High resolution nuclear studies using cyclotron beams*

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ABSTRACT

Various types of nuclear experiments which require high resolution particle beams are described. Examples of the performance of the MSU Cyclotron in providing such beams are given. Proton beam currents of approximately 200 nA for $\Delta E/E = 1/6000$ resolution are easily obtained at $E_p \geq 25$ MeV with internal beam currents of only 3 μA. The role of dispersion matching is discussed and preliminary results using the laboratory broad range magnetic spectrograph are shown.

1. INTRODUCTION

The importance of high resolution beams and detection systems in the study of the nucleus has been apparent for many years, especially in nuclear spectroscopy, i.e. the classification of nuclear levels, their excitation energies, decay properties, spin, parity, etc. More recently high resolution beams have proved to be essential in certain aspects of the study of isobaric analogue levels. Up to now these studies have been the exclusive domain of electrostatic accelerators, mostly the Van de Graaff type, which have in many ways the most desirable beam properties. In this paper it is shown that cyclotrons like the MSU sector focused cyclotron when used with a highly dispersive beam analyser such as the one presently in use in the MSU Cyclotron Laboratory[1] can compete successfully in a field previously reserved to electrostatic machines, and in some instances improve upon such machines.

2. TYPES OF EXPERIMENT

We can divide the high resolution experiments into two broad types: (a) where energy resolution is required on target and (b) where energy resolution of reaction products is desired. An example of the first requirement is the reaction:

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$$^{28}_{14}\mathrm{Si} + \mathrm{p} \rightarrow {}^{29}_{15}\mathrm{P}^* \rightarrow {}^{28}\mathrm{Si} + \mathrm{p}_0$$
$$\rightarrow {}^{28}\mathrm{Si}^* + \mathrm{p}_1$$

Here, a compound system is formed and one is studying energy levels of ^{29}P which then decays to either the incoming or other allowed channels. Detection of the outgoing particles need only be good enough to separate various modes of the decay. Since the ^{28}Si + p system can have resonances corresponding to levels of ^{29}P which have widths of a few keV or even less[2,3] high resolution of the incident beam is essential to the understanding of the resonance phenomenon.

In the second type of experiment high resolution of reaction products is desired. For example, in the reaction

$$^{28}\mathrm{Si} + \mathrm{p} \rightarrow {}^{28}\mathrm{Si} + \mathrm{p}_0$$
$$\rightarrow {}^{28}\mathrm{Si}^* + \mathrm{p}_1$$
$$\rightarrow {}^{28}\mathrm{Si}^* + \mathrm{p}_2, \text{ etc.}$$

one is investigating levels of the ^{28}Si target nucleus by the inelastic scattering of protons. Where the ^{28}Si excited levels are closely spaced, the detector resolution rather than the beam resolution is usually the limiting factor. Modern solid state devices and magnetic spectrographs have adequate resolution for studying most low lying levels. Indeed, when using a magnetic spectrograph one can effect dispersion matching and obtain separation of particle groups from levels whose energy difference is smaller than the spread of energy on target.

3. MSU CYCLOTRON AND BEAM ANALYSER

Fig. 1 shows the layout of the MSU Cyclotron and of the beam analysing and switching system. The excellent beam properties of the MSU Cyclotron have been previously reported and new data is being presented at this conference.[4] The properties of the analysing system can be found in ref. 1. Fig. 1 shows the separated function analysing system (dipoles, quadrupoles, sextupoles) which provides a highly dispersed beam ($\Delta E/E = 3 \times 10^{-4}$ per mm) at its focal plane ($S3$).

The following tabulation presents the results of two recent beam transmission studies with 36 MeV protons for energy resolution on target (full width at half maximum of 1/6000 or 6 keV).

Table 1

Date	*Run no.*	*Internal beam* (nA)	*External beam* (nA)	*Target beam* (nA)
6-8-69	1	900	900	130
6-8-69	2	2800	2800	250
20-8-69	3	700	700	135
20-8-69	4	6300	6300	600

The late August data indicates transmission close to the theoretical limit.[4]

As can be seen from Table 1, the beams provided are more than adequate in quantity and quality for the purpose of high resolution nuclear experiments.

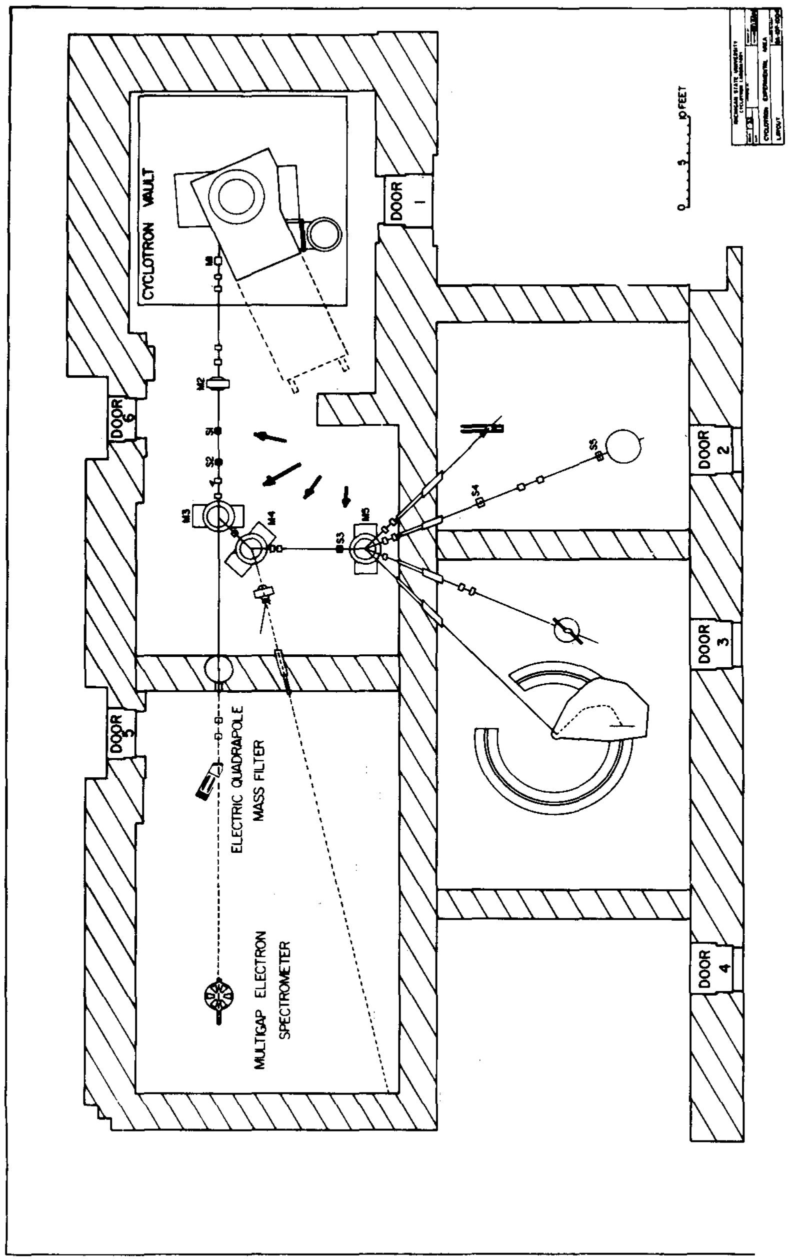

Fig. 1. Experimental area of MSU Cyclotron Laboratory. The arrows indicate the elements which constitute the analysing system

4. PERFORMANCE AND RESULTS

Fig. 2 shows data taken on the ^{28}Si + p reaction going over a 3 keV resonance at $E_p \simeq 5{\cdot}2$ MeV. The beam current for an energy spread of 1 keV (*FWHM*) was approximately 20 nA, reflecting principally the fact that at the time of these experiments the cyclotron magnetic field had not been measured at these very low excitations. The data of Fig. 2 is of particular interest in that it displays

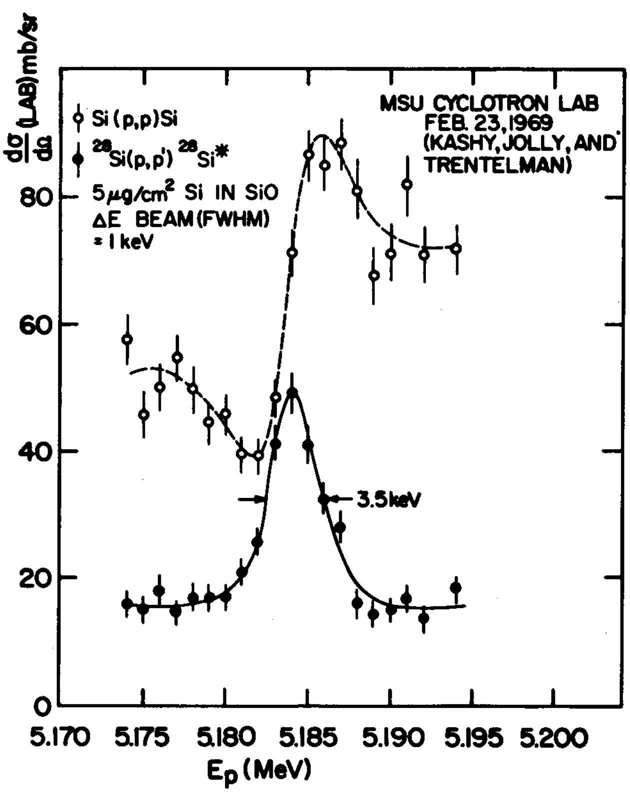

Fig. 2. Excitation function for the reaction ^{28}Si + p *at* $E_p \sim 5{\cdot}2$ *MeV showing a resonance in the* ^{29}P *compound system. The solid lines are drawn to guide the eye. (The energy scale should read approximately 10 keV higher than shown)*

nearly true line shape of the reaction cross-sections, as both beam resolution and target straggling are small compared to the 3 keV resonance width. This data was taken using a simple post acceleration system surrounding the target, i.e. a Faraday cage surrounding the target whose potential could be changed from +3 to −3 kV. It is also worth noting that when taking such data with a very thin, non-uniform target, rotation of the target is often necessary to smooth out fluctuations due to changes of the position of the beam on target.[5] In the present instance, both rotating and stationary targets were used, with no noticeable gain seen from using target rotation. This reflects the unusual degree of spatial stability in the cyclotron beam.

Fig. 3 shows scattering cross-sections of protons from ^{28}Si around 5·8 MeV. Two very narrow resonances are seen in the figure. The one at 5·834 MeV is of special interest to the nuclear structure physicist as it is identified[3] as the isobaric analogue to the ^{29}Al ground state, with a width of approximately 170 eV.

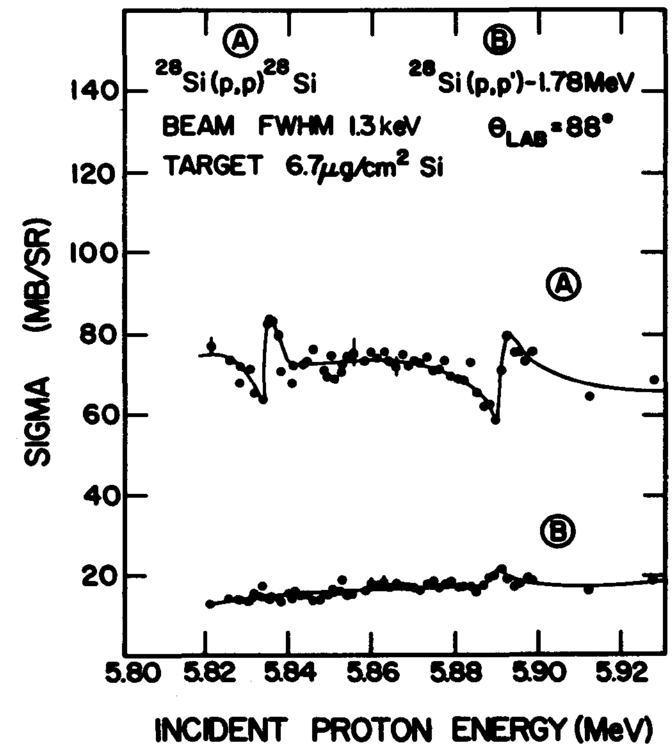

Fig. 3. Excitation function for the reaction $^{28}Si + p$ *at* $E_p \sim 5{\cdot}83$ *MeV showing two compound resonances. For both resonances the experimental resolution is affecting the line shape*

The data of Fig. 3 shows the highest resolution obtained so far for these resonances. The contributions from both straggling and beam exceed the 170 eV value considerably, but it is hoped that both can be reduced in the near future.

Fig. 4 shows proton spectra recently obtained by C. R. Gruhn and collaborators for the reaction $^{64}Ni(p, p')\,^{64}Ni$ with an overall resolution of 21 ± 2 keV.[7] Using laboratory made Ge(Li) detectors they were able to achieve these excellent results, quite comparable to those achieved by magnetic spectrographs. The cyclotron beam contribution amounted to 6 keV at the incident proton energy of 40 MeV.

It is possible to use a highly dispersed beam of incident particles in conjunction with a magnetic spectrograph to resolve reaction particles from nuclear states whose energy difference is less than the energy spread of the incident beam. The technique is called dispersion matching,[7] and is accomplished by making the energy dispersion of particles on target equal to the natural

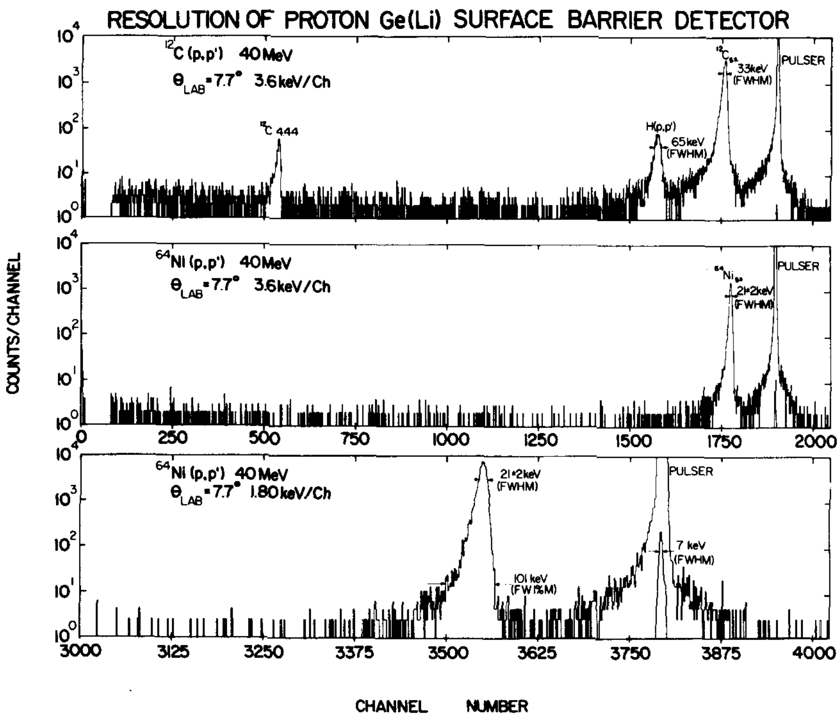

Fig. 4. Spectra of protons inelastically scattered from a ^{64}Ni *target. The incident proton energy is 40 MeV*

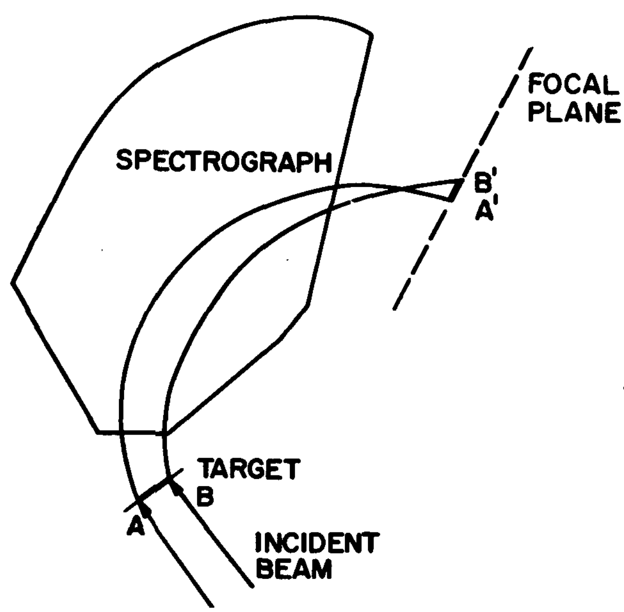

Fig. 5. Dispersion matching. If energy on target increases from B *to* A *image width* A′ B′ *will be reduced*

dispersion of the spectrograph. The result is a reduced image width for a given energy reaction particle, and hence greater resolution.

Fig. 5 shows two monoenergetic rays A and B passing from the target to the focal plane of a spectrograph. If the incident energy along the target varies smoothly making the rays from A more energetic than those from B, the radius of curvature of A will increase slightly, that of B will decrease, and the image width $A' B'$ will be reduced. The beam dispersion apparent to the spectrograph is adjusted by changing the target angle relative to it. Since the spectrograph sees the projection of the beam spot normal to it, this procedure changes the apparent beam spot size for a constant energy spread, and therefore changes the incident dispersion $\Delta E/\Delta X$. The dispersion matching can only be optimised for a limited range of angles of target and spectrograph, but partial matching is realised at all angles.

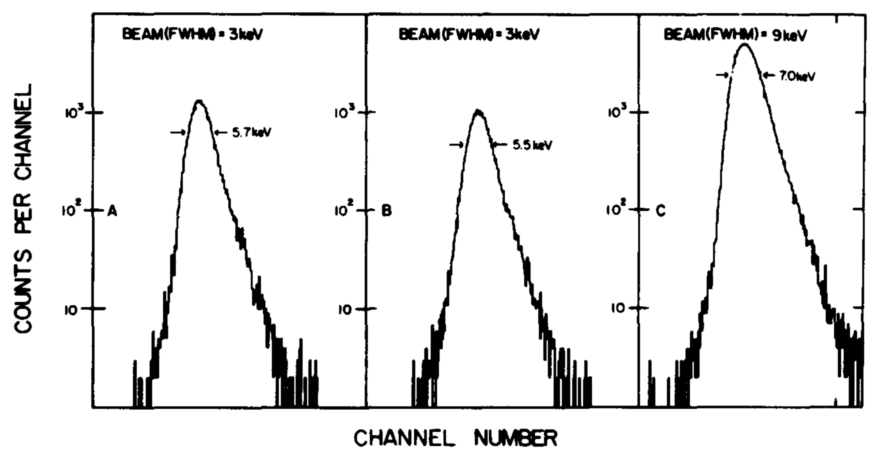

Fig. 6. Spectra are ^{209}Bi(p, p) *with* E_p = *5·83 MeV measured at spectrograph focal plane with position sensitive counter. Spectra* A *and* B *were taken with 3 keV beam and divergence limits of ±3 mr and ±1 mr respectively; spectrum* C *with 9 keV dispersed beam incoherent to 3 keV*

Table 2. CALCULATED CONTRIBUTIONS TO THE EXPERIMENTAL RESOLUTION OF 5·83 MeV PROTON IN ^{209}Bi(p, p) SCATTERING

Detector and electronics	3·0 keV
Beam incoherence	3·0 keV
Straggling	2·0 keV
Source size for ΔE_{Beam} = 3 keV	2·9 keV
Source size for ΔE_{Beam} = 9 keV	8·7 keV

	Total resolution calculated assuming no dispersion matching	*Experimental resolution obtained*
Spect a.	5·5 keV	5·5 keV
Spect b.	5·5 keV	5·7 keV
Spect c.	9·9 keV	7·0 keV

This phenomenon was tested by observing elastically scattered protons from ^{209}Bi detected in a 120 micron position sensitive detector. Fig. 6 shows three spectra taken at a bombarding energy of 5·83 MeV, the first two with non-dispersed 3 keV beams of high and low divergence respectively, the third with a 9 keV beam dispersed across the target.

The comparison of the calculated resolution with that observed is shown in Table 2. The resolution in the dispersion matched beam situation is approximately 3 keV better than that calculated for a 9 keV non-dispersed beam. Since the target angle used was not the optimum angle, it should be possible to achieve even better results. Thus, one is able to use much larger beams on target with only small degradation of the resolution.

In conclusion, it is clear that the modern cyclotron performs very successfully in high resolution nuclear experiments at low energy while achieving comparable results at energies above those available to electrostatic accelerators. It does this while retaining all the advantages usually associated with cyclotrons, such as high intensity beams at moderate energy resolution.

DISCUSSION

Speaker addressed: E. Kashy (MSU)

Question by J. W. Broer (Technological University of Eindhoven): When using a target at, e.g. 1 kV, do you have the difficulty of charge accumulation caused by the incoming beam?
Answer: We had difficulties with this problem for some time until we surrounded the target with a Faraday cage, e.g. a metal container connected to the target. The potential of the cage was then changed to change the incident energy.
Question by J. Vervier (University of Louvain): How much time is needed to change the cyclotron energy?
Answer: Only a few minutes. For small steps, say 1 keV, about 1 minute is required.
Question by P. Macq (University of Louvain): What was the incident energy?
Answer: 6 MeV.
Question by P. A. Roche (Saclay): What is the reproducibility of your energy for different settings, and is it possible to compare relative and absolute values?
Answer: With proper re-cycling procedures in exciting the analysing magnet, we have reproduced the energy to better than 1 keV at 5·8 MeV bombarding energy. We have also checked the analysing system by measuring (p, n) neutron thresholds.

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