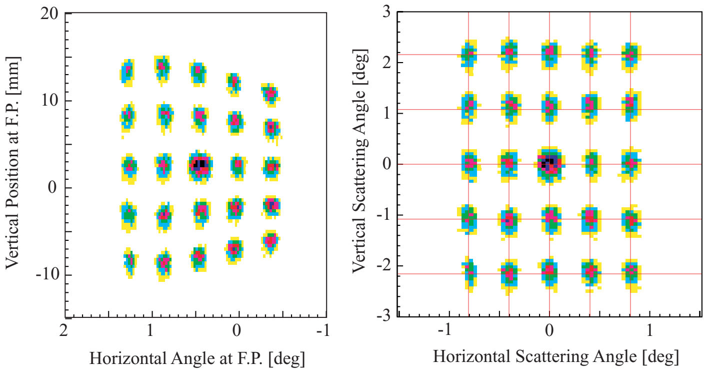

Figure 4: Sieve slit data before (left panel) and after (right panel) the calibration at lower excitation energy region. Scattering angle resolutions of 0.15° and 0.5-0.8° have been achieved for horizontal and vertical directions, respectively. The vertical scattering angle resolution depends on the excitation energy.

The ion optical parameters for the vertical scattering angle were very sensitive to the vertical beam position. Thus we employed another spectrometer LAS for monitoring the vertical beam spot during the experiment by measuring protons mainly from quasi-free scattering.

Since we employed the under-focused mode, the focal plane of the vertical ion-optics was located downstream of the detector position. By tracing the track of each event we could obtain vertical position distribution on the virtual focal plane. The particles of true events reasonably focused as shown in the left panel of Fig. 5.

By assuming a flat distribution of background events on the vertical position, background spectrum has been experimentally determined. The background subtraction procedure worked well. It can be confirmed by looking at the low excitation energy region of the ^{28}Si(p,p') reaction in the right panel of Fig. 5.

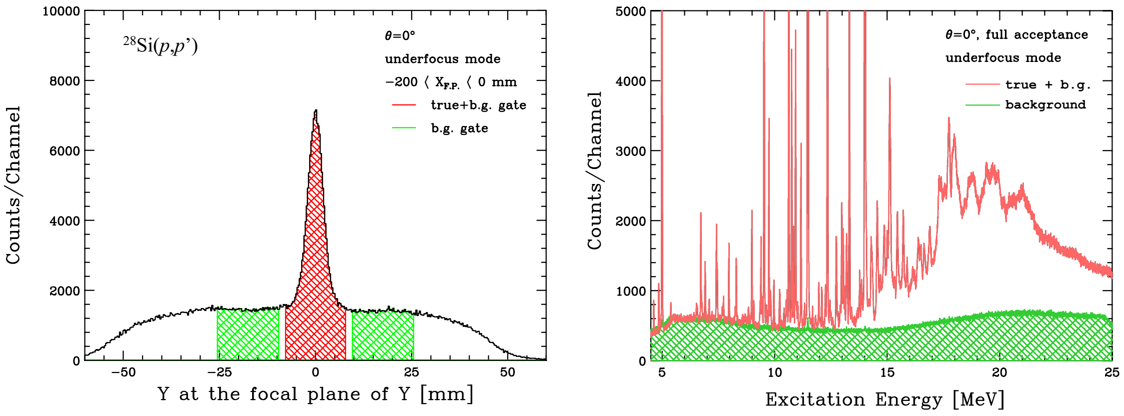

Figure 5: Vertical position at the virtual vertical focal plane (left panel). True and background regions were selected as shown by red and green lines, respectively. Background events were averaged and subtracted from the spectrum obtained by the true gate as shown in the right panel.

4 Spectra

The data of the ^{12}C(p,p') reaction is shown Fig. 6. We see a beautiful spectrum being essentially free from background events. The ^{26}Mg(p,p') spectrum is shown in the top page of this article. The ^{28}Si(p,p') spectrum is shown in another article of this annual report [9]. A spectrum of the ^{48}Ca(p,p') reaction at zero degrees is shown in Fig. 7. We observe many peaks at the foot of the strong 1^+ state at 10.22 MeV. The energy resolution was 20 keV. Extraction of angular distribution and spin-parity assignment of each peak are in progress.

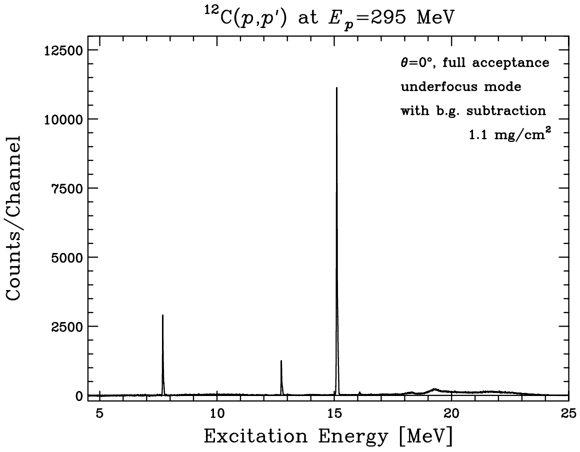
^{12}C(p,p') at E_p=295 MeV

Figure 6: Preliminary spectrum of the ^{12}C(p,p') reaction at the scattering angle of zero degrees.

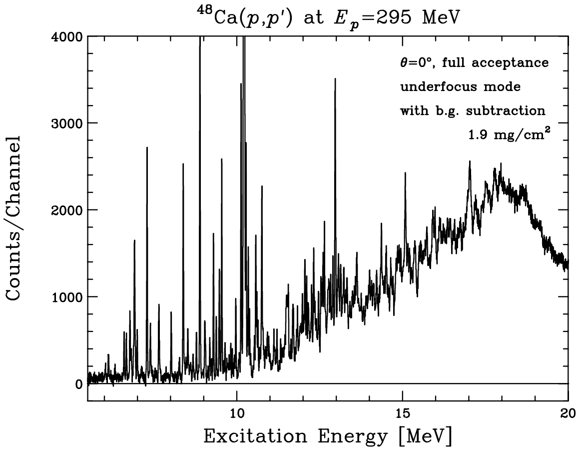
^{48}Ca(p,p') at E_p=295 MeV

Figure 7: Same as Fig. 6 for ^{48}Ca.

A spectrum of the ^{64}Ni(p,p') reaction at zero degrees is shown in Fig. 8. The 1^+; T=5 state, which is the analogue of the ground state of ^{64}Co is clearly seen at 15.6 MeV [10]. Many narrow peaks are observed in the 5-10 MeV region. The ^{90}Zr(p,p') reaction has been measured as a feasibility test. The spectrum is shown in Fig. 9. A larger bin size is used for statistical reason. Even though we spent only 30 minutes for the measurement, we can already see a broad peak at 8-10 MeV, which is considered as concentration of $M1$ strengths [11]. A measurement of its fine structure is already feasible by using a few days of beam time.

5 Summary

A general tuning technique for accelerating high-resolution halo-free beams has been successfully developed. Physics measurements of high-resolution proton inelastic scattering at forward angles including zero degrees

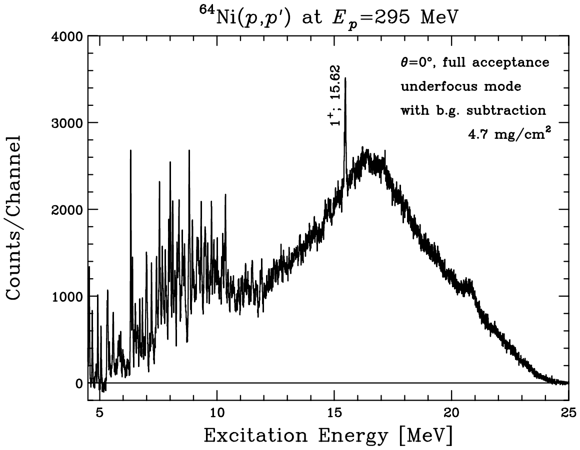

Figure 8: Same as Fig. 6 for ^{64}Ni.

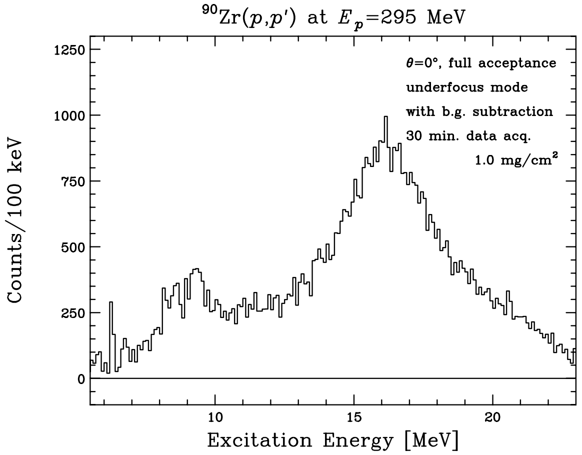

Figure 9: Same as Fig. 6 for ^{90}Zr.

have been carried out mainly for *sd*-shell nuclei. The advantages of our measurements comparing with previous ones are as follows: 1) The excitation energy resolution is as good as 20 keV, 2) The measurement at zero degree is possible in addition to the one at very forward angles such as 2.5 and 4.5 degrees, and at larger angles, 3) A wide excitation energy region of 5-25 MeV can be measured in a single measurement, 4) Absolute cross section measurement is considered feasible, Detailed analyses are in progress, 5) Polarization transfer measurements are possible including zero degrees [8], and 6) Other inelastic reactions, such as (d, d') and (α, α'), can be used for selecting non-spin-flip and/or non-isospin-flip excited states.

Detailed and systematic studies of $M1$ and other excitations by making use of these advantages are planned.

6 Acknowledgements

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