NEUTRAL HADRON DETECTORS FOR NAL

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ABSTRACT

Total absorption detectors for neutrons and neutral kaons are discussed in the context of 200-GeV experiments. The state-of-the-art of ionization calorimeters (iron-scintillator sandwich arrays) is reviewed and compared with Hofstadter's TANC (sodium iodide crystal) detector.

I. WHAT HAS BEEN DONE

The use of the ionization calorimeter or total absorption spectrometer has been discussed[1] for both cosmic-ray and accelerator experiments, the latter particularly in the context of neutron detectors in the multi-BeV range. An interesting alternative, the total absorption nuclear cascade (TANC) detector, has been discussed by Hofstadter, et al.[2] The purpose of this note is to compare the two devices and to discuss possible variants on both in the context of physics at NAL.

The existing SLAC experiments with TANC using 8-GeV pions displayed a limiting resolution of about 65% FWHM. This was primarily limited by fast neutrons escaping the detector volume laterally; the particular NaI crystals used were only of 10 inches diameter. Hofstadter proposes building a detector 30 inches in diameter to minimize the problem. From his plots of energy deposition laterally in a tin phantom, this NaI detector should contain about 85% of the energy and might thus have a resolution of about 15% at 8 GeV.

Ionization calorimeters made of iron and scintillator layers sandwiched (1 cm scintillator--4 cm iron for the CERN - Karlsruhe calorimeter, and 1/4-inch scintillator--1-1/2 inch iron or aluminum for the Michigan calorimeter) have been used for neutron detection. The Karlsruhe group has calibrated their device in a proton beam and have found about 95% FWHM at 5 GeV/c, 50% at 11 GeV/c, 35% at 15 GeV/c, and 25% at 19 GeV/c.[3]

The Michigan calorimeter resolution at 5 GeV/c is over 100% FWHM. Very crudely, the absolute resolution (in GeV) seems to change only very slowly as energy is increased, according to the CERN studies to 24 GeV. The CERN calorimeter is

$40 \times 40\ cm^2$; the Michigan calorimeter is $24 \times 34\ in.^2$ It is necessary (as Hofstadter has studied) to provide at least a nuclear mean free path of detector transverse to the incident particle direction in order to contain most of the energy. This lateral extent need be less for iron, of course, than for NaI, roughly in the ratio of the densities (about a factor of two).

Huggett and co-workers have calibrated a much smaller calorimeter with 28-GeV protons at BNL, achieving about 50% FWHM resolution. However, in their experiment it is probable that leakage through the sides and ends limited resolution. That group has recently reported[4] extensive studies of calorimeter properties based on their AGS experiments and on Monte Carlo calculations of the energy loss processes, and the longitudinal and lateral distributions of energy deposition.

II. LIMITATIONS ON RESOLUTION

The TANC detector of Hofstadter is limited so far by lateral leakage of fast neutrons. The iron scintillator sandwich "calorimeters" are also limited by leakage as well as by the non-linear response of scintillator to nuclear fragments ($\beta << 1$) and by the coarseness of the sampling of energy loss. The most important limit in existing devices is probably the scintillator nonlinearity. The point to emphasize here is that all of the resolution-limiting factors become less serious as energy is increased from 20 to 200 GeV. From calculations by Denisov et al.,[5] the fraction of energy going into nuclear disintegrations drops from 40% at 50 GeV to 30% at 300 GeV, to 18% at 1000 GeV.

Very roughly, it is probable that this fraction at 10-20 GeV is twice as great as at 100-200 GeV. The lateral spread and the scintillator non-linearity both deteriorate the resolution in proportion to the nuclear fragment fraction. Furthermore, the sampling technique should be more satisfactory at higher energies simply because each nuclear cascade results in a larger number of particles and processes.

From these arguments, it is probable that even the existing TANC and calorimeter detectors will have 10-30% FWHM resolution at 200 GeV. It should be noted that already these detectors are 4-6 nuclear interaction mean free paths thick, and this is already sufficient at 200 GeV to contain about 80% of the nuclear cascade energy.

III. DETECTORS AT NAL

Hofstadter's work[2] suggests that a 30-inch diameter, 70-inch long NaI crystal detector should contain about 85% of the energy of a 200-GeV hadron.

A scintillator-iron sandwich of the same dimensions might contain a larger fraction of the energy (by making the dimensions larger in terms of nuclear interaction lengths). In either case, the resolution for 200-GeV hadrons might be 3%-10% FWHM. The calorimeters built to date have iron absorber about two radiation lengths thick. It would be appropriate to explore the extent to which finer sampling would improve the resolution, or, in fact, whether the resolution might be as good with coarser sampling. Since at 300 GeV about one-third of the nuclear cascade energy is calculated to appear as electromagnetic showers, one-third as nuclear disintegration, and one-third as ionization loss by relativistic hadrons (mostly pions),[5] the radiation length as well as the nuclear mean free path in the detector are relevant parameters.

Calculations of the energy-loss distribution as a function of depth have been made by various groups, and experimental data on 100-1000 GeV hadron cascades are available from cosmic-ray studies.[1] More elegant predictions of resolution are clearly possible; however, it would seem at this time that the resolution of either device is sufficient for a large class of experiments and that experimental tests of resolution will be necessary in any case. Cosmic-ray studies of calorimeter resolution at 200 GeV could be made with some effort.

It is not clear to this author that the resolution of a TANC counter at 200 GeV will be superior to that of a sampling calorimeter. The resolutions will probably fall within a factor of two of each other. At lower energies (10-30 GeV) a large TANC counter may have superior resolution.

IV. COSTS

It has been estimated that a 30-inch diameter by 10-inch thick crystal of NaI might be made (by Harshaw) for \$50,000.[6] Hence, the NaI for a 5 mean free path TANC detector (70 inches) would be about \$350,000. If each crystal is viewed by 8 five-inch tubes, the phototubes and associated electronics might add \$50,000 to the cost, making a total of \$400,000.

An ionization calorimeter of 800 g cm^{-2} (7 nuclear mean free paths) or 40 inches of iron of area 30 × 30 $in.^2$ would cost less than \$10,000 (\$1000 for scintillator, \$2000 for iron plates and support fabrication, \$1000 for 2 five-inch phototubes, and \$2000 for auxiliary electronics).

V. SPATIAL RESOLUTION

Neither device, as described above, provides spatial resolution, i.e., the interaction vertex of the incident hadron. For incident charged hadrons a chamber immediately preceding the gadget is the obvious solution. For neutral hadrons (K_2^o, n, $\bar{n}$) the position measurements must be made in the detector. Two approaches have been used. In a recent Bevatron experiment, Jones, Longo, Cork, et al., used a 1/10 to 1/5 mean free path (iron plate) converter ahead of the calorimeter to convert incident neutrons and then a counter system between this converter and the calorimeter to locate the coordinates of the produced particles. This method suffers from two disadvantages; it is only 10-20% efficient, and it is easily fooled by back-scattered charged particles from neutrons converting in the body of the calorimeter.

The second method of neutron vertex determination has been the use of an iron-plate optical spark chamber, using plates of 1/2 inch steel and about five modules of 7 plates each. These chambers were used in n-p forward elastic scattering at 2-6 GeV (at the Bevatron)[7] and later in the same experiment at 14-28 GeV (at the AGS).[8] Similar chambers were also used by the CERN-Karlsruhe group in a similar experiment.[9] In these cases, the neutron detection efficiency was probably 60-90% (not measured) but no attempt was made in this device to simultaneously determine the neutron energy.

It is obvious that optical or (more probably) wire-plane chambers could be combined with scintillators and iron plates to give both pulse height (energy) and coördinate data on neutrons. Such a chamber might contain 20 or so modules each containing an iron plate, a scintillator, and an x and y spark-chamber plane.

Alternatively, the scintillators could be viewed by phototubes from two sides to give coordinate data from the transit time difference of light to the two ends of the scintillator. This is the method used in the author's Bevatron neutron experiment mentioned above, achieving a resolution of about 1-1/2 inches (FWHM). Counter hodoscopes could also be used in obvious ways, at correspondingly greater complexity.

An attractive possibility would be to use multi-wire proportional chambers to combine the functions of pulse height (energy determination) and coordinate information. Each wire might feed an emitter follower with two outputs; one summed for all wires in the array using a longer (0.1-0.3 μsec) integration time constant for total energy measurement, and the other, clipped to short pulse rise, for coordinate determination. Such gas detectors have the added virtue of avoiding the non-linear ionization response of plastic scintillator, noted above as a major limitation on the resolution of present ionization calorimeters. The major disadvantage (other than cost and complexity) of this approach is the sacrifice in time resolution _vis-a-vis_ a detector employing only plastic scintillators.

A TANC built of NaI could be constructed with clear windows into the crystals through which image intensifiers could view the detector volume. A photograph (or video tape record) of each cascade could then give the coordinates of interaction vertices while phototubes viewing from other directions would record total pulse height.

In this context, Huggett is currently operating a cosmic-ray ionization calorimeter at Climax, Colo., employing 20 layers of plastic scintillator each 3×6 ft^2 by 1 in. thick. Each scintillator pair is viewed by 5-in. PM tubes with 5% uniformity in pulse-height response over this area. In addition, mirrors collapse the light from two edges of the scintillator stack onto the cathodes of two image tubes, permitting recording of the ionization profile of each cascade.[4]

In general, adding coordinate-determining capability to a neutral hadron detector would add \$10,000-\$50,000 to the detector cost. In view of the desirability of this option, the consequent over-all cost differential between a TANC and a sampling calorimeter is reduced.

VI. TIME RESOLUTION

The systems employing plastic scintillation counters would have a time resolution and dead time typical of the scintillator technique (2-5 nsec). Some caution is appropriate for detectors of larger area due to transit-time spread of the light collection (~6 nsec per meter). Gas proportional chambers give a "first pulse" response in as short as 40 nsec; however, in order to integrate the entire pulse from 1 cm-gap counter, one can achieve 0.1-0.3 μsec time resolution, but with at least 1 msec dead time. The NaI detector has a decay ~ constant of 0.25 μsec; however, the light output is so great that clipping to 10% of this time (25 nsec) should be possible without deteriorating the energy resolution. However, image tubes (with the present state of the art) would probably limit the vertex observation to about 1 μsec time resolution.

VII. EXTENSIONS

Obvious extrapolations and combinations might be considered. The use of Cerenkov radiators in place of scintillators would be possible, but would probably reduce resolution in view of the 30% energy fraction going to slower nuclear fragments. Attempts to cause PbF (or other dense, transparent media) to scintillate will continue. Wire spark-chamber planes could be inserted between NaI modules for space resolution. Absorber plates could be immersed in tanks of liquid scintillator (although this could sacrifice the convenient light piping of total internal reflection). A plastic or liquid (density 1) detector with no iron absorber would become inordinately large, perhaps 10 m long, although by NAL scale standards it should not be ruled out. Pilot has fabricated Pb-loaded plastic scintillator, but it is expensive and not very efficient.

VIII. CONCLUSIONS

Detectors for neutral hadrons, n, $\overline{n}$, and K_2^o of energies to 200 GeV exist which should give 3-20% energy resolution at 200 GeV. It is not clear that a homogeneous detector (TANC) would give better energy resolution than a sampling detector at high energies, although it may be superior at lower energies. At the present state-of-the-art it is clearly much more expensive. Time and spatial resolution typical of scintillation counter-spark chamber-proportional chamber techniques can be achieved with these detectors.

ADDED NOTE (SEPTEMBER 1969)

At the XI International Conference on Cosmic Rays held in Agugust 1969, further studies of ionization calorimeters were reported. The Soviets (Dobrotin's group) reported Monte Carlo studies of the energy fraction going into different channels (e.m. showers, nuclear fragmentation, and ionization),[10] and a similar study was reported by the Louisiana group. The latter study also included longitudinal and lateral leakage calculations and a comparison with AGS calibration.[11] It remains true that an absolute calibration of a calorimeter with a momentum-analyzed hadron "beam" in the 100-500 GeV region is necessary for a clean interpretation of higher energy calorimeter data.

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