BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

A NOTE ON RADIOTHERAPEUTIC USE OF PARTICLE ACCELERATOR
METHODS TO DETERMINE THE STOPPING REGION

Y. Y. Lee

October 26, 1972

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A Note on Radiotherapeutic use of Particle Accelerator
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Abstract

Various methods to determine the stopping region for hadron beams are discussed. The new method using antiproton beams is proposed.

Introduction

Stopping negative pions or protons have been proposed¹⁾ for radio therapeutic applications in view of the fact that the Bragg-peak ionization region and "star" formation.

Due to the inhomogeneities of the density of the bone and the tissue layers in each patient, it is difficult to locate exact position of the stopping region. Both the π^- and the proton are hampered by this difficulties. There are, however, several attempts to measure the region using high energy capture γ -rays²⁾, mesic x-rays³⁾, and positron activities⁴⁾ from captured negative pions. The positron activity method can be applied to proton case because all the hadrons can activate C^{11} or O^{15} in the tissue.

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Sperinde et al.²⁾ have measured the capture γ -rays of energy greater than 15 MeV using magneto strictive wire spark chamber. They found clear peak in the stopping region. Their resolution was ~ 6 mm determined by lead plates in the collimator. Their sensitivity was found to be 5×10^{-6} detected γ -rays per stopping pion. Dean and Holm³⁾ attempted to measure the stopping region by mesic x-rays. When negative pion is captured in atom it will emit characteristic x-rays of few hundred KeV. Their phantom study by stopping π^- in water and using Anger camera⁵⁾ shows the peak corresponding to π^- stop and μ^- stop. Since μ^- -mesic x-rays are ten times abundant than that of pion, it might give some problem to the scheme. Nevertheless, their result shows camera resolution of 1.8 cm and sensitivity 1.2×10^{-4} photons per stopped pion. Both measurement did not mention the distance between stopping point to the detector, but if the detector has to be further away from the stopping point, both the resolution and sensitivity has to be reduced. We are going to use 20 cm for the distance in discussion below. Third measurement is done using positron activity. They irradiated the gelatin filled petri-dish of 1.5 cm thick. The positron activities were measured by resulting annihilation γ -ray of 500 KeV by NaI crystal. They found the sensitivity of .012 photon under Bragg-peak per stopping π^- . They also showed about tenths of the activity due to nuclear interaction around the end of the pion range. One should, however, take account of the fact that actual detector can not be as close as .75 cm, but have ~ 20 cm. If the Anger camera is used to detect x-rays, it will have solid angle factor x-ray absorption, detection efficiency of the x-ray and the product of those are the real sensitivity. There are two ways to measure the position of the positron activities. One is using Anger camera and the collimator to

find the direction of the photon. Using the known lateral position of particle beam one can find the depth of the penetration. The other is using the colinearity of two photons from positron annihilation and determine the direction by two opposing Anger cameras. Sensitivity of the detector using collimator is assuming .3 cm diameter collimator and 20 cm distance

$$\frac{(.15)^2}{(20)^2 \times 4\pi} \cong 1.4 \times 10^{-5}$$

For positron mode the camera sensitivity is 2000 counts per minute per $\mu\text{Ci}^{9)}$ or

$$\frac{2000}{3.7 \times 10^4 \times 60} \cong 1.1 \times 10^{-3}$$

The photon absorption factor is e^{-2} for the former and e^{-4} for the latter. The combined sensitivity becomes to

$$\begin{array}{ll} 1.4 \times 10^{-5} \times e^{-2} \cong 1.8 \times 10^{-6} & \text{for collimator mode} \\ 1.1 \times 10^{-3} \times 10^{-4} \cong 1.85 \times 10^{-5} & \text{for positron mode} \end{array}$$

It is clear that positron mode is more sensitive than the other. The resulting sensitivity is

$$.012 \times 1.85 \times 10^{-5} \cong 2.20 \times 10^{-7} / \text{stopping } \pi^-$$

One also have to mention that the even scattered photon can be counted in Anger camera but they are going to reduce resolution of the measurement.

Maccabee et al.⁶⁾ studied the tissue activation from α -particle and possibility of determining α -particle range by positron activity. Their calculation shows initial activity of .15 μCi for 30 rad of α particles. Suppose one uses same Anger camera mentioned above, one can estimate the sensitivity.

$$.15 \mu\text{Ci} \times 3.7 \times 10^4 \times 1.85 \times 10^{-5}$$

$$\cong 1.03 \times 10^{-1} \text{ counts/sec} \cong 6 \text{ counts/min}$$

or for each rad of radiation .2 counts/min/rad.

For the range determination of protons we can make simple calculation assuming entire tissue is consisted of oxygen and main reaction is

Assuming the cross section of 90 mb, one would get

$$e^{-90 \times 10^{-27} \times 6 \times 10^{23} / 16} \cong 3.4 \times 10^{-3} \text{ gm/proton}$$

Using half life of 2 minutes for O^{15} and same Anger camera used above we get

$$3.4 \times 10^{-3} \times \frac{.69}{2.} \times 1.85 \times 10^{-5} \cong 2.2 \times 10^{-8} / \text{proton/min/gm}$$

We summarize these in Table 1.

Table 1

Method	Resolution	Sensitivity	Ref.
High energy γ-rays	6 mm	$5 \times 10^{-6} / \text{stopping } \pi^-$	2 b)
Mesic x-ray	1.8 cm	$1.2 \times 10^{-4} / \text{stopping } \pi^-$	3 b)
Positron activity pion	a)	$12.2 \times 10^{-7} / \text{stopping } \pi^-$ c)	4
Positron activity α-particle	a)	.2 count/min/rad c)	6
Positron activity proton	a)	$2.2 \times 10^{-8} / \text{proton/gm/min}$ c)	-

- a) Resolution is given by Anger camera resolution.
- b) Reference did not give the distance of detector from the stopping point nor amount of the material photon has to go through
- c) Assuming 20 cm of tissue (or 2 photon absorption length of material) and the Anger cameras are placed 20 cm from the stopping point.

The radiation caused by each proton or pion at the entrance where particles are minimum ionizing is

$$2 \text{ MeV} \times 1.6 \times 10^{-8} \text{ rad/MeV} = 3.2 \times 10^{-8} \text{ rad/particle}$$

and around the Bragg peak

$$30 \text{ MeV} \times 1.6 \times 10^{-8} \text{ rad/MeV} = 4.8 \times 10^{-7} \text{ rad/proton}$$

and

$$45 \text{ MeV} \times 1.6 \times 10^{-8} \text{ rad/MeV} = 7.2 \times 10^{-7} \text{ rad}/\pi^-$$

Therefore, the each counts for high energy γ -ray the radiation caused is

$$\frac{7.2 \times 10^{-7}}{5 \times 10^{-6}} = 1.44 \times 10^{-1} \text{ rad/count}$$

for mesic x-ray

$$\frac{7.2 \times 10^{-7}}{1.2 \times 10^{-4}} = 6 \times 10^{-3} \text{ rad/count}$$

for positron activities

$$\text{pion} \quad \frac{7.2 \times 10^{-7}}{2.2 \times 10^{-7}} \cong 3.3 \text{ rad/count}$$

$$\alpha \text{ particle} \quad 5. \text{ rad/count/min}$$

$$\text{proton} \quad \frac{4.8 \times 10^{-7}}{2.2 \times 10^{-8}} \cong 22. \text{ rad/count/min}$$

As can be seen none of the positron activation method can be suitable for probing the area and planning the radiation. We propose here entirely different method to determine the hadron range and probe the area.

II. Anti proton as a tool

a) General

The range⁷⁾ of hadron in the matter is expressed by the equation

$$\frac{R}{m} = F\left(\frac{P}{m}\right)$$

where R, P, and m are the range, momentum, and mass of the particle. F is the universal function for all the masses. Thus, if the range momentum relation for one particle is known it can be found for other particles. If we know the range energy relation for anti-proton we can find it for pions and protons. In fact for proton it is exactly the same because one is anti-particle of the other.

When anti-proton stops in the matter it will be annihilated with one of the nucleon in the nucleus. Experimentally⁸⁾ it was found that 42.6% goes to two charged prongs and 45.8% goes to four charged prongs. Average energy for two prong case is 600 MeV and 450 MeV for four prongs. Fig. 1 shows schematic of the chamber arrangement.

Fig. 1. Plan view of the schematic.

The two layers of proportional wire chambers measure the directions and positions of annihilation product and incoming $\bar{p}$ beam. The resolution of the chamber is about 1 mm in present technology. Time resolution of the chamber is about 20 n sec and each event can be resolved if the beam intensity is less than 10^6 per second. The resulting tracks are extrapolated back to vertex point and recorded. It should be pointed out that the events are over-constrained, namely only two tracks are needed to find the apex. Since we have three or more tracks in general we can have improved apex point by means of least-squares method. We can also eliminate the events of which any of the tracks are interacted in the body.

b) Resolution

As mentioned above chamber resolution is order of 1 mm. Since the particle must go through the tissue layer of 20 cm or $1/5$ of radiation length it will multiple scatter. For multiple scattering

$$\langle \theta \rangle = \frac{15}{p\beta} \sqrt{\frac{L}{L_r}} = \frac{15}{600} \sqrt{\frac{1}{5}} = 11.2 \times 10^{-3} \text{ rad}$$

and projected displacement is

$$\langle y \rangle = L \langle \theta \rangle / \sqrt{3} = 20 \times 11.2 \times 10^{-3} / \sqrt{3}$$

$$\cong .13 \text{ cm} = 1.3 \text{ mm}$$

Where $\langle \theta \rangle$ and $\langle y \rangle$ are the projected r.m.s. angular and spacial displacements, L is the length of the material for the particle to go through, and L_r is the radiation length of the material.

Multiple scattering and chamber resolution matches. In the case of 4 prong event constraint will compensate for higher multiple scattering.

c) Radiation

Radiation by antiprotons are sum of the radiation caused by antiproton and annihilation products. At the Bragg peak

$$(30 \text{ Mev}) + (3 \times 2) \text{ Mev} \times 1.6 \times 10^{-8} \text{ Rad} = 5.76 \times 10^{-7} / \bar{p}$$

$\bar{p}$ From Secondaries

and rest of the area has far less radiation. If allowable radiation is 30 Rad, then

$$\frac{30}{5.76 \times 10^{-7}} \approx 5 \times 10^7 \text{ anti-protons}$$

Of course we don't need that many particles

d) Availability

At low energy separated beam of AGS we have about 600 $\bar{p}$ of the desired energy per pulse and a few pulses can map the density. If one wants to collaborate with 200 MeV linac we can transport the $\bar{p}$ from almost any target station. One interesting point is anti-proton beam transported far away from the target station is free of contamination due to the decay of any contaminant we might have.

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References

1. P. H. Fowler et al, Nature London 189, 524 (19 61) and see for example. Proceeding of the Symposium on Pion and Proton Radio therapy N AL Dec. (1971).
2. J. Sperinde et al, Phys. Med. Biol. 15, 643 (1970).
3. P.N. Dean et al, Rad. Res. 48, 201 (1971).
4. M.C. Taylor et al, Science 169, 377 (1970).
5. H.O. Anger, R.S.I. 29, 27 (1958).
6. H.D. Maccabee et al, Phys. Med. Biol. 14, 213 (1969).
7. See example D.M. Ritson Techniques of High Energy Physics, Inler Science Publishers, Inc., N.Y., Pp. 38 (1961).
8. C. Boltay et al Phys. Rev. 145, 1103 (1966).
9. Anger, H.O. IEEE Trans. Nucl. Sci. NS-13(3) 380 (1966).