IMPROVED ENERGY RESOLUTION WITH THE MSU CYCLOTRON

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Abstract

Recent measurements at MSU of inelastic proton scattering at 35 MeV using the Enge split-pole magnetic spectrograph have been made with energy resolution of $E/\Delta E$= 23,000 (1.5 keV FWHM). The cyclotron-magnetic spectrograph system is operated in the dispersion matching mode, with the full cyclotron beam delivered to the target. Several phenomena which can limit the ultimate resolution have been observed. The narrowest lines recorded (50 μm FWHM in the spectrograph focal plane) imply as an absolute upper limit that 80% of the cyclotron's beam is contained within an incoherent radial emittance area of 0.4 mm-mr.

1. Introduction

The close relation between the ability to resolve nuclear levels and the ability to get information necessary to understand nuclei better is widely accepted. This fact has served as one strong motivation for the construction of several large magnetic spectrograph systems in various cyclotron laboratories, because the geometrical nature of the focusing process involved in particle detection in a spectrograph is uniquely adaptable for exploiting dispersion matching, which allows the resolution to approach the limit determined by the incoherent beam emittance area, even in the presence of large coherent energy fluctuations.

At the previous cyclotron conference calculations were presented[1] to indicate line width limits imposed in the MSU dispersion matching system by cyclotron emittance considerations. Since that time we have improved the resolution obtained in test runs by more than a factor of 2, from $E/\Delta E$=10,000 to 23,000. This result sets a new upper limit on the cyclotron emittance, as discussed below.

Although the cyclotron ion source emittance sets the ultimate resolution limit of the system, other phenomena may determine the limit in actual practice. The effects of several such phenomena, which we have observed, are described below. Some of these parameters, such as target thickness, are often selected in actual experiments to increase the count rate rather than optimize resolution. The resolution of most experiments is limited by the aberrations and low dispersion of the Enge split-pole magnetic spectrograph,[2] which was not originally designed for use in such a high resolution system.

2. Recent Results

A brief description of the procedure used to tune the cyclotron and beam transport system will be given here. The object is to transport a beam to the target with an energy spread of $\lesssim$0.1% with the spatial correlations necessary for the spectrograph to operate in the dispersion matching or energy-loss mode, and to thereby obtain line widths with $\Delta E/E \lesssim 0.01\%$ in the focal plane.

All cyclotron and beam transport system parameters are initially set at precalculated values. The beam transport quadrupole lenses are fine tuned to obtain good images visually at scintillator locations. Without further optimization this procedure normally yields energy resolution of 2000-4000 in the spectrograph.

The resolution is improved beyond this point via the on-line tuning procedure described previously.[3] With this method it has recently been possible under ideal conditions (very thin targets, very small spectrograph solid angle, etc.) to obtain an energy resolution of 23,000 or 1.5 keV FWHM with the 35 MeV proton beam scattered from carbon and nickel targets. In these runs all of the extracted cyclotron beam (~1μA) was transported to the target, and the runs were as long as one hour. The recent improvements came from a reduction of spectrograph solid angle and the elimination of excessive voltage ripple on the electrostatic deflector.

The results obtained from inelastic proton scattering from a 20 μg/cm^2 ^{58}Ni target are shown in Fig. 1a. The beam energy was 35 MeV, the scattering angle 15°, and the state indicated is the first excited state of ^{58}Ni recorded on a nuclear track plate in the focal plane of the spectrograph. The line width is 50 μm FWHM, and 82% of the area of the peak is contained within 100 μm. The spectrograph solid angle was limited to 0.06 msr for this exposure.

3. Resolution Limiting Phenomena

We have identified 6 important line-broadening phenomena, which we now discuss.

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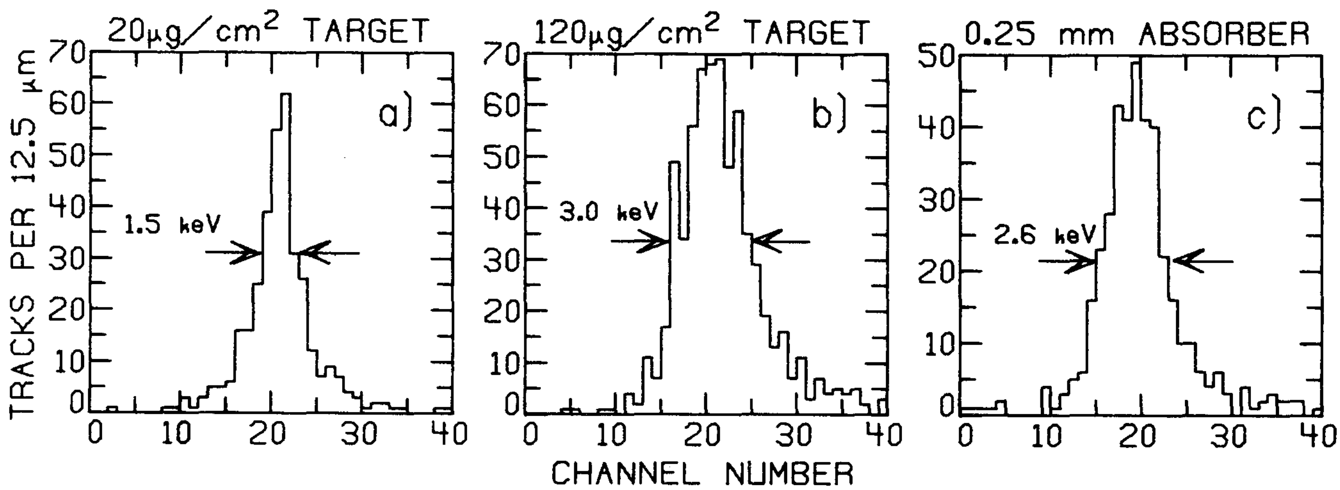

Fig. 1.--The results of inelastic scattering of 35 MeV protons from Ni targets. The spectra were recorded on nuclear track plates in the focal plane of a magnetic spectrograph. a) A scan of the peak corresponding to the first excited state of ^{58}Ni. The target was 20 μg/cm^2 of ^{58}Ni evaporated onto a 20 μg/cm^2 carbon backing. b) Similar to a), except a 120 μg/cm^2 target was used. c) Similar to a), except a 0.25 mm thick stainless steel absorber was used just before the nuclear track plate.

They are 1) scattering from residual gas in the beamline and the spectrograph, 2) aberrations, 3) target energy loss and scattering effects, 4) scattering from absorbers placed before photographic plates, or in the case of live detectors, scattering from the detector window, 5) instability of a bending or focusing element, and 6) ion source luminosity (non-zero emittance).

3.1 Scattering from Residual Gas

The air pressure in the spectrograph is typically 100 to 200 μTorr over a path length of about 3m. In the beam transport system the pressure typically varies between 100 and 500 μTorr over the 18 m. path from the cyclotron to the spectrograph. We have made an estimate of the upper limit of the effect of scattering in the spectrograph alone, using the usual approximate multiple scattering theory that gives a Gaussian distribution. At a pressure of 100 μTorr the full width at half maximum along the focal plane (45° incidence) is about 100 μm. This is an overestimate because 1) focussing is neglected and 2) the statistical assumption of many collisions occurring is violated, which leads to a more sharply peaked angular distribution. A more realistic calculation of this effect has not been done, but it seems likely that it may be contributing a significant fraction to our 50 μm line widths. On one occasion a small leak occured in the beam line during tuning for best resolution. When the leak was repaired the resolution improved noticeably.

3.2 Aberrations

The fact that an energy resolution of 23,000 has been obtained indicates empirically that the net spatial aberrations of the cyclotron and beam transport system are very small at least in the radial or x-direction. Any residual x^2 aberration due to any optical component before the target can in principle be compensated for by an adjustable sextupole magnet which is located at a vertical cross-over point in the beam transport system. The strength of this magnet is adjusted empirically via the on-line tuning procedure. It is not known at this time if cyclotron or beam transport system aberrations are contributing any significant amount to the line widths obtained to date.

Spectrograph aberrations, on the other hand, are very significant and are often the dominant limitation of resolution in practical experiments. The aberrations of the Enge split-pole magnetic spectrograph are discussed in reference 2, and our measurements are in approximate agreement with these predictions. The resolution of 23,000 was obtained with a 1/2° diameter circular spectrograph aperture (0.06 msr), whereas the resolution has never been better than 15,000 with a 1° x 1° (0.3 msr) aperture. For these small apertures it seems that the x/θ^3 and x/ϕ^2 aberrations are comparable in magnitude, where θ and ϕ are the horizontal and vertical entrance angles, respectively. Resolution values of approximately 5000 can be obtained with a 2° x 2° aperture (1.2 msr). Clearly a highly corrected magnet such as a Q3D spectrograph is necessary to provide large solid angle at a resolution properly matched to this accelerator beam quality.

3.3 Target Thickness Effects

The empirically obtainable energy resolution deteriorates very quickly as a function of target thickness. We are currently trying to interpret these results quantitatively in terms of energy loss straggling and multiple angular scattering in the targets. Some preliminary results will be presented here.

In Fig. 1b the line broadening due to a 120 μg/cm² ^{58}Ni target is shown under conditions identical to those of Fig. 1a for the 20 μg/cm² ^{58}Ni target. Even though the total average energy loss of the protons in a 120 μg/cm² target is only ~1 keV the effect of this target on the overall line width is clearly significant, since the resolution decreased by a factor of two.

The combined calculated effects of energy loss straggling and multiple scattering in the target are not adequate to explain the effect quantitatively. These effects, calculated according to the theory of Molière, given in Ref. 4, are 0.6 keV and 0.06° rms, respectively. The multiple angular scattering nulifies the kinematic compensation by (0.10°) x $\Delta E/\Delta\theta$=0.55 keV FWHM in this case. Adding both of these effects in quadrature to the intrinsic line width of 1.5 keV yields a predicted resolution of 1.71 keV which is much less than the 3 keV empirical result. Large target thickness variations within the area of the beam spot could explain the effect, but the target did not appear nonuniform or granular. It is possible that the theory of Ref. 4 underestimates the straggling effects for such thin foils. At the present time we do not have a satisfactory quantitative explanation for the rapid deterioration of resolution with target thickness.

3.4 Absorbers and Detector Windows

It is sometimes necessary to put a sheet of material in front of a photographic plate in the spectrograph to prevent less-penetrating unwanted particles from reaching the plate, for example deuterons in a proton scattering experiment. The multiple scattering of the desired particles broadens the spectral lines. The amount of broadening increases as the atomic number of the absorber increases or the density decreases, since the thickness for a given energy loss is inversely proportional to the density. Using the full width at half maximum of the Gaussian distribution on the plate as a criterion, the best material appears to be copper, as illustrated by Table 1. Elements in the copper region have relatively high density and moderate atomic number. Note that the use of the rms scattering angle as a criterion would favor light elements.

Table 1.--Multiple scattering effects for 35 MeV protons in several absorber materials for constant proton energy loss[5] (ΔE). Calculations assume Gaussian angular distribution, and that absorber is in contact with plate. Columns marked FWHM give the full width at half maximum along the focal plane, which is inclined at 45° to the incident direction. T is the normal absorber thickness, ρ is density.

Absorber material	ρ	ΔE = 5 MeV			ΔE = 15 MeV		
		T	FWHM	θ_{rms}	T	FWHM	θ_{rms}
	g/cc	mm	μm	deg	mm	μm	deg
Copper	8.92	.358	61	3.6	.944	301	6.7
Tungsten	19.3	.227	61	5.7	.602	304	10.6
Stainless Steel	7.7	.398	64	3.4	1.05	313	6.3
Gold	19.3	.231	65	5.9	.613	320	11.0
Beryllium	1.85	1.31	84	1.3	3.41	406	2.5
Mylar	1.40	1.55	108	1.5	4.05	526	2.7

The absorber thicknesses in Table 1 give a constant energy loss to the incoming proton. If one uses the thickness required to stop, say deuterons of the same magnetic rigidity a different order results, as shown in Table 2. This would be appropriate for our inelastic proton scattering experiments.

Table 2.--Multiple scattering effects for 35 MeV protons in several absorber materials. The thickness T is adjusted to stop deuterons of the same magnetic rigidity (17.76 MeV). See Table 1.

Absorber material	Density [g/cc]	T [mm]	FWHM [μm]	θ_{rms} [deg]
Copper	8.92	.284	43	3.2
Stainless Steel	7.7	.312	44	2.9
Beryllium	1.85	.892	46	1.1
Tungsten	19.3	.205	53	5.4
Gold	19.3	.212	56	5.6
Mylar	1.40	1.077	62	1.2

We see that the optimum use of absorbers in the traditional way places a limit on the resolution at about 20,000 in a spectragraph with the dispersion of the Enge split-pole. This effect is smaller in spectrographs with larger dispersion.

In Fig. 1c the empirical effect of a 0.25 mm stainless steel absorber is shown. The resolution would have been as indicated in Fig. 1a if the absorber were not present. The actual line width obtained was even larger than calculations such as those in Table 1 predicted. The discrepancy can be explained by assuming a 0.3 mm gap between the absorber and the photographic plate. Such gaps are hard to avoid in practice unless very flat absorbers are used.

The plastic windows that are generally employed on gas-filled position sensitive detectors can be at least 10 times thinner than a typical absorber used on a plate, but the counter is also much thicker than the absorber. The limit on line width imposed by window and gas scattering is in the 100 to 200 μm range for a typical counter. Low atomic number materials are favored because of the large distance (several mm) between the window and the remote side of the active region of the detector. One such detector[6] using a tapped delay line for position readout gives a resolution of 220 μm FWHM and has been in use for a few months at the MSU cyclotron.

3.5 Instability of a Bending or Focusing Element

Fluctuations in the strength of bending or focusing elements in the beam path can reduce the spatial coherence of the beam and thereby decrease the resolution. The cyclotron and beam line magnets are sufficiently stable that they do not contribute appreciably to the observed line widths. The only instability which we have linked with a loss of resolution was a case of excessive ripple (5% peak to peak) on the voltage to the electrostatic deflector. After normal operation was recently restored (ripple ~0.3%) the present higher resolution data were obtained. Attempts at high resolution before that failed to yield values better than 10,000 (typically 6000).

3.6 Cyclotron Emittance

If the radial phase space of a cyclotron beam is not distorted by crossing resonances or by non-linear effects such as result from centering errors, and if the beam is extracted on a single turn then its effective emittance area is determined by the ion source. In that case, one can arrange for the beam spot on the target to be an image of the ion source aperture, and the width of the spectral line in the spectrograph focal plane is limited in principle by the width of the ion source slit, rather than by other slits in the beam transport system. Thus, the maximum resolution obtainable with a given beam current is limited by the source brightness. The narrow line widths observed in our spectrograph place a smaller upper limit on the emittance of our cyclotron beam and ion source than inferred from previous measurements.

We have measured line widths of 50 μm FWHM on elastic scattering of 35 MeV protons from ^{12}C at 15 degrees in the laboratory. A conservative upper limit on the incoherent beam emittance can be estimated by assigning the full line width to the incoherent spot size (Δx_{max}) and divergence ($\Delta\theta_{max}$) separately. We shall use the line width of 100 μm, which includes 82% of the area. Since the radial magnification perpendicular to the trajectory in the spectrograph is 0.35, Δx_{max}=202 μm (corresponding to 100 μm in the focal plane). The divergence limit is related by kinematic energy change with angle to the line width expressed in terms of energy (3.0 keV) as follows:

$$\Delta\theta_{max}=(3.0 \text{ keV})/(27 \text{ keV/degree})=1.9 \text{ mr}$$

The extreme upper limit on the emittance (assuming a rectangular shape) is, therefore, 0.4 mm-mr. If the divergence were as large as 2 mr, there would be a noticeable improvement in resolution when going from carbon to a heavier nucleus. The fact that the line width for scattering from nickel (kinematics: 5.5 keV/deg) is no better than for carbon implies that the divergence may be substantially less than 2 mr. Considering this it seems likely that the incoherent radial emittance is <0.2 mm-mr, with a beam current of 1 μa on target.

The emittance measurements by Mallory[7] on the precursor of our present ion source predict a 6 mm-mr emittance at 35 MeV for a source with a 1.5 mm wide slit. We now use a slit 0.2 mm wide, which furthermore has a 30° bevel that was not present on the old source. Thus, the line width data are loosely consistent with the measured emittance. A source testing facility is under construction as part of a new beam line at MSU, and we hope to be able to measure the source emittance within a few months.

4. References

1. E. Kashy, H.G. Blosser, and D.A. Johnson, AIP Conference Proceedings No. 9, Cyclotrons--1972, Eds. J.J. Burgerjon and A. Strathdee, p. 430.
2. J.E. Spencer and H.A. Enge, Nucl. Instr. and Methods 49,181(1967).
3. H.G. Blosser, G.M. Crawley, R. de Forest, E. Kashy, and B.H. Wildenthal, Nucl. Instr. and Methods 91,61(1971).
4. H.A. Bethe, Phys. Rev. 89,1256(1953).
5. C.F. Williamson, Jean-Paul Banjol and Jean Picard "Tables of Range and Stopping Power of Chemical Elements for Charged Particles of Energy 0.05 to 500 MeV" Commissariat a l'Energie Atomique, France. CEA-R 3042 (1966).
6. R.G. Markham any R.G.H. Robertson MSUCL-173 (June 1975) and to be published.
7. M.L. Mallory and H.G. Blosser, IEEE Trans. on Nuclear Science NS-13 #4 163(1966).

DISCUSSION

G. SCHATZ: What is the lifetime of your ion source when you put 1 μA into that emittance?

P.S. MILLER: About two to three days.

J. REICH: Is the 0.06 m.s.r. of solid angle a current situation required by experimentalists?

P.S. MILLER: Experiments are usually done with larger solid angle; consequently, with poorer resolution.

J. REICH: What would be the resolution, if you open up the solid angle to 1 m.s.r?

P.S. MILLER: At a solid angle of 1 m.s.r. the best energy resolution is approximately 8'000 FWHM.

F. RESMINI: Could you comment about the beam current you get with the emittance you just quoted?

P.S. MILLER: The experiment was performed with 1 μA on the target.

Y. JONGEN: I am wondering, how short is your pick-up electrode? What is the axial length of the beam burst?

P.S. MILLER: Approximately 6 cm, corresponding to a phase width of 3°.

G.C.L. VAN HEUSDEN: What is the time constant of the feedback loop?

P.S. MILLER: The time constant of the feedback loop is limited by the response of the magnetic field to a change in current, which is a few tenths of a second. The frequency response of the trim coil field is more suitable for feedback control than the main magnet is.

G.C.L. VAN HEUSDEN: What is the minimal current at which the control loop can run?

P.S. MILLER: The minimum beam current that is usable for feedback control is about 0.2 μA.