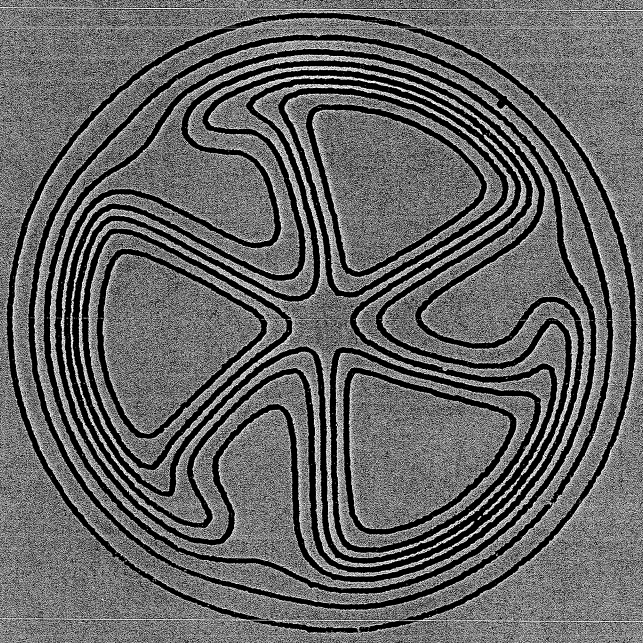
MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

STUDYING NUCLEI WITH 30 TO 40 MeV PROTONS AND 3 TO 4 keV RESOLUTION

H.G. BLOSSER



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STUDYING NUCLEI WITH 30 TO 40 MeV PROTONS AND 3 TO 4 keV RESOLUTION*

H.G. Blosser

Invited Paper
presented at
1973 New York Meeting
of the
American Physical Society

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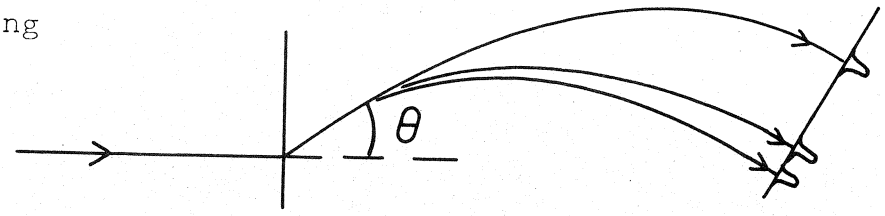
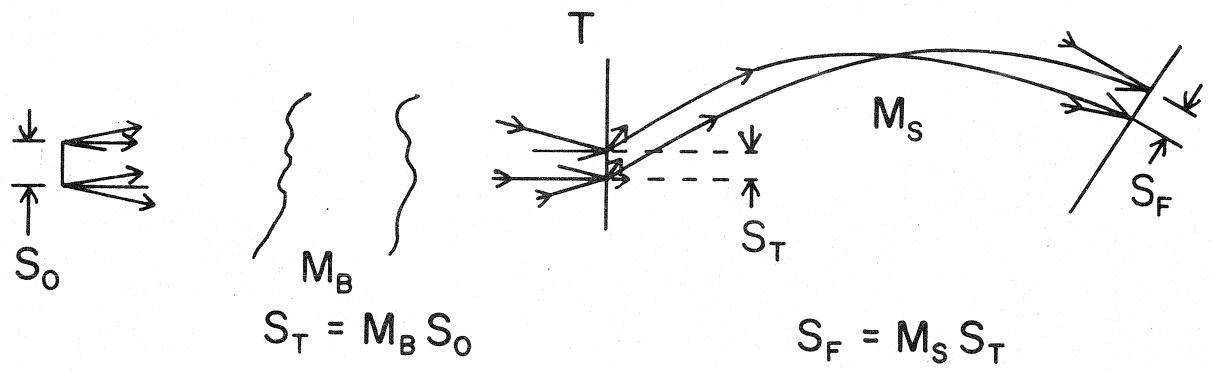
At Michigan State we have a 50 MeV variable energy Cyclotron and an Enge 90 cm split-pole spectrograph. The general layout of this equipment is shown in Slide 1. The cyclotron is at the upper right and feeds through a 90° analyzing magnet and a 45° switching magnet to the spectrograph scattering chamber located at the bottom center. The split-pole spectrograph can be used to analyze reaction products over an angular range from -20° to +165°. With this system we are able to obtain an energy resolution of 1 part in 10,000—which is a momentum resolution of 1 in 20,000—and we can do this with beams of about 1 μa on target. The key experimental techniques of this system are 1) to operate the cyclotron in the so-called single-turn mode; 2) to satisfy a dispersion matching condition at the target; and 3) to use an on-line resolution meter to guide fine adjustment of parameters. In this talk I want to review the conceptual basis of these techniques and then show some examples of results.

Suppose we first think a bit in detail of the kinds of things that happen at the target as seen in Sketch A. We have a beam incident and a spectrograph collecting and analysing particles scattered at some angle Θ and producing lines in the spectrograph focal plane. What are the factors which determine the widths of these lines and hence the resolution of the system? There are a lot of



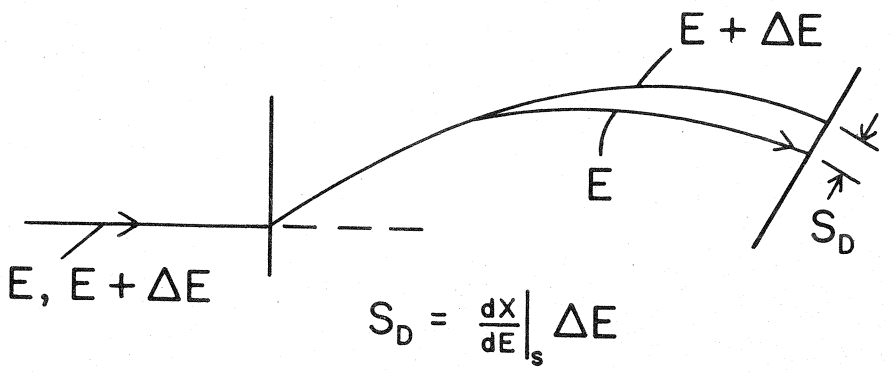
Sketch A

contributions—I will go through the more important ones step by step. First consider the so-called spot size contribution as seen in Sketch B. Even if the incident beam is monochromatic the



Sketch B

particles will come from some effective source of a particular size and thus will be distributed over a finite spot on the target corresponding to the size of the effective source multiplied by an effective magnification for the total beam system before the target. This will then image into a spot in the spectrograph focal plane whose width is just the target spot times the horizontal magnification of the spectrograph. For our system, for example, we have an S_o of about 0.3 mm an M_B of about 1 and an M_S of about 0.3 and so we get a line width contribution of about 0.1 mm from this spot size effect. This is for a monoenergetic beam. The incident beam will of course have an energy spread as indicated in Sketch C; this will give a corresponding spread in the energy of reaction products and the particles will bend by differing amounts in the spectrograph and go to different places on the spectrograph

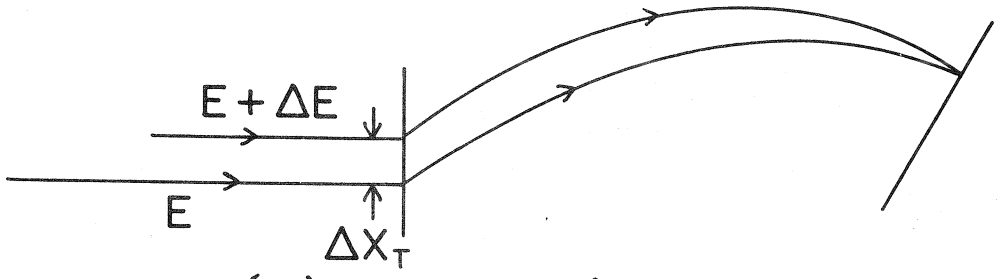


Sketch C

focal plane. This displacement due to the energy spread is determined by the dispersion of the spectrograph. For a 90 cm split-pole the dispersion is given fairly accurately by the simple rule that a 1 percent change in energy gives 1 cm of displacement measured along the focal plane. If the energy spread in the incoming beam were .05% which is a fairly typical value in our setup we would then expect a .5 mm contribution to the line width from the dispersion. Fortunately this large line width contribution can be very nicely eliminated by using the dispersion matching technique as was first pointed out by B.L. Cohen quite a few years ago. The arrangement is also often called an energy-loss spectrograph.

The key point is to notice from Sketch B that a shift in the position of the spot on target will produce a shift in position of the image in the focal plane with the ratio of the two shifts given by the magnification. If I then coherently shift the particles of high energy up on the target this will move them down in the focal plane and will bring them back to the same position as the particles

with the reference energy, if the displacement shift just balances the energy spread shift as indicated in Sketch D. When this cancellation is satisfied the system is said to be dispersion matched.

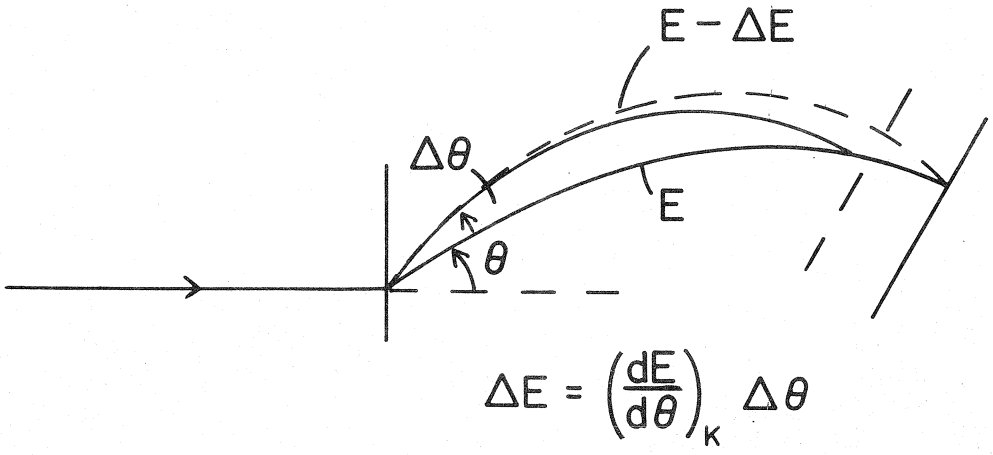


$$M_S\ \Delta X_T = \left(\frac{dE}{dX}\right)_S \Delta E \Longrightarrow \left(\frac{\Delta X}{\Delta E}\right)_T = \left(\frac{dE}{dX}\right)_S \frac{1}{M_S}$$

Sketch D

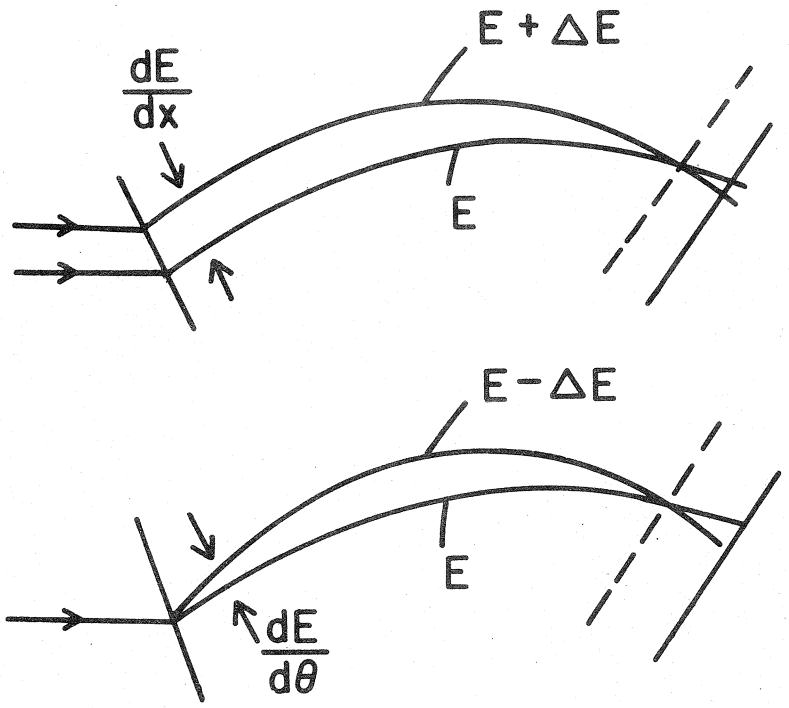
A coherent shift of the energy displaced part of the incident beam of course corresponds simply to putting dispersion into the incident beam. This is easy to do since any bending magnet introduces dispersion and quadrupoles change the magnitude and sign of dispersion. I will come back later and talk about just how this is done in practice for various reactions. Please, also note that the formulas in the various sketches should have geometrical terms coming from things like how the target angle relates to the scattering angle and how the focal plane is oriented relative to the particle direction. I have left out terms of that sort since they do not effect the main concepts.

Let us then go on and consider other contributions to the line width. Another important effect is the kinematic spread indicated in Sketch E. If the scattered particle goes off at an angle $\theta+d\theta$



Sketch E

it will leave more energy in the recoiling nucleus and hence will itself have a lower energy so that the actual particle energy depends on the scattering angle. The net effect of this phenomenon is however just a shift of the focal plane position since the ray at the larger Θ value has a lower E and therefore bends more and crosses the reference ray earlier and likewise the ray at a smaller Θ value bends less and crosses the reference ray earlier. If we then shift the focal plane to the new crossover point the line width contribution from this effect is eliminated. Is it possible to simultaneously correct the kinematic shift and cancel the dispersion? The answer to this is yes, for any one point on the focal plane. Qualitatively what we have are two independent linear effects as shown in Sketch F—we have rays diverging from a point with a coherent energy variation dE/dΘ—the place where they cross we call the kinematic focus—and we have displaced parallel rays with a coherent energy variation dE/dX and the place that they

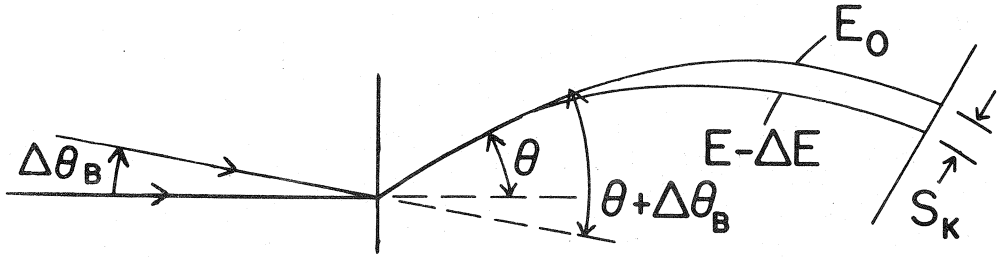


Sketch F

cross we call the dispersion focus. By changing the dispersion I move the E+ΔE ray up or down and therefore shift the crossover point in or out—with the right choice I can make the two planes coincide. If I look at the problem quantitatively though I find that the two crossover conditions coincide at just one point. Slide 2 shows a real calculation for the case of 30 MeV protons incident on ^{12}C with the spectrograph set at a lab angle of 20°. The dashed curves show the location of the kinematic crossovers for protons, deuterons, and tritons where in each case the magnet is assumed to be set to put the ground state group for the particular reaction at 87 cm. Elastic protons would hence focus at

87 cm and displaced towards the magnet by a bit over 1 cm, protons of 10 MeV less energy corresponding to a 10 MeV excitation would focus around 70 cm and also with an approximate 1 cm shift. If the magnet is now reset to put ground state deuterons from the reaction $^{12}C(p,d)^{11}C$ at 87 cm, the kinematic crossover occurs about 3 cm from the normal focal plane and 4 MeV excitation occurs at about 70 cm and so on. The dispersion crossover location is shown by the solid curves in Slide 2. These curves have a distinctly different slant than the kinematic curves. I can shift the dispersion curves up and down as I like, by changing the incident beam dispersion and therefore I can make the dispersion curve for a particular reaction cross the kinematic curve whenever I want to. At this location the beam energy spread and the kinematic spread are simultaneously cancelled. Minimum line width will occur close to the kinematic plane or close to the dispersion plane depending on the relative size of $\Delta\Theta$, the spectrograph acceptance angle, and ΔE, the energy spread on target.

Another contribution to the energy spread comes from the angular spread of the incident beam on target as seen in Sketch G.



$$S_K = \left(\frac{dE}{dX}\right)_S \Delta E = \left(\frac{dE}{dX}\right)_S \left(\frac{dE}{d\theta}\right)_K \Delta\theta_B$$

Sketch G

This angular spread in the incident beam means that particles that come off at a fixed scattering angle in the laboratory actually have a distribution of scattering angles corresponding to the spread in the incident beam and there is hence an incoherent energy spread at any angle proportional to the kinematic shift $dE/d\theta$. This contribution to the line width, in combination with the spot size effect, leads to the statement that the minimum attainable line width will be determined by the phase space density of the incoming beam. If I put on more powerful quadrupoles for example to make the contribution from the incident spot size smaller I will make the incoming beam divergence larger and therefore enlarge this kinematic contribution to the line width. I should also note that there is a scheme suggested by J. Thirion for cancelling even this effect by moving the focal point away from the target. Whether this really helps or not is a bit up in the air right now and I will not talk about it more here. In fact I will not talk in detail about any other contributions. There are axial motion effects which are small, there are target thickness effects which are well known and there are aberration effects which I will discuss further on. What I want to do now is go on and talk about the problem of matching a cyclotron into such a system.

From the previous discussion we have seen that the phase space density is a key quantity in determining the two residual contributions to the line width, namely that coming from the on target spot size and the on target divergence of the incoming beam. How then do we arrange a cyclotron to produce a beam of maximum phase

space density? We can immediately draw a major qualitative conclusion from Liouville's theorem which tells us that a system of conservative fields cannot change the microscopic phase space density of a beam and thus can readily reduce the macroscopic phase space density by a variety of disorderly processes which mix filled and unfilled phase space. The way to obtain maximum phase space density is then to arrange the cyclotron so that there is a single well-defined and highly linear optical path from the cyclotron ion source all the way through the accelerator and beam transport system to the target. When the cyclotron is operated with such a one track optical path it is called single-turn operation since all of the particles enter the deflector on the same revolution. The requirements for such operation can be qualitatively understood from Slide 3. Present cyclotrons use a sinusoidal accelerating voltage and particle "a" on the peak of the wave will receive an energy gain proportional to the maximum voltage on each revolution and after some number of revolutions will enter the deflector. If I consider particles away from the peak of the wave they receive a smaller energy gain and therefore the turn pattern shrinks in and starts to hit the deflector. There is an interesting situation when energy gain is down by just a factor of 1/n where n is the number of turns—this particle "b" will slip in radius by just one turn in the acceleration process and will come to the deflector lined up in radius and ready for extraction. It will however still have a different optical path and will be different in other characteristics such as the direction it is heading. If this

second group is then piped to the target it will have a slightly different position or direction and will then go to a different place in the spectrograph focal plane thus broadening the final line. One requirement for single-turn extraction is hence to use only a narrow region of the rf wave, the interval being set so that the voltage variation in this range is small compared to the 1/n condition for a second turn to be extracted. In a similar way a change in the amplitude of the accelerating voltage as a function of time will shift the turn pattern in or out proportional to the voltage and if the shift is sufficiently large particles from a different turn will start to enter the deflector and go to the target thus again giving a different optical path. Also, time variations in the magnetic field strength will cause the radius of a particular turn to shift in or out and again, beyond a certain tolerance level, multiple turns will enter the deflector. The requirements for single-turn extraction are then in a nut shell: to accurately stablize both the magnetic field and the accelerating voltage and to confine the beam to a narrow phase interval relative to the voltage.

Techniques for phase selection in a cyclotron are a substantial topic in themselves and have been dealt with in a number of papers. Phase selection in the MSU cyclotron is accomplished by a set of three strategically placed slits located on different turns in the central region of the cyclotron. I do not want to go into detail about this system this morning. Let me simply say that with the system in use beams of 1 to 5 microamperes can be obtained in a

phase interval corresponding to a few rf degrees. Stablization of the rf voltage and of the magnetic field are basically accomplished with normal analogue feedback loops but in addition, once the single-turn condition is met, beam sensing feedback loops can be employed to further improve the stablization. Slide 4 shows a schematic diagram of the cyclotron and analyzing system. In the single-turn mode the cyclotron is functionally equivalent to an rf acceleration system and a bending magnet. If the voltage rises the beam will bend less in the magnet and hence will move to the right as it leaves the cyclotron and if the voltage falls the beam will bend more and will move to the left as it leaves the cyclotron. This then allows us to put a feedback slit at the exit port of the cyclotron and feedback to the rf voltage in a manner exactly analogous to the feedback circuit which Van de Graaffs normally employ to control their terminal voltage. An independent feedback loop to a magnetic field is also possible since the first order effect of a change in the field is to shift the phase of the beam relative to the rf and this is qualitatively different from the effect of an rf voltage change. Finally then from the cyclotron we have a very high quality beam characterized by emittances of about .5 mm milliradians in the radial plane and 5 mm milliradians in the axial plane.

Now let us talk about the beam transport system. The job of the beam transport system is to carry the beam from the cyclotron to the spectrograph target and in the process to shape the spot size and the dispersion in a way which will give optimum resolution. In the first part of the talk I mentioned that the requirement on

dispersion was determined by the Q-value of the reaction whereas the optimum compromise between spot size and divergence was determined by the mass of the target nucleus. For heavy nuclei, resolution is improved by setting the optical system for smaller magnification and large divergence whereas for light nuclei the opposite is true. Any arrangement of quadrupoles effects all of these properties. We have for instance at MSU three quadrupoles between the last bending magnet and the target. Each is separately powered so that the system is really a set of three singlets. It is then a straightforward beam transport problem to obtain a set of currents for these three singlets which will satisfy the three conditions of producing a horizontal focus and a vertical focus on the target and give a dispersion of a specified value. So by using these three quadrupoles one can set the dispersion to any value desired while maintaining a double focus. This system alone cannot however in addition give a freely adjustable value for the magnification—that would be 4 constraints and three variables. It still could not be done though, even with a 4th quad, since one can show mathematically that a system of quadrupoles will always change dispersion and magnification in an exactly coupled way. If there are bending magnets in the system however such as the 90° and 45° bends which we have, it is possible to independently change dispersion and magnification corresponding to optimization for light and heavy nuclei respectively, and hence by appropriate use of the variable parameters in the transport system we match the beam to the requirements for best resolution. This then is all I want to say about the basic concepts of our system.

Let me proceed to talk about the use of the system in a practical sense. In practice we find that simply setting all the elements in the system to calculated or even to previously used values is not adequate to insure resolution of much better than 1 part in 2000. It is usually necessary for the best resolution to perform an on-line adjustment. The success of any such adjustment procedure depends heavily on the speed with which information as to the effect of a given incremental change can be obtained. Our way of doing this is based on a device which we call a resolution meter. This is shown in Slide 5. The resolution meter consists simply of a solid state detector placed behind a very narrow slit. This is in fact an old slide—we now use a slit with 1.4 mil opening. The slit is constructed with one thick jaw and one thin jaw. This assembly is then placed in the spectrograph focal plane and some strong group—usually the elastic scattered particles—are lined up on the slit. The two jaws are very much thinner than the range of particles. In fact, the thickness of the jaws is selected to be just thick enough to produce an energy shift which can be resolved by the solid state detector. Slide 6 shows the type of spectrum which is obtained in the detector. The high energy peak corresponds to particles which went through the slit, the low energy peak corresponds to particles which penetrated the thick jaw and the intermediate energy peak corresponds to particles which penetrated the thin jaw. We then use this spectrum for two purposes. First of all we have a computer routine which senses the counts in the two penetration peaks and

from this we derive a feedback signal for the spectrograph magnet such that the magnet is adjusted to keep the counts in the two peaks equal. The spectrum is therefore locked in place in the focal plane. The second function of the computer routine is to compute the fraction of the counts which lie in the high energy peak. This is presented on the oscilloscope screen as a digital percentage for instance 42% in this particular run and it is also presented on an analog meter at the cyclotron console to which some anonymous person has attached the label "relative goodness". Fine adjustment of the total system is then a knob twiddling operation in which one changes dispersion, makes fine adjustments of the focus, shifts the spectrograph focal plane, etc. while watching the "relative goodness" meter. The experimenter continues the process until he is satisfied with the resolution after which a photographic plate or other detection system is moved into position in the spectrograph and a spectrum is recorded.

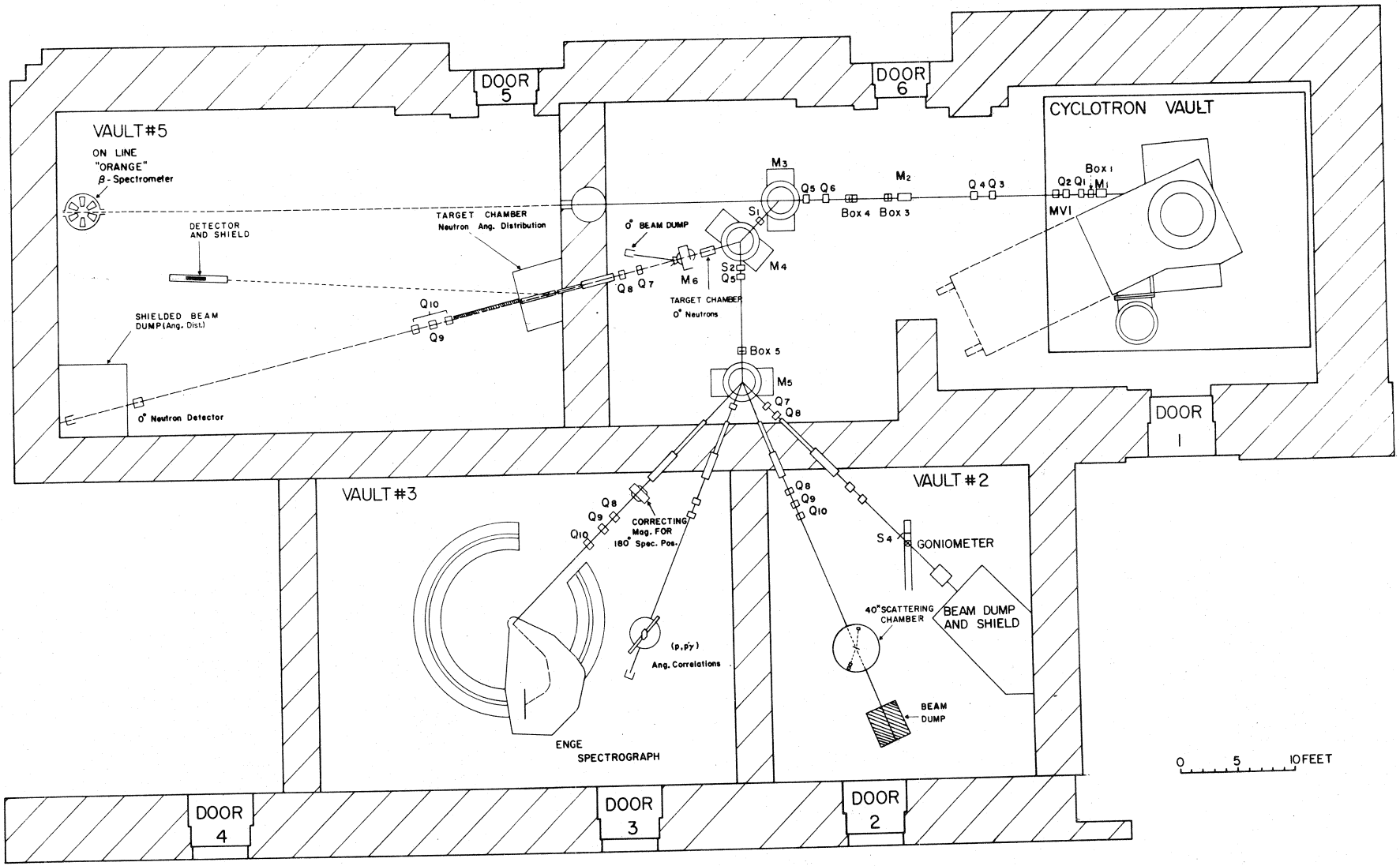
One last comment on the hardware, namely on the question of aberrations. One of the adjustable elements in the beam transport system is a sextupole magnet located at a point which causes it to preferentially effect the horizontal motion. One of the resolution adjustments is then to set the sextupole while watching the resolution meter until maximum resolution is obtained. The sextupole than cancels the dominant aberration of the system, and typically improves the resolution by a factor of 2.

Finally I would like to show a series of slides displaying results obtained with this system. A few of these are

specific instrumentation runs done for the purpose of testing resolution; others are a sampling from various nuclear experiments. Generally the latter have less good resolution principally because the experimentalist is strongly inclined to opt for thicker targets in order to shorten his running time. In any case let us look at the slides. Slide 7 is a (p,p') run on ^{209}Bi taken in the early days of development of the system. We are looking at a well know multiplet at about 2.5 MeV of excitation and the resolution is about 5 kilovolts. Further refinements of the system were later introduced and resolution in p,p' test runs on Carbon has been brought down to 2.8 keV for 30 MeV incident beam. Slide 8 is a (p,p') test run on ^{60}Ni by Nolen. The resolution is 3 keV and the bombarding energy is 35 MeV. Slide 9 is a spectrum from an experiment on ^{208}Pb by Wagner and Crawley. The resolution is 6 keV and the bombarding energy is 40 MeV. The resolution shows for example that the 3^- state at about 4.6 MeV has a weaker closely adjacent neighbor. Slide 10 shows results from a (p,d) experiment on ^{59}Co by Robertson and Nolen. The resolution is about 4 keV which allows them to clearly resolve the 8 kilovolt doublet at .4 MeV. A more detailed scan of this doublet is shown in the box and a photograph of actual proton tracks in the detection plate is shown in Slide 11. Slide 12 shows results from a $^{12}C(p,t)$ test by Kashy. This is the group going to the ^{10}C ground state. The full-width half-maximum is 3.7 keV and the bombarding energy was 40 MeV. Slide 13 shows data from a (p,t) experiment by Goles, Warner, McHarris and Kelly. The resolution is about 6 keV and it allowed them

to pickup even very weak members of rotational multiplets such as the 15/2 level at 1.3 MeV.

Finally let me make just a comment on future plans. Our main effort over the past year has gone into study of the reproducibility of the system. We would like to remove erratic elements and push to a situation where there would be less dependence on knob twiddly. We are also at the moment engaged in a program of improving the cyclotron performance for other particles, particularly deuterons, so that we will be able to run deuteron induced reactions with resolution comparable to proton results. Finally we think we can do about a factor of 2 better in resolution by further refining the stability of the whole system. This expectation is based on phase space density arguments and measurements done in a DC test facility on an actual cyclotron source. All of these areas involve knotty problems and progress is rather slow. We are also doing some planning work on a larger spectrograph. The 90 cm split-pole is really too small for our energy range. It was really designed for use with Tandems. If we had a larger spectrograph we would gain resolution just from the size. We will issue reports as we progress.


DOOR 5
DOOR 6
CYCLOTRON VAULT
VAULT #5
ON LINE
"ORANGE"
β - Spectrometer
DETECTOR
AND SHIELD
TARGET CHAMBER
Neutron Ang. Distribution
0° BEAM DUMP
M3
Q5 Q6
M2
Q4 Q3
Box 1
Q2 Q1
M1
MVI
Box 4
Box 3
S1
M4
S2
Q5
M6
Q8 Q7
TARGET CHAMBER
0° Neutrons
Q10
Q9
SHIELDED BEAM
DUMP (Ang. Dist.)
Box 5
M5
Q7
Q8
0° Neutron Detector
DOOR 1
VAULT #3
VAULT #2
Q8
Q9
Q10
CORRECTING
Mag. FOR
180° Spec. Pos.
Q8
Q9
Q10
S4
GONIOMETER
40° SCATTERING
CHAMBER
BEAM DUMP
AND SHIELD
(p,p'γ)
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BEAM
DUMP
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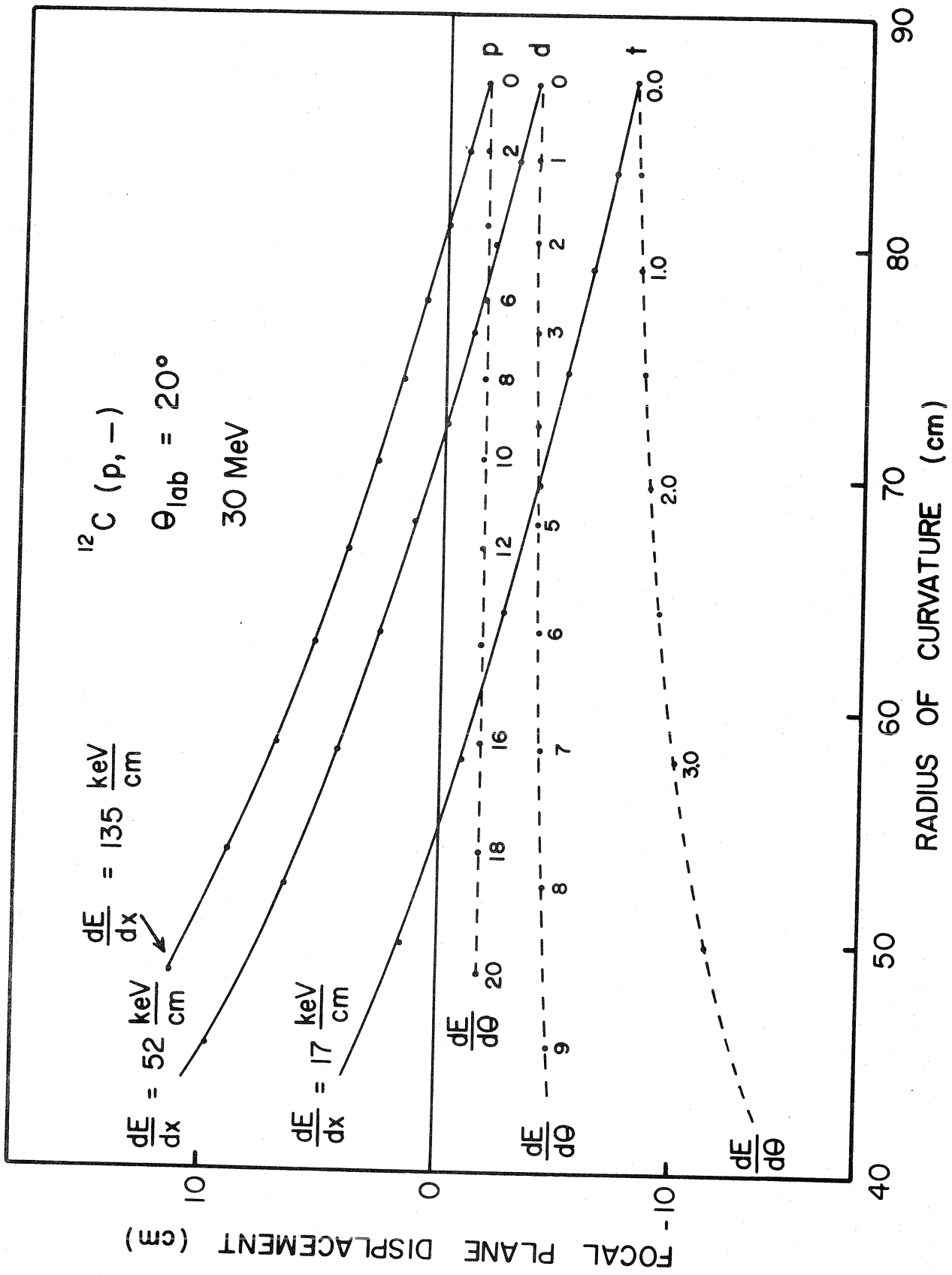
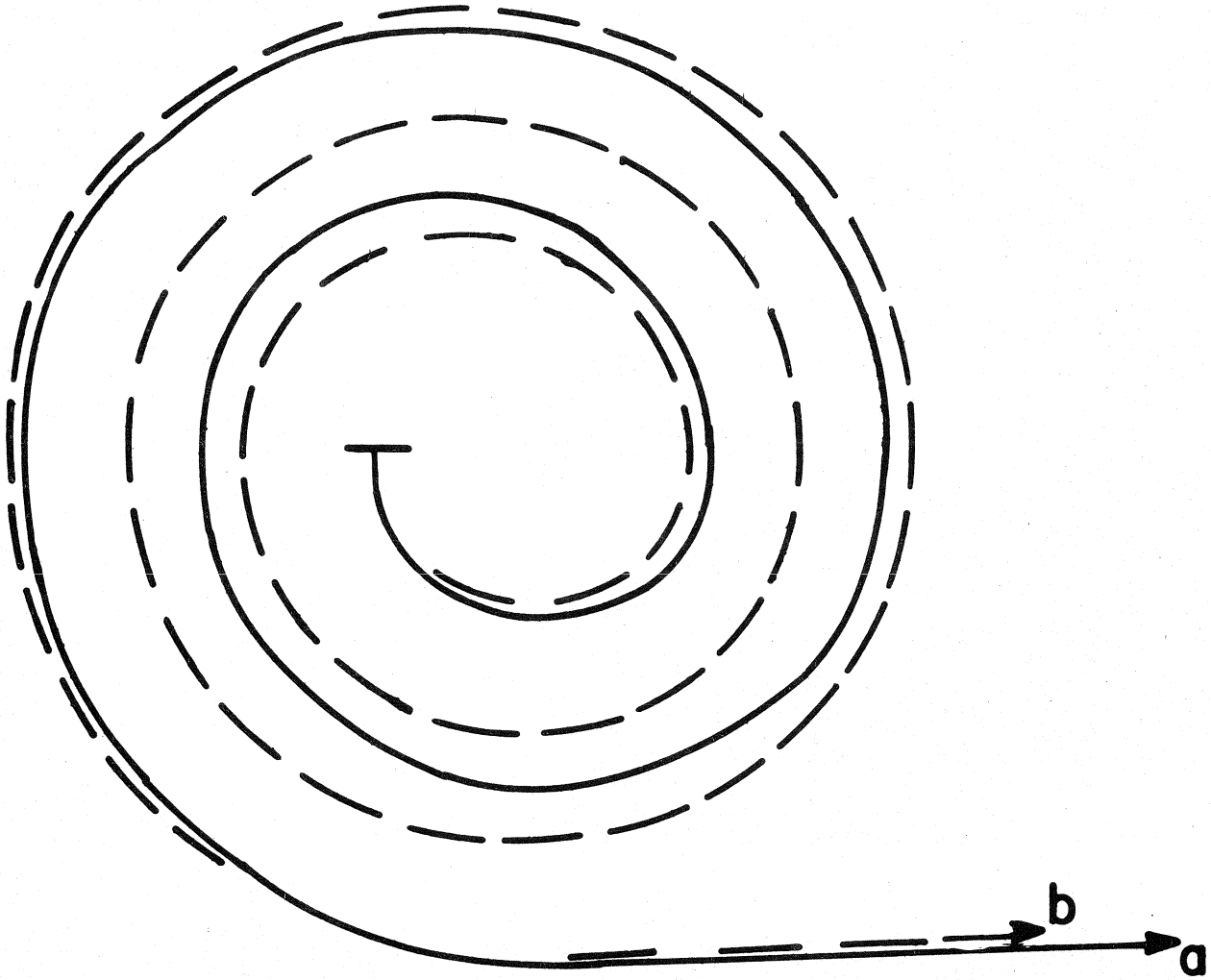
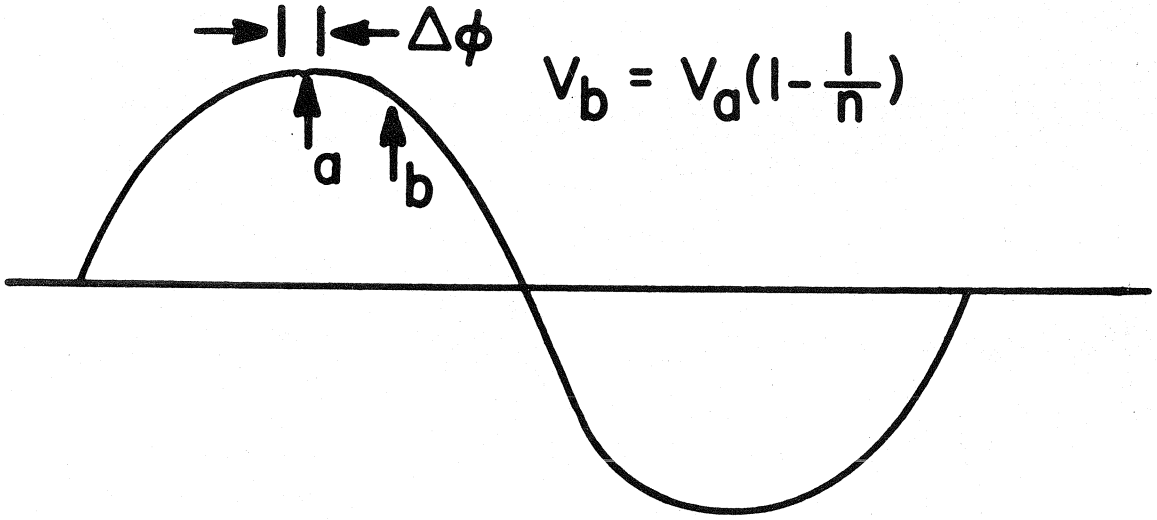
0 5 10 FEET
DOOR 4
DOOR 3
DOOR 2

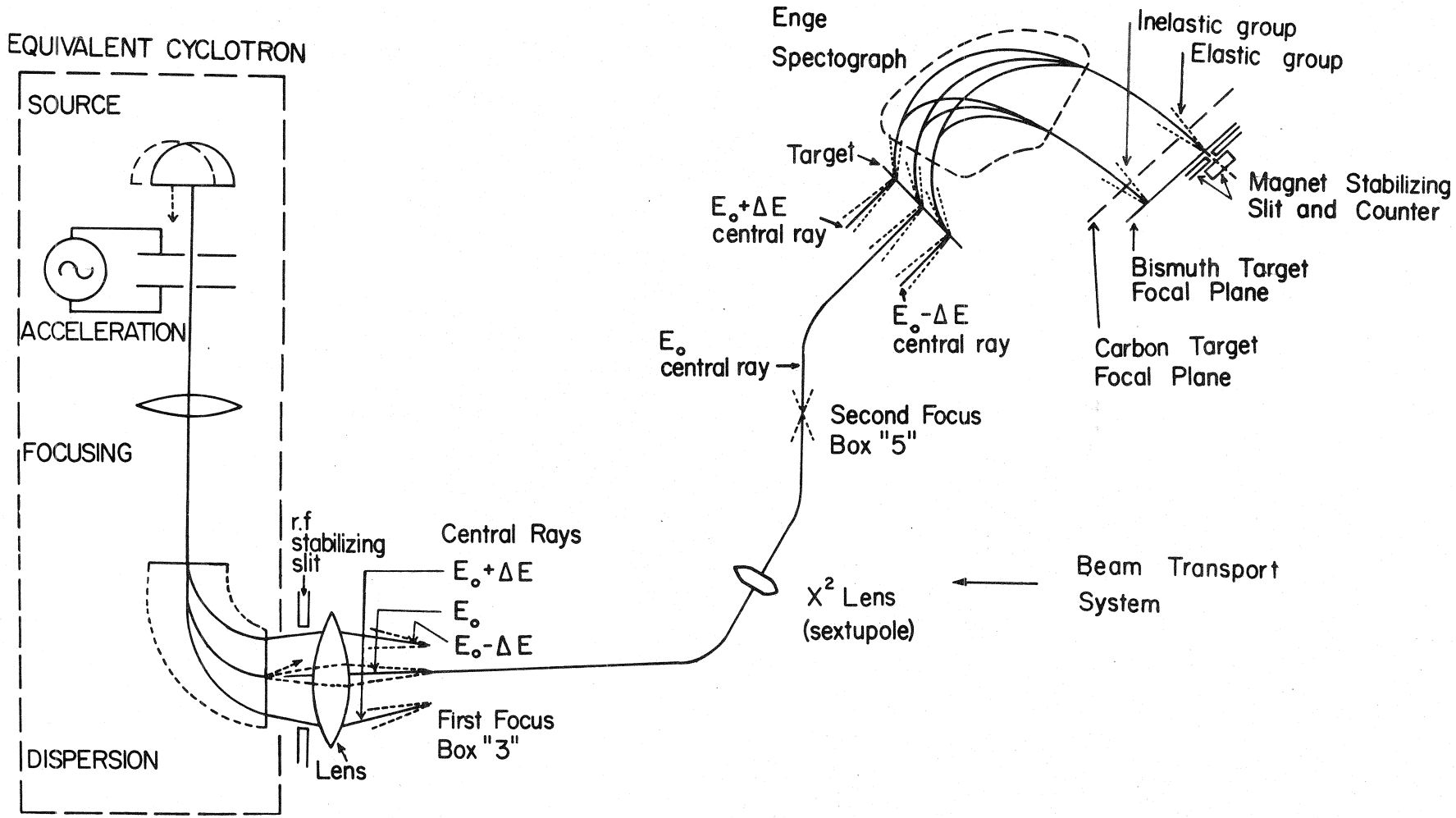
Slide 1


^{12}C (p, –)
θ_{lab} = 20°
30 MeV
$\frac{dE}{dx}$ = 135 $\frac{keV}{cm}$
$\frac{dE}{dx}$ = 52 $\frac{keV}{cm}$
$\frac{dE}{dx}$ = 17 $\frac{keV}{cm}$
p
d
t
$\frac{dE}{d\theta}$
FOCAL PLANE DISPLACEMENT (cm)
RADIUS OF CURVATURE (cm)
10
0
-10
40
50
60
70
80
90

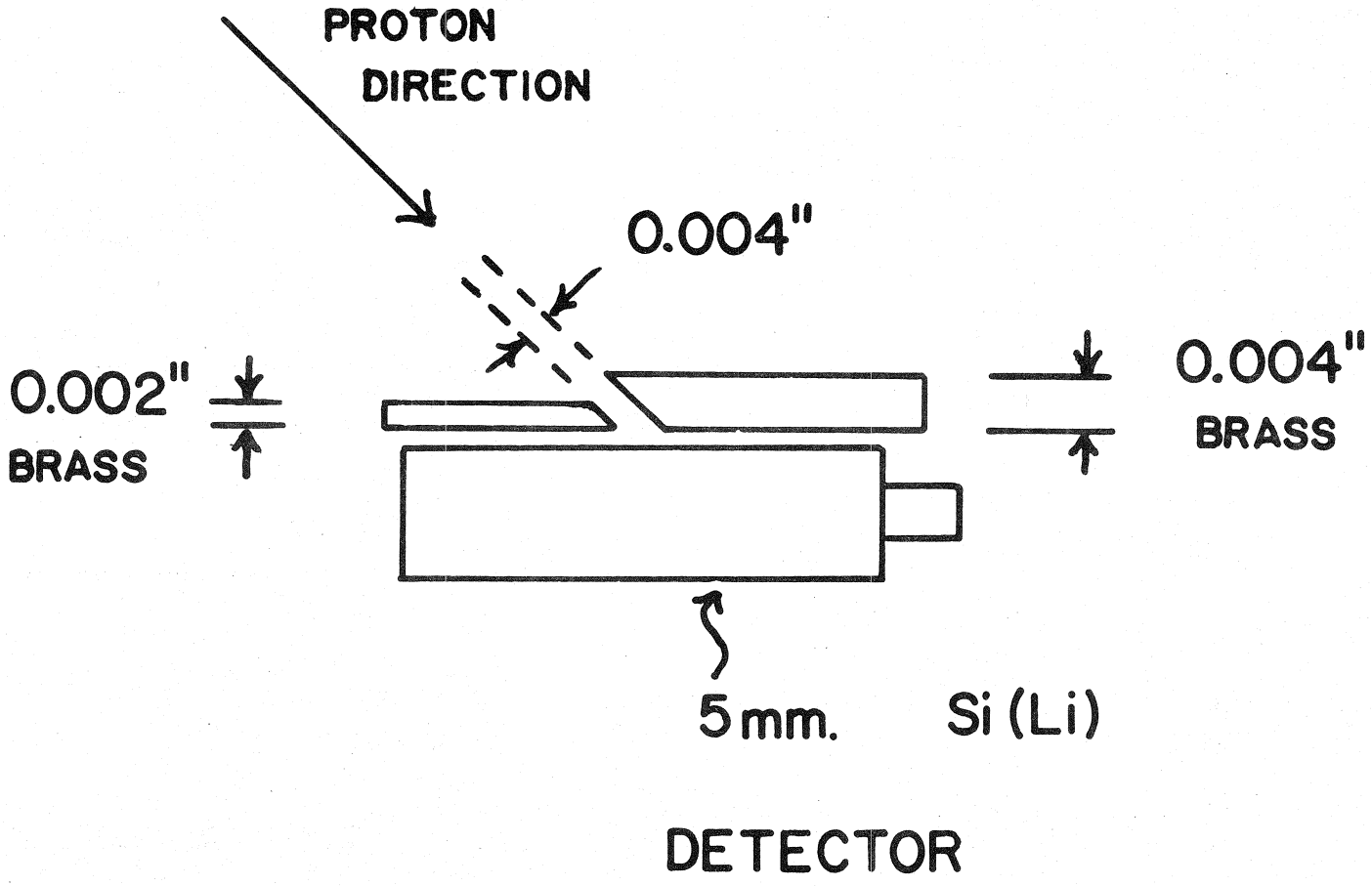




$$V_b = V_a\left(1-\frac{1}{n}\right)$$


EQUIVALENT CYCLOTRON
SOURCE
ACCELERATION
FOCUSING
DISPERSION
r.f stabilizing slit
Lens
Central Rays
$E_o+\Delta E$
E_o
$E_o-\Delta E$
First Focus Box "3"
X^2 Lens (sextupole)
Second Focus Box "5"
E_o central ray
Beam Transport System
Enge Spectograph
Target
$E_o+\Delta E$ central ray
$E_o-\Delta E$ central ray
Inelastic group
Elastic group
Magnet Stabilizing Slit and Counter
Bismuth Target Focal Plane
Carbon Target Focal Plane

DETECTOR SETUP — ELASTIC PEAK



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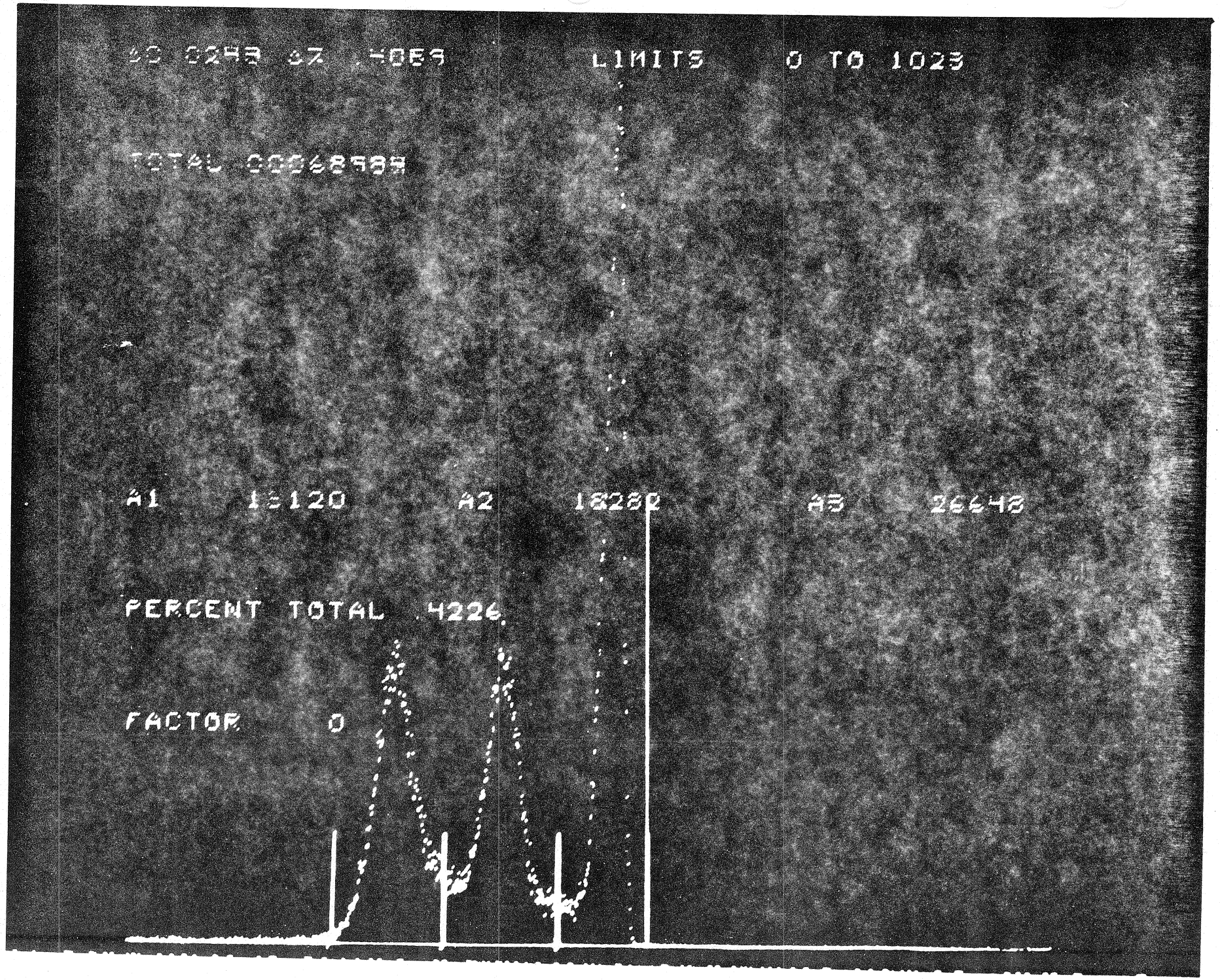
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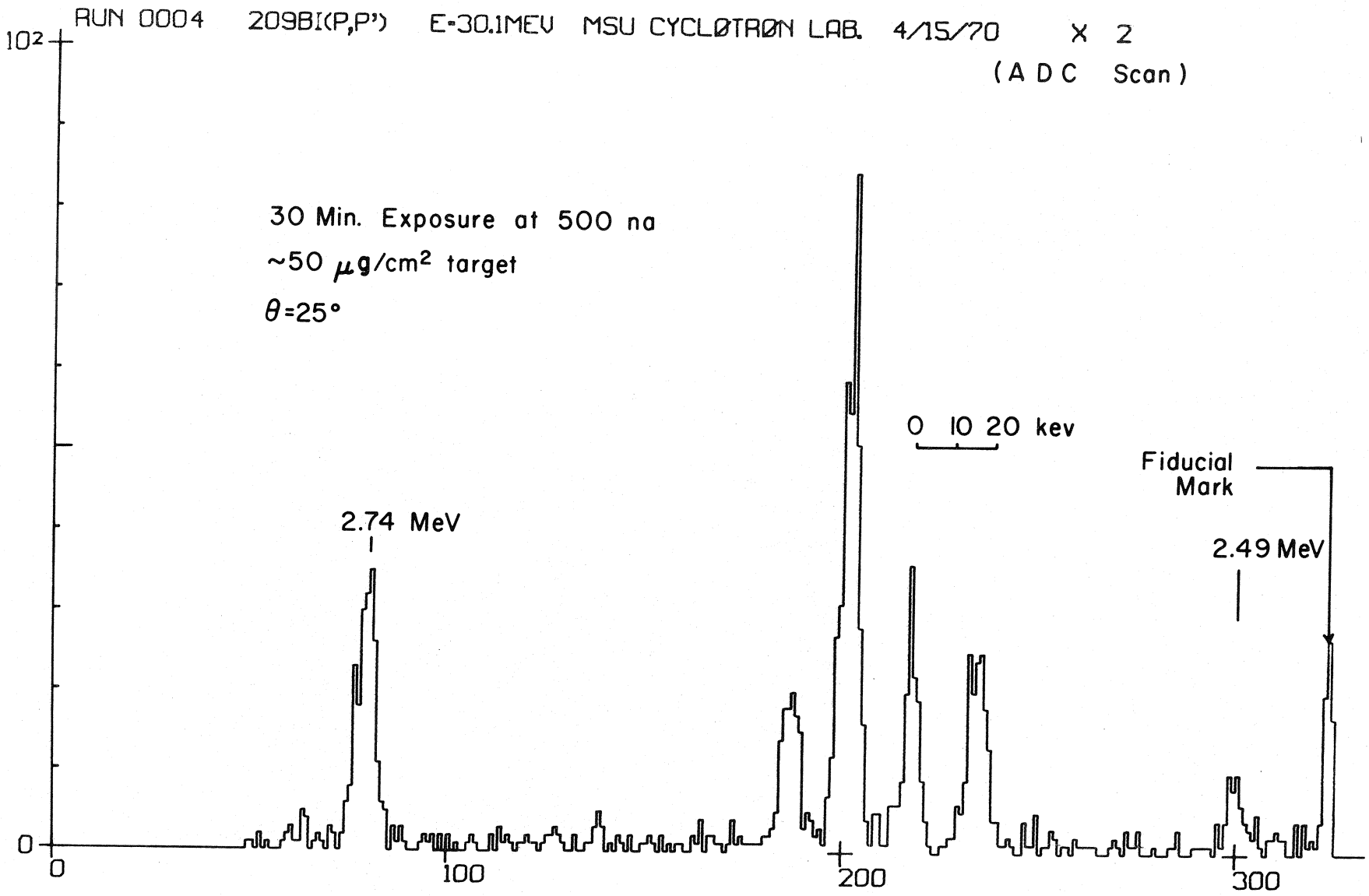
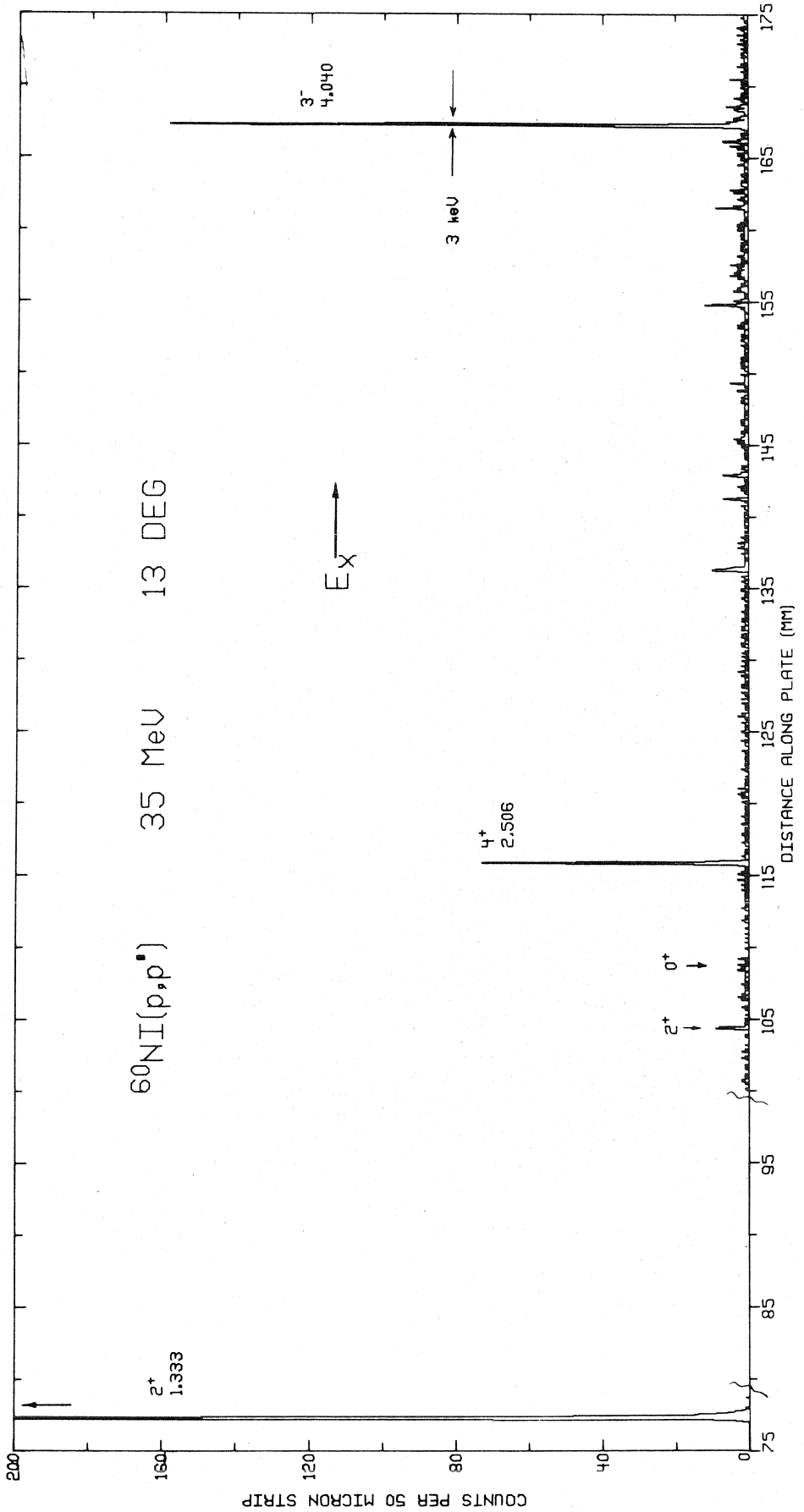
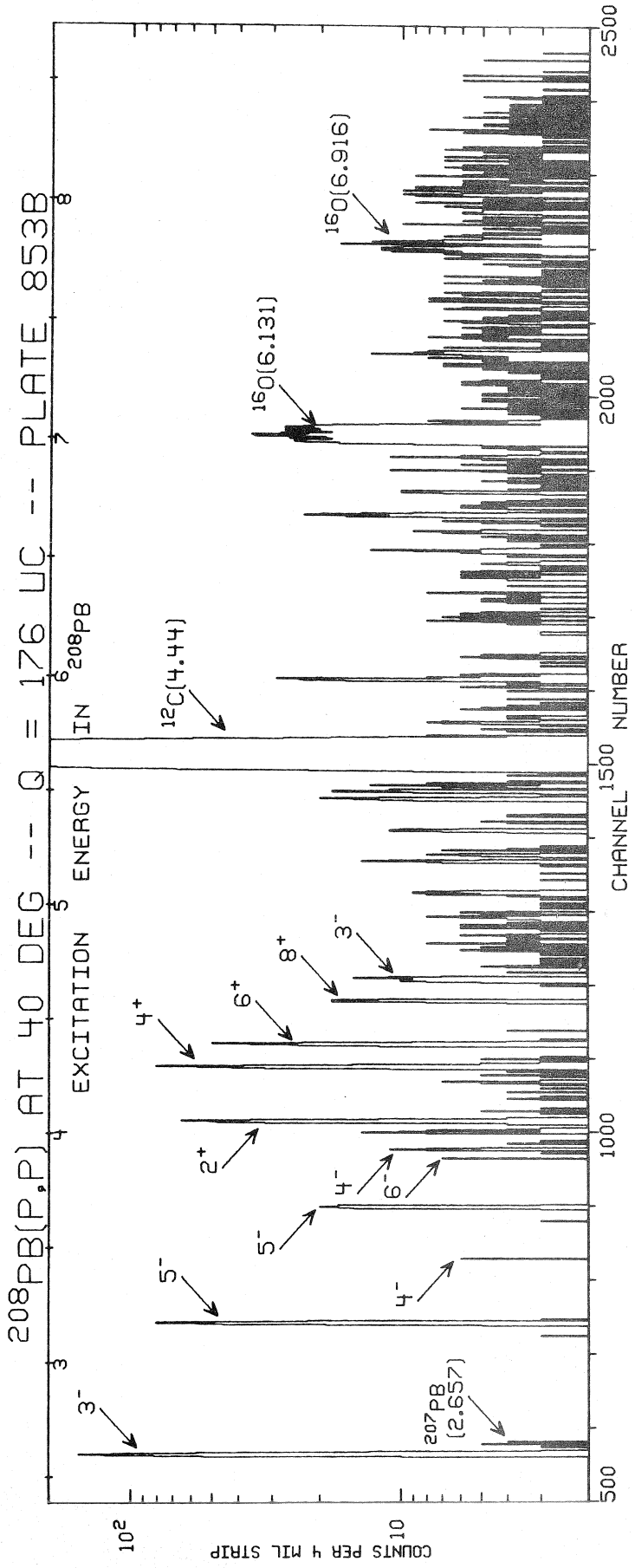
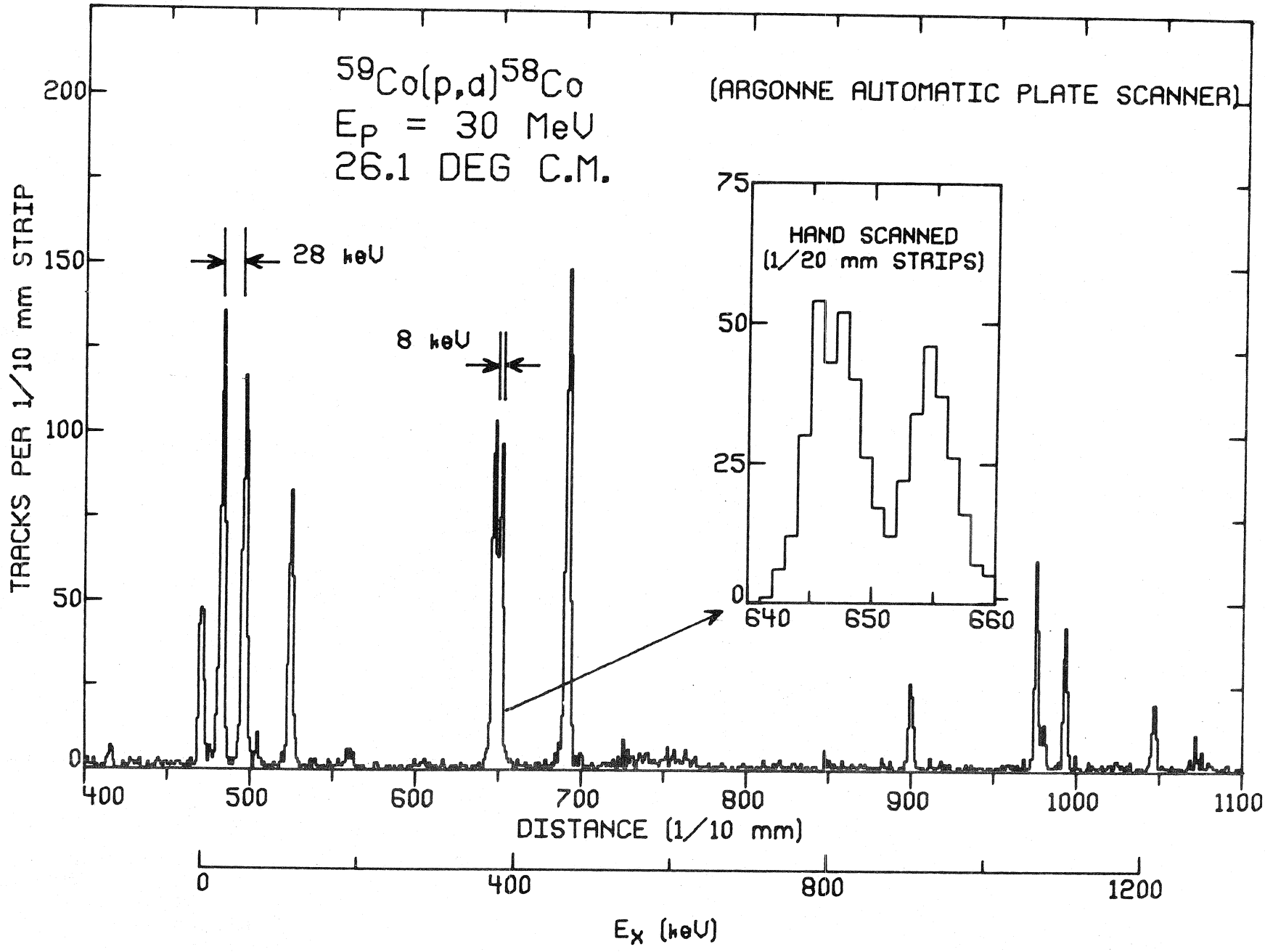
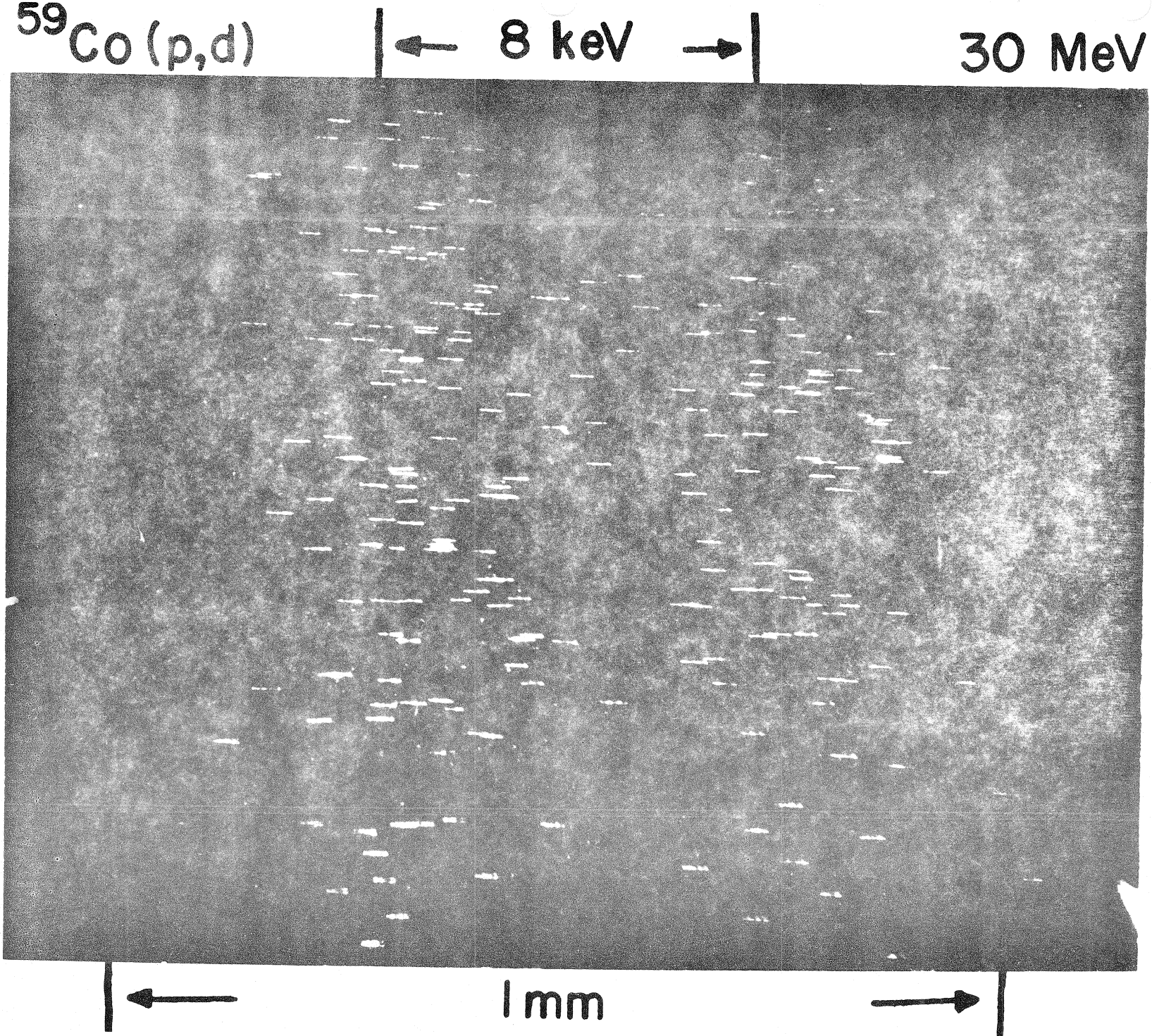
A2 18280
A3 26648
PERCENT TOTAL .4226
FACTOR 0


RUN 0004 209BI(P,P') E-30.1MEV MSU CYCLOTRON LAB. 4/15/70 X 2
(A D C Scan)
10²
0
30 Min. Exposure at 500 na
~50 μg/cm² target
θ=25°
0 10 20 kev
Fiducial Mark
2.74 MeV
2.49 MeV
0
100
200
300


^{60}NI(p,p')
35 MeV
13 DEG
Ex
2+ 1.333
2+
0+
4+ 2.506
3- 4.040
3 keV
COUNTS PER 50 MICRON STRIP
DISTANCE ALONG PLATE (MM)
0
40
80
120
160
200
75
85
95
105
115
125
135
145
155
165
175


208PB(P,P) AT 40 DEG -- Q = 176 UC -- PLATE 853B
EXCITATION ENERGY IN 208PB
COUNTS PER 4 MIL STRIP
CHANNEL NUMBER
500
1000
1500
2000
2500
10
10²
3
4
5
6
7
8
3⁻
5⁻
4⁺
2⁺
5⁻
4⁻
6⁻
6⁺
8⁺
3⁻
4⁻
12C(4.44)
16O(6.131)
16O(6.916)
207PB (2.657)


$^{59}Co(p,d)^{58}Co$
E_p = 30 MeV
26.1 DEG C.M.
(ARGONNE AUTOMATIC PLATE SCANNER)
28 keV
8 keV
HAND SCANNED
(1/20 mm STRIPS)
TRACKS PER 1/10 mm STRIP
DISTANCE (1/10 mm)
E_X (keV)



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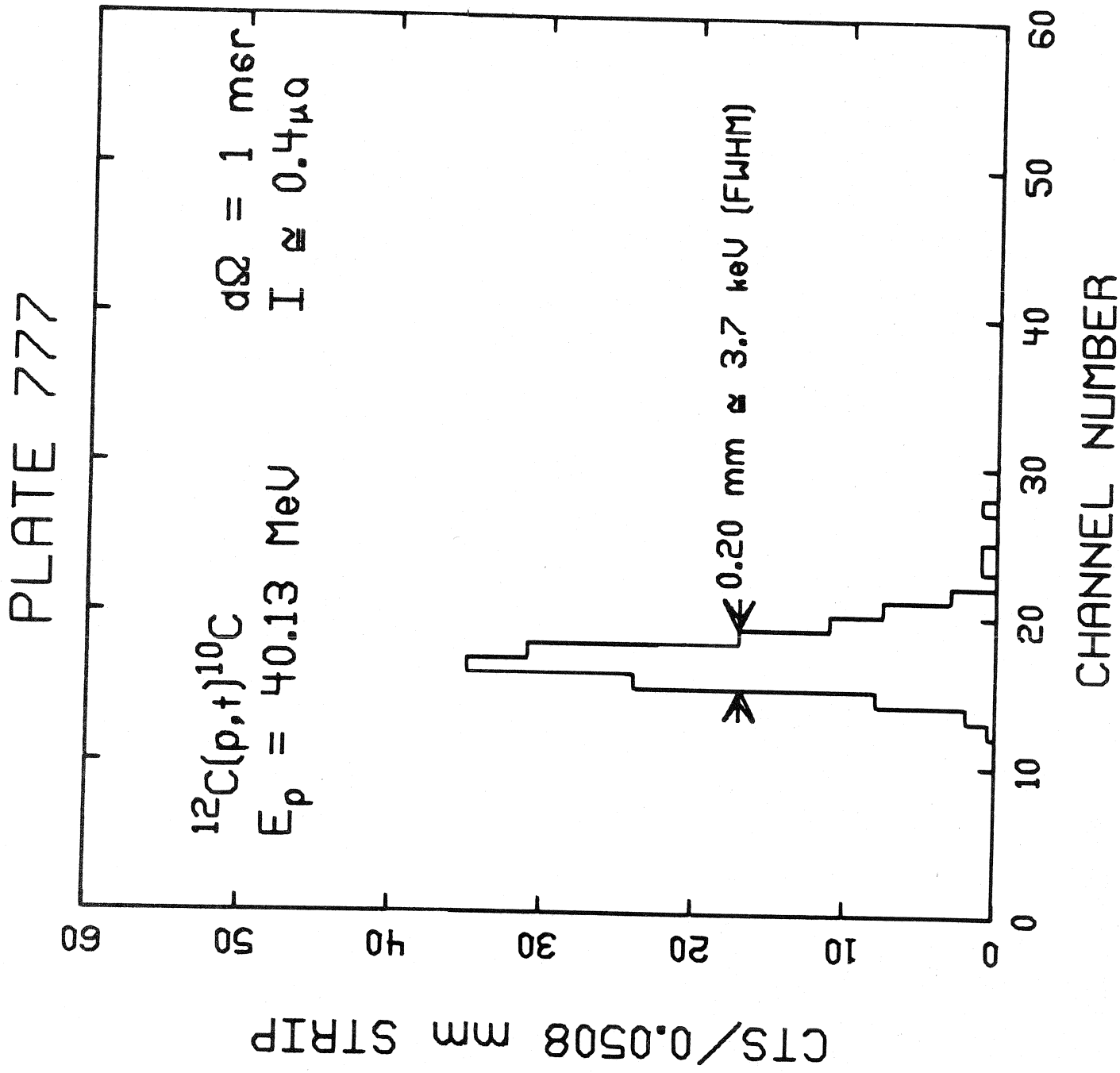
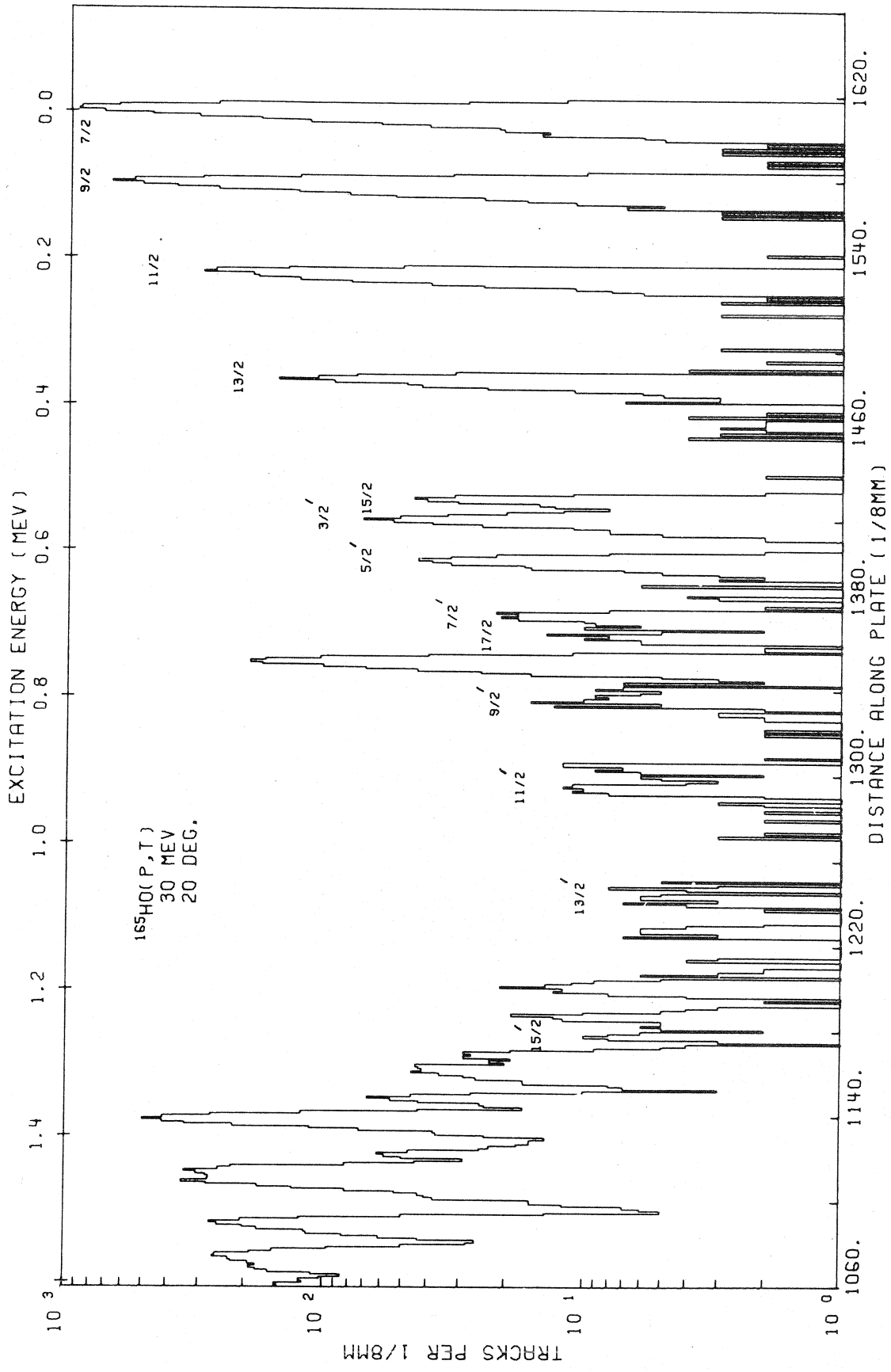


PLATE 777
dΩ = 1 msr
I ≅ 0.4μa
$^{12}C(p,t)^{10}C$
E_p = 40.13 MeV
0.20 mm ≅ 3.7 keV (FWHM)
CTS/0.0508 mm STRIP
CHANNEL NUMBER
0
10
20
30
40
50
60


^{165}HO(P,T)
30 MEV
20 DEG.
EXCITATION ENERGY (MEV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
DISTANCE ALONG PLATE (1/8MM)
1060.
1140.
1220.
1300.
1380.
1460.
1540.
1620.
TRACKS PER 1/8MM
10^0
10^1
10^2
10^3
7/2
9/2
11/2
13/2
15/2
3/2'
5/2'
7/2'
17/2
9/2'
11/2'
13/2'
15/2'