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SUBJECT THE USE OF LIQUID NOBLE GASES IN PARTICLE DETECTORS WITH 1)HIGH SPATIAL RESOLUTION OVER A LARGE AREA, AND 2)HIGH ENERGY RESOLUTION AS TOTAL ABSORPTION COUNTERS.	NAME L. W. Alvarez
	DATE 26 November 1968

Introduction

A presently unfilled need in the field of high energy particle detectors is for a device that would record, in real time, an accurate positional measurement of the intersection of the path of a minimum ionizing particle with a detector plane. Modern thin gap spark chambers, with digital readout, have spatial resolutions of the order of 1/2 mm. The proposed device should improve this resolution by at least two orders of magnitude.

In order to improve any device by two orders of magnitude, one must first of all understand the limitations of its current technology. Wire spark chambers, with magnetostrictive readouts, or magnetic core readouts, have typical wire-to-wire spacings of 1 mm. The most obvious way to increase the resolution is to space the wires more closely. But if one keeps the spark chamber gap at a typical value of 1/2 to 1 cm, then simply decreasing the wire spacing and wire size will have no appreciable effect on the resolution of the system. The reason for this is simply that one must deal with tracks that are not normal to the plane of the spark chamber, and these tracks have a range of "X intercepts" given by 2t tan θ, where t is the width of the spark chamber gap, and θ is the maximum angle of the particle from the normal. In practice, one often minimizes this effect, by using several narrow gap spark chambers in tandem, and fitting a particle trajectory to the several visible sparks. But it is clear that to make a two order of magnitude improvement in spatial resolution, one must make something like a two order of magnitude decrease in the spark chamber gap width. Such a decrease is quite impossible, if one uses gases in the spark chamber, since typical values for the number of ion pairs produced by minimum ionizing particles are 30 per cm of track length. Values of specific ionization such as this, lead to spark chamber gap widths as they are now known, and obviously prohibit the

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use of gap widths in the neighborhood of 50 microns.

It is therefore obvious that a device of the type under discussion must incorporate a detecting material with liquid or solid density, in order to produce enough ion pairs or photons in a thickness of the order of 50 or 100 microns. And since densities of condensed matter are typically several hundred times those of gaseous materials, one picks up more than the required factor of 100, by going from gas to condensed matter.

Others who have considered the need for large detectors with greatly in-creased spatial resolution have not come to this conclusion, but have attempted to retain the ionization of gases as their primary detection phenomenon. For example, Charpak and his collaborators (G. Charpak, R. Bouchier, T. Bressani, J. Favier, and Č. Zapačič, Nuclear Inst. & Meth. 62, 262(1968)) have tested a multi-wire proportional counter system, with wire spacing in the range from 1 to 3 millimeters. They confirmed the independent action of neighboring wires as gas amplifiers, and they showed that some indication of the proximity of the track to a wire could be gleaned from the signal delay caused by the migration of the electrons through the gas. If it were possible to measure a typical 100 nano-second delay to 1 nanosecond, and if there were a linear relationship between delay and "miss distance", from wire to particle trajectory, then one could consider a device of this sort as a candidate to yield positional data to 5 microns. But the physical limitations of the device do not permit its development to such a state. The first limitation is simply geometrical: If we want to specify the x and y coordinates of a track to 5 microns, as it crosses a plane, we must know where the plane is to 10 microns, if we allow particles to pass the plane with angles of $\pm 30°$ to the normal. If we assume there are 30 ion pairs per centimeter of gas, and we want to trigger several gaps to record the passage of a particle, our gap spacing must be at least 1000 microns wide -- this

yields an average of 3 ion pairs per gap. This condition is in gross violation of the condition just derived, and by itself should eliminate the multiple wire proportional system from serious consideration for the purposes of this note.

A further difficulty arises from the generation of delta rays in a gas counter. Delta rays have higher specific ionizations than the relativistic primaries, and can deposit these extra ions at considerable distances from the primary tracks.

In concluding this discussion of the Charpak development, it is probably fair to say that it will fill a need in the arsenal of the high energy physicists, but it will not give the spatial resolution that is being asked for in this note.

The first technique that comes to mind, in the field of condensed matter detectors, is the use of a scintillating fiber detection plane. About ten years ago, there was a good deal of activity directed towards the building of what was known as a fiber scintillation chamber. Such devices were to consist of planes of plastic scintillating fibers with typical diameters of 1 mm. Alternate planes of plastic fibers had their fiber directions oriented at 90° to each other, to form roughly a cube of plastic scintillator. Beams of particles were to be incident roughly normal to the planes of plastic scintillators, and the light that was piped from the intersection of particle trajectories and fiber scintillators was to be recorded photographically from two orthogonal faces of the cube in which the ends of the plastic fibers lay. Since the light intensity was far too faint for direct photography, image intensifiers were interposed between the ends of the fibers and the camera.

As far as can be ascertained, no physics was ever done with such devices, but the pursuit of practical fiber scintillation chambers apparently played an important role in the development of modern image intensifiers. One of the basic problems with the fiber scintillation chamber was that no one was able to

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produce a fiber with an attenuation length more than about 10 cm, and a diameter of less than 1 mm. As the diameter was reduced, the attenuation length was reduced proportionately, which showed that the attenuation was due to leakage of light from the surface of the fibers, at "craze marks". (In contrast to this experience with plastic scintillating fibers, the attenuation distances of non-scintillating fibers of plastic material and of glass, correspond roughly to the attenuation distance in large volumes of the same material. This indicates that no loss takes place during reflection at the surface of these fibers.) Plastic fiber scintillation chambers were therefore confined to cubes of roughly 10 cm on a side, with resolutions set by the 1 mm diameters of the fibers, and the rather poor imaging qualities of the image intensifying tubes then available.

One might think that it would be useful to attempt the production of plastic scintillating fibers with diameters of a few microns, perhaps coated with non-scintillating material of lower index, so that the problems of crazing could be eliminated. There is little doubt that such a program would be marked with eventual success, but that would still leave, for the intended application under discussion here, the problem of laying down several hundred thousand fibers on a plane, with each fiber in its proper position, to a few microns, at all points on the plane. Although someone may have an idea as to how this rigid specification could be met, the present author has been unable to suggest a solution. For this very practical reason, the phenomenon of scintillation has been rejected as a possible technique for realizing a detector with high spatial resolution.

Shortly after this last paragraph was written, a reference was found that might be the key to a scintillation type solution to the problems posed in this note. Work at UCLRL Livermore, by Bauer and Weingart (R. Bauer & R. C.

Weingart, Nuclear Inst. & Meth. <u>55</u>, 55(1967)) has produced evaporated layers of
NaI (Tl), from 0.2 to 20 mg/cm^2 thick, with scintillation efficiency and uniformity
of light output comparable with commercially available, thick NaI (Tl) crystals.
These thicknesses are appropriate to our problem, and the evaporation technique
can take care of the problem of making sure that the fibers are where they should
be, but other serious problems remain to be solved. Perhaps someone else will
see his way from this point to a practical high resolution device - it is for
this reason that this interesting reference is included in this note.

Since the considerations outlined above show that one must use a detector
made of condensed matter, and since scintillation techniques look too difficult,
the only other technique available appears to involve electrical conduction in
condensed matter, under the influence of ionizing radiation. At the present
time, such techniques usually involve lithium drifted silicon, and similar exotic
single crystal solid state devices. Such devices have some very marvelous
properties, particularly in their energy resolution. This energy resolution
comes from the fact that it takes only about 3 electron volts to make an electron-
hole pair as contrasted to the 20 or 30 electron volts required to make either
an ion pair or a scintillation photon. One therefore has much higher statistical
accuracy in energy measurements made by solid state detectors. The difficulty
in using such detectors for the purposes under discussion comes from the fact
that the detectors must be single crystals, and this presently limits the size
to an inch or two in diameter, So, in order to have a large area of such detectors,
one would have the problems of aligning them and connecting them together, and
these appear to be an almost insoluble, using presently available techniques.
Therefore, for practical reasons, we will not consider this technology any further.

"Crystal Counters"

All the electrical counting devices that were used up to and including
the end of World War II, involved the ionization of a gas by some source of
ionizing radiation, with the ions subsequently being collected, with or without
amplification in the gas. Many experimental physicists had voiced the need for
a radiation detector involving condensed material, but in spite of a good deal
of experimental work, no such device was available, even to the affluent ex-
perimenters at Los Alamos. Shortly after the end of World War II, it was learned
that P. J. van Heerden, a Dutch physicist, had earned his Ph.D. degree in 1945,
with a thesis entitled "The Crystal Counter". van Heerden had shown that if one
took a single crystal of silver chloride, with electrodes evaporated on faces
perhaps a centimeter apart, and annealed it for several hours at high temperature,
and then cooled it to liquid air temperature, that sizeable ionization pulses
could be obtained when the crystal was exposed to beta or gamma rays. So quite
unexpectedly, physicists were presented with a counter that gave pulses that were
at least two orders of magnitude larger than any they had seen before, in devices
of comparable size. And even more unexpectedly, the collection time of the
electrons in the crystal was faster than it had been in the earlier gas counters.
As a direct result of van Heerden's discovery, there was a great flurry of ex-
citement and experimental work in the nuclear physics community, but it quickly
subsided, when the practical organic scintillation counter was discovered by
Kallmann, in about 1947. The scintillation counter avoided two very serious
difficulties that had quickly been found in crystal counter technology. (1)
Crystals, with the exception of cadmium sulfide, had to be kept at liquid air
temperature and (2), much more seriously, after about a million counts, the
crystals became polarized, by electrons which were caught on trapping centers.

The polarization reduced the applied field to the point that the counters stopped counting. Many attempts were made to avoid the polarization difficulty, such as irradiating the crystals with infrared light or by periodically reversing the electric field, but these techniques did not provide sufficient relief from the polarization difficulties to make crystal counters attractive as practical detecting devices. No doubt, ways could have been found to make crystal counters useful, but the need for them disappeared with the discovery of scintillation counters. Such counters did not require single crystals, did not need to be cooled, and the technology of photomultiplier tubes was well advanced. So scintillation counters quickly preempted the field of condensed matter counters, and crystal counters passed into the history books.

Most of the knowledge that was gained about crystal counters in their brief period of glory is described in two review articles by Robert Hofstadter, Nucleonics, Vol. IV, No. 4, 2(1949), and Vol. IV, No. 5, 29 (1949). With one exception, almost everything described in these two very interesting articles makes the crystal counting technique unattractive as the basis for a large counter with high spatial resolution. The one exception relates to experiences with liquid and solid argon. The use of liquids would clearly avoid the difficulty due to polarization of the crystal. N. Davidson, and A.E. Larsh, Jr. report on experiments in liquid argon in Physical Review 74, 220 (1948), and independent work of more breadth, on the same subject, is reported by E. W. Hutchinson, in Nature 162, 610(1948). Hutchinson points out that each electron pair requires an average of 25 electron volts to produce. Saturation pulses were observed in liquid argon at 10,000 volts per cm., in gaps of 1 mm and 5 mm. At this electric field, the mobility of the electrons was approximately 40 cm^2 per volt second (40 cm/sec per volt/cm). The effective collection time of the electrons in a gap of 50 microns would therefore, be approximately $2.5 \times 10^{-3}/40 \times 10,000 =$

6×10^{-9} seconds. (2.5×10^{-3} is half the assumed electrode spacing of 50 microns; 40 is the mobility, and 10,000 is the electric field.) The potential difference across such a gap would be only 25 volts.

Hutchinson made two additional interesting observations. He compared the size of the pulses obtained in solid argon with those found in liquid argon, from the same gamma ray source. The pulses in liquid argon were of the proper size to have been due to direct collection of electrons, with 25 electron volts per ion pair. But the pulses in solid argon were 12 times as large, indicating that there was electron multiplication in the solid. Hutchinson noted the usual behavior of a solid counter -- the rapid polarization of the material reduced the sizes of the pulses. But, of course, this phenomenon was missing in liquid argon.

Hutchinson then looked for multiplication in liquid argon, by building a proportional counter, with a 5.2 mm diameter cylinder, and a 15 micron diameter wire. He raised the potential to 4000 volts, and found that the pulses were all of the size he observed at much lower voltages. But when he solidified the argon in the proportional counter, the pulses were 10 times larger, at potentials as low as 500 volts. These observations indicate that it is unlikely that multiplication is important in liquid argon, compared to its importance in solid argon. Hutchinson gives no reason for having stopped his measurements at 4000 volts, but it could have been a trivial thing such as the limit of the power supply he had available. It hardly seems possible that spark breakdown could have taken place at such a low voltage in such a geometry. Probably Hutchinson was discouraged to find no multiplication in the liquid at almost ten times the voltage at which multiplication appeared in the solid.

Neither the bubble chamber nor the spark chamber, the two most important

high energy physics detectors, work when they are put into a state of continuous
sensitivity. In the spark chamber, the continuous application of high voltage
leads to sparking at sharp points, and in the bubble chamber, bubbles form
spontaneously at sharp points on the surface. So bubble chambers, in the practical
sense, only work when they are sensitized just before the passage of the particles
to be studied, and spark chambers work only when they are sensitized just after
such passage. The development of spark chambers was delayed for many years,
until fast electronic circuits were available to apply high voltages across gaps,
immediately following the passage of particles to be studied. Their success
certainly depends upon the existence of fast pulsing circuits.

Let us assume for the moment that Hutchinson was unable to go beyond 4000
volts, because at that potential difference, spontaneous sparking took place
somewhere in his proportional counter. His work was done before high speed
electronic pulsing circuits were available, so he would have been unable to try
the obvious addition of a fast coincident circuit plus a fast pulser, to apply
much higher voltages to this chamber. There is a good chance that had he tried
this rapid application of high voltage to either his solid or liquid argon
detectors, they would have broken down at the site of the primary ionization.

The conclusion just stated is based on the clear demonstration, by Hutchinson,
that the radiation-induced conductivity of liquid argon is due to electron, rather
than to ion drift. It has been known for more than 30 years that pure hydrocarbons
such as hexane, make good quasi-D.C. ionization detectors. The carrier mobilities
in such liquids are of the order of 10^{-3} cm/sec per volt/cm, indicating that the
carriers are ions. Work in other laboratories has recently shown that high
field breakdown in hexane, under nanosecond pulsed conditions of more than 10^6
volts per centimeter is insensitive to the presence or absence of radiation
sources. These studies show that there is no possibility that liquid hydrocarbons

could play a useful role in detectors of the type we are now discussing.

But the electron conduction observed by Hutchinson in liquid argon (by its high mobility), and in solid argon (by its mobility, confirmed by its multiplication) appears to promise a solution to the problem under discussion. With the rapid pulsing circuits that have been developed for spark chamber applications, it should be a simple matter to extend Hutchinson's observations to the higher field regime, to see if multiplication and perhaps triggered sparking occurs, We shall first take the optimistic point of view and assume that triggered sparking will occur, and show how the desired spatial accuracy can be obtained. We shall later take two steps in the direction of pessimism, and show (1) what could still be done if multiplication, but not sparking, were attainable, and (2) what could be done if simple electron collection without multiplication was the only phenomenon observable.

Since the 1948 work on the radiation-induced electrical conductivity of argon, a number of research papers have been published on D.C. electric break-down in argon, and its explanation. Most of this work has been oriented toward the electrical engineering aspects of electric breakdown, but the papers are interesting to read and contain much useful information. In particular, Swan predicts that at 1 million volts per cm, the average electron energy will be 5.5 electron volts, and the high energy tail of the distribution will extend up to energies that will make spark breakdown almost assured.

The following references are of interest:

D. W. Swan & T. J. Lewis, Proc. Phys. Soc <u>78</u>, 448(1961)

        "   <u>78</u>, 423(1961)

        "   <u>76</u>, 36(1960)

R. L. Williams   Canad. Jour. Phys. 35, 134(1957)

"   & F. D. Stacey   "   "   "   35, 928(1957)

F. D. Stacey   Austral. Jour. Phys. 11, 158(1958)

The work of Swan suggests strongly that in very narrow gaps, the rapid application of high fields after the passage of an ionizing particle will lead to spark chamber performance.

Naturally, we will want to look at the heavier liquified noble gases, in particular Xenon, because the higher the density of the detecting material, the thinner is the layer that can be tolerated. A short conversation with Professor Charles Kittel suggests the Xenon may be a better electronic "semi-conductor" than argon. If that turned out to be true, we would have the "best of all worlds".

At this point, we can make either one of two assumptions--spark breakdown in liquids, initiated by an ionizing event, can take place, or such a spark discharge cannot take place. I think it is most reasonable to adopt the first hypothesis, and proceed with a tentative design of a very accurate spark chamber detector using such a phenomenon. But in the unlikely event that such a phenomenon does not occur, one could still design a device with the same properties, but making use of integrated circuit amplifiers connected to the two sets of sense lines. Such a device would be called a digitized ionization chamber, instead of a digitized spark chamber, and its output signals would be quite equivalent to those from the device we are about to design. Liquid argon could, of course be used as the working fluid, but it is probable that Xenon will have better properties. It is even possible that some other normally non-conducting liquid will be found, with an appropriately located vacant conduction band.

Note added November 12, 1968

The manuscript for this note, up to this point, has been on my desk for several months. For certain reasons, it appears that this year I won't have time to describe in detail what I had planned as the modus operandi for the digitized detection of high spatial resolution. But there will be time later, and my ideas are rather well worked out. I have described a new kind of Gray Code to my associates, that seems ideally suited to the construction of a high resolution device. For satellite use, one would back up the electrically-read-out detector with a double sided nuclear emulsion plate. This would permit particle location to one micron, and give good enough "rough" positional information to permit exposures to cosmic rays of several weeks.

As a total energy detector, (to compete with Robert Hofstadter's large sodium iodide devices), I will simply suggest a "barrel" of liquid argon, with layers of metallic foil for charge collection. The low cost of liquid argon- compared to sodium iodide - makes the idea attractive. The number of electrons collected per unit energy loss could be twenty times higher than in the NaI case, so if statistical effects had any significance, they would be minimized in the "barrel". The low cost makes it reasonable to have very much larger detectors, thereby minimizing leakage across the boundaries. The development of "charge sensitive amplifiers" obviates the need for accurate control of geometry or voltage in the device, in contrast to devices that use photomultipliers.

$$P_\pi = \mathcal{E}[r_\| - \beta \sqrt{r_\|^2 + r_\perp^2 + m_p^2}]$$

shown in Figure 1 are for one value of $r_\perp$. We use $\mathcal{E}$ and β , the usual center-of-mass transformation parameters.

One important distinction between the pi plus and proton center-of-mass momentum spectra is that the kinematics of a symmetric reaction does not allow a particle as heavy as the target (or beam) to go backwards in the laboratory. Thus we can identify as pi plus, all tracks with negative laboratory longitudinal momentum. For a pi plus mass hypothesis this corresponds to a center-of-mass longitudinal momentum being less than $-\mathcal{E} \beta \sqrt{m_\pi^2 + p_\perp^2}$.

The identification of a pure sample of pions in conjunction with the forward-backward symmetry can be used to infer the proton and pi plus center-of-mass distributions from the laboratory momentum distribution of all positive tracks. The following example demonstrates the method with diagrams for proton-proton interactions at an incident beam momentum of 13 GeV/c. The diagrams depend upon $p_\perp$ which we have taken as $\langle p_\perp \rangle \approx .3$ GeV/c. Other values of $p_\perp$ allow a similar treatment.

Two distributions contribute to the center-of-mass distribution of all positive tracks interpreted with a pion mass:

a. The pion distribution which is forward-backward symmetric when assigned the correct mass hypothesis.

b. The asymmetric proton distribution assigned the incorrect mass hypothesis.

The resultant total center-of-mass distribution of all positive tracks taken as pions is asymmetric. Similarly, the center-of-mass distribution of all tracks taken as protons is asymmetric.

Note added December 12, 1968.

     Robert Smits has recently observed ionization pulses in liquid argon as reported by N. Davidson and A. Larsh [Phys Rev 74, 220 (1948) and Phys Rev 77, 706 (1950)] and amplification in solid argon, as reported by G. Hutchinson [Nature 162, 610 (1948)] . In addition, we believe that we have observed multiplication in liquid xenon using steady fields of 10^4 volts/cm in a parallel plate geometry. Work is now in progress to produce spark discharges in liquid argon and xenon in pulsed fields of 10^5 to 10^6 volts/cm.