**A MEASUREMENT OF THE LOCAL ENERGY DEPOSITION BY
ANTIPROTONS COMING TO REST IN TISSUE-LIKE MATERIAL**

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A B S T R A C T

The measurement of the energy deposited in tissue-like plastic as a beam of low-energy antiprotons slows down is described. The resulting depth-dose curve is presented and compared to that of protons measured under similar conditions. The size of the stopping peak relative to the dose in the plateau is about twice that for protons which indicates that relatively small amounts of energy are deposited locally in an antiproton annihilation. Analysis of the data shows that out of the 2000 MeV available in an antiproton annihilation, on average less than 33 MeV is deposited close to the site of the interaction. This leads to the conclusion that antiprotons are unlikely to offer any marked advantage over other radiations for radiotherapeutic applications of the future.

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1. INTRODUCTION

When an antiproton comes to rest in contact with matter it will annihilate with a neutron or a proton and their combined mass of about 2 GeV will transform into energy. The physics of antiproton annihilation suggests that the major part of this energy will manifest itself as pions with a kinetic energy of the order of a few hundred MeV and hence will escape from the site of interaction. Particle track analysis from emulsion [1] and bubble chamber [2] experiments in antiproton beams have been interpreted to imply that a relatively large amount of energy could be dissipated by way of charged fragments of the nucleus on which the annihilation occurred. This local energy deposition has been estimated to be in the range 100-200 MeV [3], which can be compared with the 20 MeV or so left behind in a negative pion annihilation [4]. Hence there has been some speculation on the possibility of the use of antiproton beams as a therapeutic radiation in the future. Antiprotons also have the additional advantage that the position of the annihilation can be imaged by way of the multiple pion emission [5] and that as antiproton beams are practically monoenergetic the particles can be made to stop and deposit energy at a precise location in an absorber.

Therefore, although the availability of antiproton beams is very limited and their cost very high, it is of interest to make basic measurements of local energy deposition by stopping antiprotons in tissue-like materials in order to have a direct assessment of their possible future biomedical usefulness.

2. ANTIPROTON PRODUCTION

Intense beams of antiprotons have recently become available at the European Laboratory for Particle Physics (CERN). A diagram of the accelerator complex required to produce them is shown in Fig. 1. Protons are first accelerated to 26 GeV in the proton synchrotron (PS). They are then extracted and made to strike a target where the antiprotons are produced, these are then collected and passed into an accumulator ring. In the antiproton accumulator (AA) differences in momentum and position of the antiprotons are sensed and correcting

fields applied until after circulating for about 24 h the antiprotons have migrated to a central core of particles which have properties suitable for extraction and can be returned to the proton synchrotron. Once back in the synchrotron the antiprotons can either be accelerated and sent to a proton-antiproton collider experiment or decelerated and passed into a low-energy antiproton storage ring (LEAR) where the particles may be further conditioned before being sent to various physics experiments. The lowest energy so far to which antiprotons have been decelerated in LEAR is 49.4 MeV (308.5 MeV/c).

The overall efficiency of antiproton production is very low, some 4×10^6 protons of 26 GeV are needed to obtain one antiproton of 50 MeV in LEAR. The antiprotons from LEAR are highly monoenergetic with a momentum spread of less than $\pm 0.2\%$.

3. EXPERIMENTAL LAYOUT

During the setting up phase of the LEAR ring small quantities of antiprotons may be dumped, and in order to use these particles it was necessary to have an experiment permanently set up in the dump line that could be put into operation at short notice. The experimental set-up therefore had to be very simple and be capable of being operated from outside the experimental area, as once there were antiprotons in the LEAR ring there would be no way of getting at the equipment.

A drawing of the layout of the experiment is shown in Fig. 2. The equipment consisted of a thin-walled air-filled transmission ionization chamber through which the whole beam passed and which was used to monitor the beam intensity. The radiation detector used to measure energy deposition was a parallel-plate ionization chamber made of tissue-equivalent plastic of composition 10.2% hydrogen, 76% carbon, 5.2% oxygen, 5% nitrogen, and 5% by weight of the elements iron, calcium and silicon [6]. The chamber was air filled with a 3 mm plate spacing and a collector electrode diameter of 60 mm. The entrance window had a thickness of 450 mg/cm^2 , thick enough to ensure that short-range secondaries from an antiproton annihilation would have a maximum probability of reaching the chamber sensitive volume. The chamber was polarized with a collecting field of about 750 V/cm which

should be sufficient to minimize problems of ionization recombination along tracks of heavily charged particles. The narrow air gap that forms the chamber sensitive volume acts as an ionization cavity (in the longitudinal direction) where the ionization is primarily due to secondaries from the chamber walls rather than from interactions in the gas itself. Hence the chamber measures the energy deposition or dose rate in the material of the chamber wall over the 60 mm diameter of its collector electrode. As the entire beam will fall within this diameter the measurement will be of the energy loss by the beam, independent of the beam diameter.

A polythene step wedge was driven across the front of the chamber so that energy deposition as a function of absorber depth could be measured. The first three steps of the wedge were relatively coarse but thereafter the steps were about 40 mg/cm^2 thick thus allowing the strong variation of energy deposition that occurs with depth as the particles reach the end of their range to be measured with a high resolution. A bar of polythene of $10 \times 10 \text{ mm}$ cross-section was fixed across the wedge at one position and the passage of this bar through the beam could be detected in the chamber output, thus providing an exact reference for the position of the wedge in relation to the beam.

The beam monitor and the detector were connected via suitable electrometers to an analogue recorder outside the experimental area. It was also possible to stop the movement of the absorber and integrate digitized signals from the beam monitor and detector chamber and thus improve the precision of the measurements in critical regions.

4. THE MEASUREMENTS

Measurements were made in an antiproton beam of momentum 310 MeV/c with intensity of about 9×10^4 per second over a period of about 20 min. The effective beam energy at the experiment after allowing for absorption in the beam line vacuum window and air path up to the absorber, was 47.2 MeV . The beam intensity was determined from the spill rate of the machine and this intensity reasonably coincided with that estimated from the beam monitor reading assuming 33 eV were required to form an ion pair in the chamber. An idea of the beam size was obtained from a multiwire proportional chamber, which was some 2 m

in front of the experiment, and gave beam half widths less than 1 cm both in the horizontal and vertical plane. Comparison of the readings of the beam monitor and the detector chamber showed that more than 95% of the beam was passing through the sensitive volume of the chamber. The polythene wedge was driven through the beam several times during the run and reproducible sets of measurements of ionization current versus absorber position were obtained.

The LEAR machine can also be filled with protons and it was possible to make measurements of the energy deposition by a slowing down beam of protons of the same energy and energy spread as the antiprotons which could be used for comparison.

The results of both the proton and antiproton measurements are presented in Fig. 3 which shows the relative energy deposition as a function of absorber depth. The two curves have been normalized to each other at a depth of 0.5 g/cm^2 thus enabling the size of the stopping peaks relative to the plateau region to be directly compared.

5. ANALYSIS AND DISCUSSION

The proton curve is a typical Bragg curve of a slowing down charged particle beam and has been compared with the theoretical slowing down curve of a single proton in Fig. 4. As can be seen, the measured Bragg peak is slightly broadened due to range straggling and the momentum spread of the beam as well as the finite resolution of the measurement method. Comparison of the form of the theoretical and measured proton curves indicates that only very small amounts of energy are being missed by the detector and that all the proton energy has been deposited in the absorber.

The antiproton curve is the slowing down peak plus a contribution of energy from the antiproton annihilation which produces on average 3 charged pions of mean energy about 400 MeV plus 3 high-energy gamma rays that result from neutral pion decay, as well as neutrons and short-range highly-ionizing nuclear fragments [3]. The long-range pions, gamma rays and neutrons, which are emitted isotropically, will irradiate the surrounding material. In particular, the plateau region of the antiproton depth-dose curve contains a contribution from these

secondaries that originate from annihilations in the peak region. The slowing-down ionization curve is further complicated by the probability of antiprotons interacting and annihilating while still in flight.

A crude analysis of the depth-dose curve is possible as the geometry of the experiment was reasonably well defined. The plateau region can be considered to occur over absorber depths from x_1 to x_2 , shown in Fig. 3, where the slowing-down antiproton loses 20 MeV in kinetic energy; to this must be added an estimated 8 MeV deposited by secondaries from antiproton annihilations in the peak region. The proportion of energy from these secondaries depends on the beam and detector size, as in general the dose rate in the beam is proportional to particles per cm^2 whereas the dose from annihilation products will depend on the total number of stopping particles. In addition antiprotons may interact and annihilate in the plateau region before they come to rest. If a fraction f of the antiprotons interact between depths x_1 and x_2 and deposit on average an energy ϵ MeV locally, then the total energy per incident antiproton, deposited in the plateau region will be $(28 + f\epsilon)$ MeV. The energy deposited in the peak region between depths x_2 and x_3 will be the remaining 20 MeV of kinetic energy of the antiproton plus the local energy deposition, also of ϵ MeV per annihilation, making a total of $(1 - f)(20 + \epsilon)$ MeV. The ratio of the areas under the peak and plateau regions of the curve in Fig. 3, which is also the ratio of energy deposition, was 1.42. If a 10% inflight annihilation probability is assumed, then the above analysis leads to a value of 29 MeV for the energy locally deposited in an antiproton annihilation.

The 10% inflight interaction probability is an extreme assumption and the reality will be somewhat less. The energy deposition from highly ionizing nuclear fragments could be underestimated in the above analysis. The particles carrying the annihilation energy are isotropically distributed and about 5% of short range secondaries could escape radially through the sensitive volume of the chamber. A further underestimation may have occurred as the measurements analysed are those of the ionization in the air forming the sensitive volume of the chamber. These measurements should be corrected to allow for variations in the chamber wall to air stopping power ratio which could

result in an up to 6% underestimation for the energy deposited by highly ionizing fragments. Another correction should be applied to allow for the increase in the amount of energy that is dissipated by slow charged particles in forming an ion pair. An upper limit of 3.5% has been estimated for the correction necessary for this effect in ionization by the fragments from a negative pion annihilation [7].

Hence the analysis of the depth-dose curve could result in an underestimation of the energy locally deposited of up to 15%. Applying this correction, the measurements show that the total energy deposited locally by an annihilating antiproton does not exceed 33 MeV. The volume of tissue-equivalent material over which the energy has been integrated is determined by the of chamber diameter and the total depth of about 0.5 g/cm^2 in which the stopping peak occurred. The minimum ionizing particles departing from the site of an annihilation could be expected to deposit of the order of 10 MeV in this volume. Hence the net energy left that can be attributed to nuclear fragments from the annihilation will only be of the order of 23 MeV on average. This energy is rather less than has been predicted on the basis of nuclear track analysis and is the same order as that deposited locally in a negative pion annihilation.

6. CONCLUSIONS

The results of measurements of energy deposition in tissue-like materials by slowing down antiprotons indicate that less than 33 MeV is deposited near the site of an antiproton annihilation even though the total energy involved is nearly 2000 MeV. Hence, even if antiprotons were not excessively expensive, their depth dose distribution does not appear to have sufficient advantage to justify optimism concerning their future application to radiotherapy.

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FIGURE CAPTIONS

- Fig. 1. Layout of the accelerator complex used to produce low-energy antiprotons. Protons of 26 GeV extracted from the proton synchrotron (PS) strike a target to produce antiprotons. These are then collected in the accumulator ring (AA) before being sent back to the proton synchrotron where they are decelerated and sent to the low-energy antiproton storage ring LEAR.
- Fig. 2. Diagram of the experiment. The beam passes through a monitor chamber and a variable absorber before entering the detector chamber which measures the energy deposition by ionization at the position of its sensitive volume.
- Fig. 3. Variation of energy deposition by beams of protons and antiprotons with depth in an absorber.
- Fig. 4. Comparison of the slowing down ionization curve (Bragg curve) measured for a proton beam of less than 0.2% momentum spread with that calculated for a single proton of 47.2 MeV.

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