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USE OF ELEMENTARY PARTICLE INTERACTIONS FOR RADIOLOGICAL IMAGING*

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Summary

The potential for the use of inelastic high energy particle reactions to produce radiological images is discussed. This technique promises image quality comparable to that of computerized axial tomography at a fraction of the radiation exposure. In addition, the comparison of coherently produced events to the total inelastic cross section should allow a probe of the chemical composition (i.e., average Z) of the material being studied. The performance of this technique is reviewed and some preliminary results using a 5 GeV/c π^- beam at SLAC are presented.

Introduction

Clinical radiology has benefited in recent years from the advent of CAT scanners which provide high resolution and high sensitivity to small density changes in the anatomy. While the density information is quite high in quality, the concomitant high radiation dosage (which can approach the maximum recommended annual exposure when a series of scans comprising a three dimensional volume are undertaken) is of major concern. The high quality and quantativeness of the data seems to justify the high risk. Similar risks from clinical x-ray procedures have been revealed recently by a study demonstrating a considerable increase of induced cancers in a group of women, each of whom underwent a yearly mamogram over a fifteen year period. While CAT scans will probably not be used in such an annual diagnostic manner, its increased use as a screening test for patients with demonstrated problems will introduce the risk at some level. It is therefore of interest to consider other techniques which could provide the comparable information with much lower dosage.

Imaging Capability of Particle Interactions

We have begun a study of an alternate approach to obtain high resolution, three dimensional density distributions through the use of high energy (> 1 GeV/c) particle induced reactions such as:

$$\pi^- A \rightarrow \pi^- \pi^- \pi^+ A'$$

$$\pi^- A \rightarrow \pi^- \pi^+ \pi^- A$$

where A represents the atomic nucleus in the radiological target. These reactions are chosen because of the two or more fast, forward-going particles in the final state; the nucleus, A, is usually displaced very little in these reactions. Detection of the fast tracks' trajectories allows us to trace back to find the location of the interaction point in three dimensions, even without knowledge of the incident particle. The density distribution of these interaction points, each is called a vertex, is a measure of the macroscopic density of the material. The density function can be displayed a slice at a time or can be projected onto any axis for a high statistics image.

Vertex Resolution

The fast forward tracks in the above reactions are detected with high resolution by a variety of proportional and spark chambers at physics spectrometers around the world. These devices are capable of 0.5 mm resolution at each point along the particle's trajectory. A series of chambers spread over a one meter lever arm resolve the track angle to better than one milliradian, which is less than the expected multiple scattering which will occur as the secondary particle exits the radiological sample. For example, a 2 GeV/c particle would undergo 3 milliradians scatter in passing through 10 cm of water.

The ability to extrapolate these tracks to a common vertex will determine the vertex positional uncertainty and therefore the smallest volume element that can be measured. Figure 1 demonstrates the lateral (perpendicular to the beam) resolution of a forward-going track relative to the beam track; the sigma is 1.3 mm. When two tracks are fitted to a vertex without using the beam track, one obtains, typically, the 2 mm or better resolution shown in Fig. 2. Therefore, with this resolution, it is possible to measure densities on 2×2 mm grid in the lateral direction. The resolution in the third direction (along the beam) will depend on the opening angle of the tracks selected and will be somewhat worse, approximately 5 mm, which is similar to the width of a CAT scan slice. One can expect to measure volume elements of $2 \times 2 \times 5$ (mm)^3.

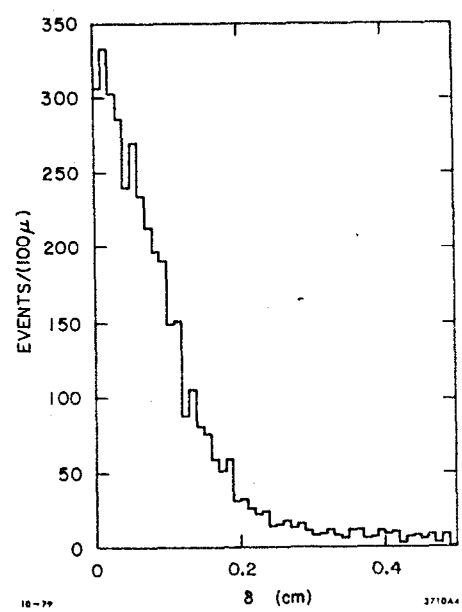

Fig. 1. Radial distance between a beam track and a secondary track in the LASS spectrometer.

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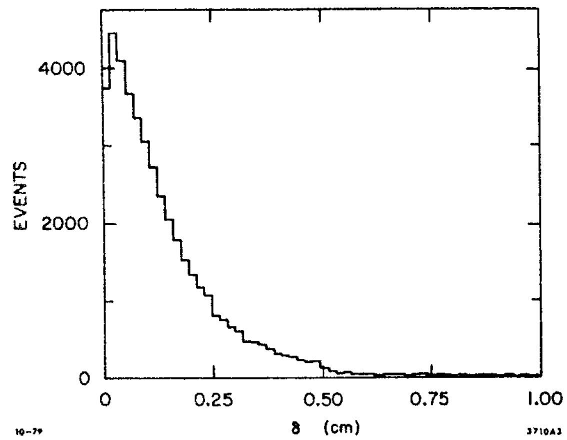

Fig. 2. Closest approach of two secondary tracks in the SLAC E75 experiment.

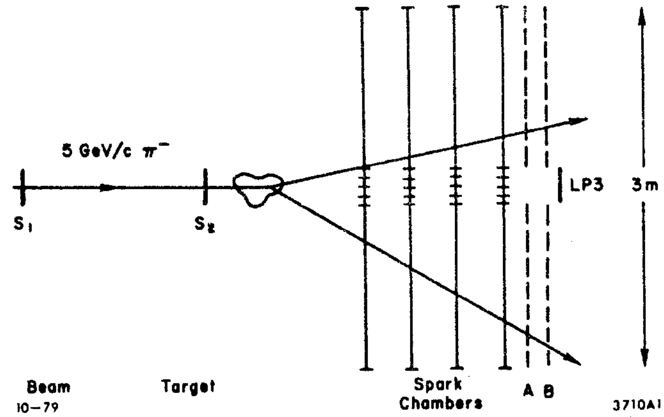

Fig. 3. Schematic of the track-finding package used to produce a vertex radiograph.

Radiation Dosage with Particle Beams

In order to estimate radiation dosage, we need to estimate the number of particles per square centimeter needed to produce a quality image. A high energy proton beam passing through 20 cm of water (the major constituent of tissue) has a 25% chance (absorption length = 79 cm) of producing a non-elastic event. Since image quality is determined by event density, we will need four times as many beam particles as events. A high quality 3D image would be 100 events per $2 \times 2 \times 5$ cubic millimeter. This would require 4×10^5 incident protons per square centimeter. Radiation dosage that can be expected from high energy particles can be estimated by using the health physics rule[1] that 3.5×10^7 minimum ionizing particles per square centimeter in carbon deposit one rad. Other materials are usually within a factor of two of this number. The 4×10^5 protons be equivalent to 0.017 rad. Thus a high quality image could be obtained with a dosage that would be two orders of magnitude less than the recommended maximum annual dosage. This exposure is also less than a normal chest x-ray. With .17 rad three percent density resolution could be achieved.

Because of the rotation required, the CAT scan method also requires exposure to all parts of the section being scanned, whereas a particle beam could be directed only at an area of interest thereby reducing the extent of the dose.

A 5 GeV/c Pion Vertex Radiograph

An image has been made using a target in front of the downstream spark chamber track-finding package in the LASS spectrometer at SLAC (see Fig. 3). A pion beam was used because of its availability and properties, which are similar to the proton beam. This section of the spectrometer consists of four double-gap spark chambers with magnetostrictive readout and two plastic scintillation hodoscopes to trigger the spark chambers. The beam was a 5 GeV/c secondary pion beam created by the primary electron beam. The primary beam was being used at the time to fill the SPEAR storage rings (colliding electron and positron beams), so between fills (less than once per hour) it was available to standby experiments such as this one.

The target used was an 8 cm diameter aluminum extrusion with many fins protruding outwardly and inwardly from a cylinder. The beam was defocused so as to fill the 10×10 cm paddle counters (S1 , S2) and illuminate the target. The A and B hodoscopes were used to determine the presence of the particles in the spark chambers. The trigger coincidence required two hits in each A and B and a beam coincidence in S1 and S2 and a beam anti-coincidence in the LP3 counter — i.e., $S1 \cdot S2 \cdot (A \geq 2) \cdot (B \geq 2) \cdot \overline{LP3}$.

The tracks reconstructed from the spark chamber points were matched to find vertices by looking for the point of closest approach. No attempt has been made yet to separate 3 track vertices; the best 2 track vertex was used in each event. The image produced is shown in Fig. 4. The image was made using a half-tone (dot density) program. The data was binned in 2 mm bins, but was interpolated and smoothed to 1 mm bins to avoid the finite binning artifact. The image has a 5% background subtraction and a 75% upper threshold cut. No correction was made for the beam profile, hence the slight fading at the edges.

Such a high contrast image demonstrates the imaging ability and resolution of the technique. Further work is underway to study more realistic radiological targets with lower intrinsic contrast.

Chemical Composition Contrast Enhancement

There exists a problem using x-rays as a diagnostic tool in that two very different chemical compositions may have the same density and therefore be indistinguishable by x-ray densities. This can be understood because of the physics of the interaction of x-rays below 100 keV with matter. They are absorbed primarily by photoelectric and compton interactions with the orbital electrons of the atom. Two chemicals with the same mass density have the same electron density even though the nuclei are different. High energy particle interactions take place with the nucleus however, and may be used to identify the nucleus under study, for certain types of events. In particular, the production of three pions in the nucleus by an incident pion shows a significant dependence on atomic number A. When the three pions have an effective mass between 1 and 1.3 GeV/c^2 they form the A_1 resonance. Figure 5 shows the production cross section[2] for this resonance as a function of the number of nucleons in the nucleus, A. Rather than increasing linearly as A, the cross section increases as $A^{1.6}$ for $A = 1$ to 40.

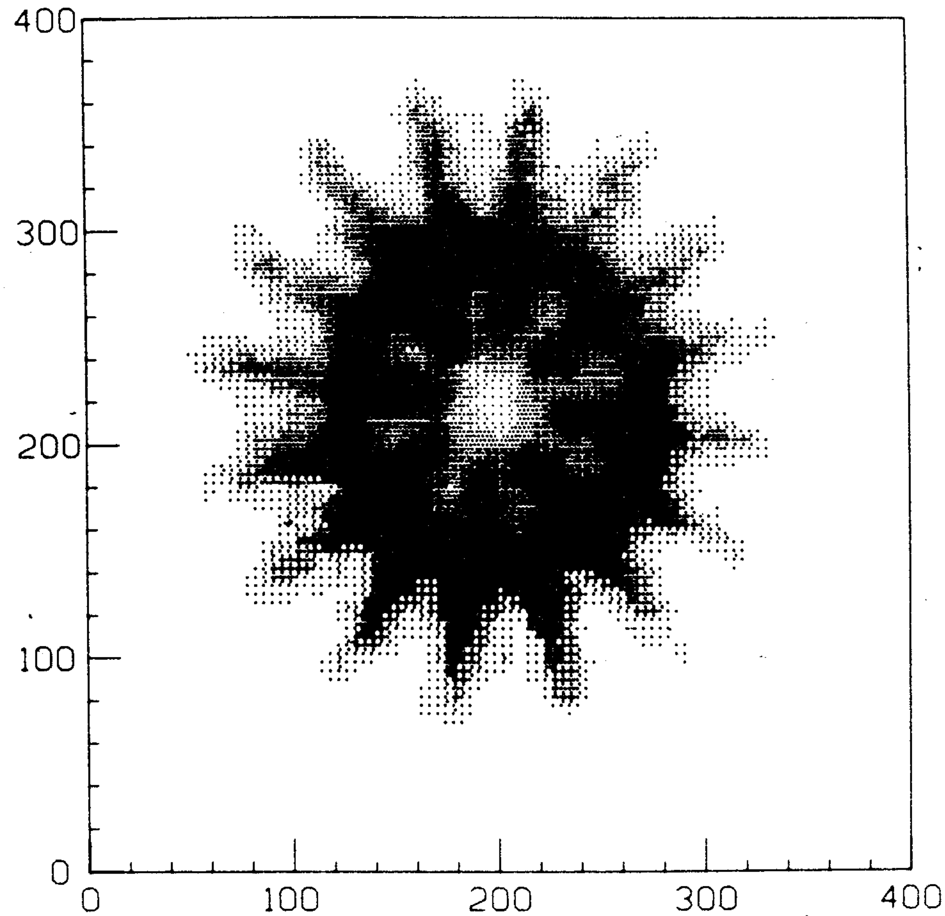

Fig. 4. Vertex radiograph of an 8 cm diameter aluminum extrusion.

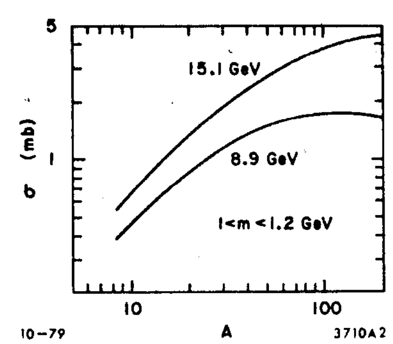

Fig. 5. A_1 (three pion) cross section versus atomic number, showing the coherence effect.

Two pion production does not show this coherence effect and so is a measure of the mass density. An interesting image would be the ratio of 3 pion A_1 events to 2 pion events. This image would be a map of the average atomic number of target material rather than electrons per cubic centimeter.

Conclusion

We have demonstrated the imaging capability of elementary particle vertex distributions and have suggested the possibility of chemical composition enhancement which could provide an interesting new tool to radiology research. While it is not expected that a few GeV accelerator will now be required in every community hospital, the development of proton and neutron therapy facilities at physics accelerators may be extended to do diagnostic imaging. It has been convenient to use pions for the image created here, a similar potential exists for high energy neutron beams with substantially reduced radiation exposure. The unique ability of elementary particle interactions to produce vertices in radiology targets deserves to be explored.

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References

1. Particle Data Group, "Particle Properties Data Booklet," Phys. Lett. 75B, (1978).

2. P. Muhlemann et al., Nucl. Phys. B59, 106 (1973).