REFERENCES

1. R. Davis Jr., K. C. Hoffman, and D. S. Harmer, Phys. Rev. Letters <u>20</u>, 1205 (1968); R. Davis Jr., Proc. Informal Conf. on Status and Future of Solar Neutrino Research (BNL 50879) <u>1</u>, 1, G. Friedlander, Editor.

2. J. N. Bahcall, Rev. Mod. Physics <u>50</u>, 881 (1978).

3. A. W. Wolfendale, E. C. M. Young and R. Davis, Nature Physical Sci. <u>238</u>, 1301 (1972); G. A. Cassidy, Proc. 13th Int. Conf. on Cosmic Rays, Denver, Vol 13, p 1958 (1973).

4. E. L. Fireman, Proceedings 16th International Cosmic Ray Conference, Kyoto, Vol. 13, 389 (1979).

5. J. N. Bahcall, S. H. Lubow, W. F. Huebner, N. H. Magee Jr., A. L. Merts, M. F. Argo, P. D. Parker, B. Rozsnyai, and R. K. Ulrich, Phys. Rev. Letters <u>45</u>, 945 (1980).

6. G. Friedlander (editor), Proceedings Informal Conference on Status and Future of Solar Neutrino Research (1978), BNL 50879, Volume I, see reports by J. N. Bahcall p 55, P. D. Parker p 77, W. F. Huebner p 107, S. H. Lubow and R. K. Ulrich p 157, and I. W. Roxburgh p 207.

7. Ibid, Vol I, R. T. Rood p 175.

8. J. N. Bahcall, B. T. Cleveland, R. Davis Jr., I. Dostrovsky, J. C. Evans, Jr., W. Frati, G. Friedlander, K. Lande, J. K. Rowley, R. W. Stoenner and J. Weneser, Phys. Rev. Letters <u>40</u>, 1351 (1978).

9. L. W. Alvarez, Memo no. 767, Lawrence Radiation Laboratory, Univ. of California, March 23, 1973.

10. F. Reines, H. W. Sobel and E. Pasierb, Phys. Rev. Letters <u>45</u>, 1307 (1980).

DIRECT DETECTION AND SPECTROSCOPY OF SOLAR NEUTRINOS USING INDIUM

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ABSTRACT

The development of the Indium Solar Neutrino Spectrometer is reviewed. The importance of position sensitivity in this detector is emphasized. A novel concept for a "neutrino chamber" is advanced and being developed. A solar prototype chamber could be applied to reactor $\bar{\nu}$ experiments.

1. INTRODUCTION

Almost since the development of the ^{37}Cl radiochemical solar neutrino detector some 20 years ago, there has been a parallel but unsuccessful search for a physical technique by which solar neutrinos could be directly counted[1,2]. The desirability of such a method stems largely from the fact that this approach offers the only way to measure the energy of the detected neutrino. The energy spectrum of solar neutrinos constitutes the most complete experimental information on the solar interior that can possibly be obtained.

In 1976, a promising development occurred with the discovery of the possibility of inverse β-decay in ^{115}In[3]. This approach, with a threshold of 128 keV $\ll E_\nu^{max}$(pp) = 420 keV, a distinctive delayed coincidence signature and only a relatively small target mass of 4 tons of In (for 1 ν-capture/d) offers, in principle, most of the features long sought for in an ideal solar neutrino detector. In practice, however, the problems imposed by the weak ($\tau = 7\times10^{14}$y) β-radioactivity of In necessitate no less than the development of a new kind of counting instrument to realize the potential offered by this approach. Ideas underlying a novel "neutrino chamber" have been developed in this laboratory and experimental work to demonstrate 'proof of principle' of this device is in progress. The problem of electronic signal conversion in such classes of devices is being studied by a group at MIT led by Martin Deutsch as part of a Bell Labs-MIT collaboration[4] aimed at developing the In solar neutrino detector.

2. THE NEUTRINO CAPTURE REACTION IN ^{115}In

Fast Gamow-Teller β-decay is observed systematically between $9/2^+$ states of In isotopes and $7/2^+$ Sn nuclides throughout the mass range 111-131 (see Fig. 1). At the lighter end of this range Sn decays to In by electron capture, crossing over to In→Sn β-decay at the heavier end. Near the crossover, at A = 115, the two levels are only 128 keV apart, the $9/2^+$ level being the ground state of ^{115}In while the $7/2^+$ level which lies above, is an excited metastable state (τ = 4.7 μsec) of ^{115}Sn. These systematics and the nuclear structure data show that inverse β-decay induced by solar ν-capture in ^{115}In would populate only this $7/2^+$ metastable state in ^{115}Sn the matrix element for which can be inferred with confidence from the β-decays of the neighbouring members of this family[3]. With the cross section for ν-capture calculated[3,5] on this basis and the neutrino fluxes predicted by the standard solar model, the mass of In for an average ν-capture rate of 1/d is ~4 tons. ^{115}In (isotopic abundance 96%) is a long-lived nuclide (see Fig. 2) decaying by a highly hindered β-transition (Q = 490 keV) to ^{115}Sn (stable). The ^{115}Sn $7/2^+$ isomeric state is depopulated by a cascade of a 116 keV transition which is 50% internally converted into a ~94 keV electron (e_1) followed by a 498 keV γ-ray (γ_2).

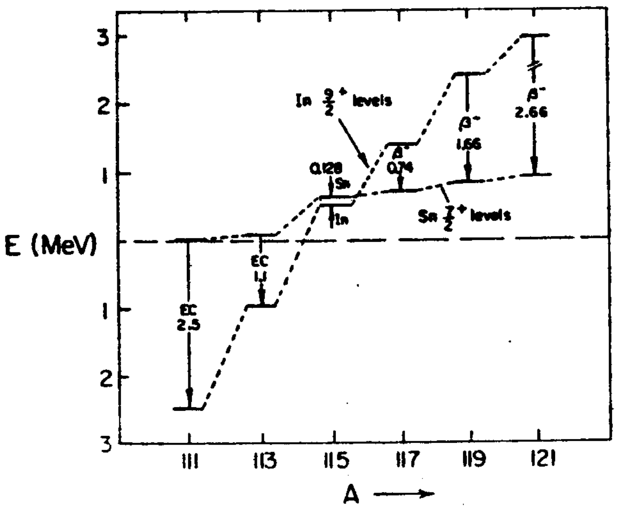


Fig.1. β-decay systematics of odd In-Sn isotopes.

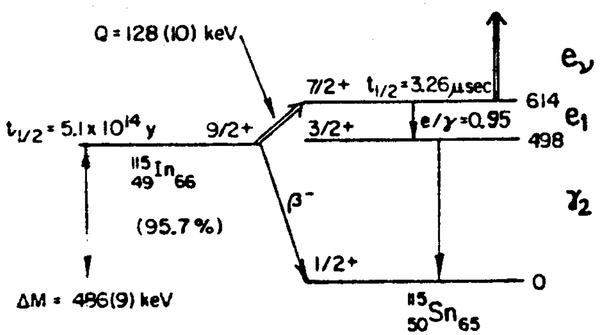


Fig.2. Nuclear physics of the ν-capture reaction $^{115}In(\nu,e_\nu)^{115}Sn^*$

3. NEUTRINO SIGNATURE

A measurement of the energy of the prompt electron e_ν of the reaction $^{115}In(\nu,e_\nu)^{115}Sn^*$—delay—$e_1+\gamma_2$ directly yields the energy of solar neutrino: $e_\nu = E_\nu - 128$ keV. The identification of the e_ν pulse can be accomplished by the following signatures[3]:

a) Delayed triple coincidence ($e_\nu \leftrightarrow e_1 + \gamma_2$).

b) Spatial coincidence ($e_\nu \leftrightarrow e_1$).

If the prompt electron e_ν (0-300 keV for pp neutrinos) is used to start a clock and a coincidence of $e_1+\gamma_2$ is used to stop it, the time-delay spectrum of the ν-signals is exponential with a signature time constant of $\tau = 4.7$ μsec. In practice, this time spectrum sits on a flat background due to random coincidences of events mimicking e_ν, e_1 and γ_2 such as the ^{115}In β-decay electrons (0-500 keV) which start the clock and γ-rays (≅600 keV) in the ambience which simulate the $e_1 + \gamma_2$ cascade by a Compton sequence and stop the clock. A stringent additional signature for reducing these accidental events is the demand that a low energy electron in a Compton sequence stopping the clock, occur in the same spatial location as the prompt electron since in a true ν-event, the conversion electron e_1 is emitted in spatial coincidence with e_ν. The background is thus proportional to the positional volume resolution Δv within which the observation of the e_ν and e_1 signals could be restricted. Since Δv/v could be as small as 10^{-10} a background rejection by this factor may be available. The accompaniment of the Compton shower of γ_2 in the vicinity of the $e_\nu \leftrightarrow e_1$ coincidence is a confirmatory signal which rejects accidental clock signals activated solely by uncorrelated In decay electrons.

The crucial role of the spatial coincidence signature demands a high position sensitivity in the detector. Other requirements are: fast time response, adequate sensitivity to low energies, moderately good energy resolution, high radioactive purity of the detector materials etc. Our study indicates that while these requirements could be fulfilled with known detector technology, the concurrent achievement of the necessary position resolution needs path-breaking ideas.

4. SPATIAL RESOLUTION AND FIGURE OF MERIT

How much spatial resolution do we need? Consider a single resolution volume Δv of the detector homogeneously interspersed with In. Let m be the mass of In contained in this volume and mC the total mass of Δv. C is the ratio of the total detector mass to the mass of In (4 tons). Then the accidental rate N in Δv is the product of m times the known specific activity of In, the duration of the coincidence time window ($\tau = 4.7$μsec) and mC times the γ-ray background rate/gm of the detector. The signal rate S is (m/4 tons) × 0.5 × 0.64/d as modified by the 50% conversion probability of e_1 and the fractional decay in a time τ. A realistic γ-ray background can be inferred from a γ-spectrum observed by a large liquid scintillator[6] as 2×10^{-7}/keV/gm/sec at 600±100 keV. Thus the figure of merit is:

$$S/N = 20/mC \quad (m \text{ in mg})$$

Typical concentrations of In range from C = 5 to 20. Thus for S/N = 1 the mass of In/resolution volume Δv is limited in the range 1 to 4 mg. This points to the need of $\Delta v/v \cong 10^{-9}$.

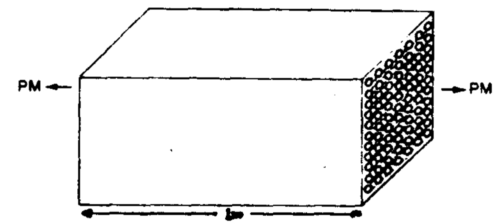
How much spatial resolution can we get? In the last few years a number of approaches available with currently known detector technology have been studied[5,7,8]. The design of closest approach to a viable detector is schematically shown in Fig. 3. It consists of close-packed bundles of plastic scintillation fibers coated with In[8]. The plastic fibers typically have a diameter d = 0.5 mm and clad with a low refractive index optical layer over which a thin coating of In is applied. The electrons from the In ν-reaction are stopped in the fiber and a portion (~25%) of the scintillation light is trapped and guided to the ends where it is detected by a position sensitive array of phototubes which register the 2-dimensional location of the active fiber. Typical specifications achievable in this design (see Fig. 3) show that S/N is still short of break-even by a factor of ~35 while the luminous area of the fibers is very large (equivalent e.g. to 40,000 2" phototubes at 50% cathode area utilization). If the event location along the fiber (z) is also determined[9], an improvement of S/N by better than two orders of magnitude is possible. For example, if the fiber planes in the bundle are arranged alternately in orthogonal orientations, a penetrating particle could activate 2 orthogonal fibers[10] pinpointing its 3-dimensional location to a precision of $\Delta v \cong d^3$. Unfortunately this old idea cannot be applied to low energy neutrino detection because of the soft electrons emitted in these reactions. Besides this, the fiber luminous area remains unreduced.

Thus the major problems that need to be solved are: a) Three dimensional position determination; b) Compatibility to low energy spectroscopy; c) Significant reduction of the fiber luminous area. In 1979 the author formulated a novel concept which simultaneously addresses these three problems and points to the realization of spatial resolution at the $(mm)^3$ level in such a scintillation type device resulting in effect, in a continuously live "chamber" for low energy neutrino spectroscopy.

5. A NOVEL NEUTRINO CHAMBER

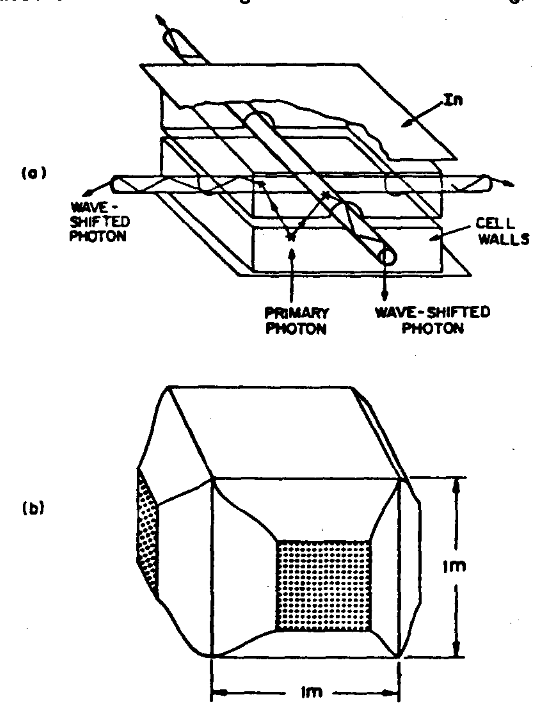
Consider a tank of liquid scintillator. The scintillation light from a localized low energy event spreads out isotropically providing almost no position sensitivity. Let a grid formed by planes of scintillating fibers stacked alternately crosswise, be immersed in the tank. Let the fluorescent solutes in the fiber be spectrally matched to the scintillation light which would then be strongly absorbed by the fibers. Since the fluorescence light re-emitted in the fibers is Stokes-shifted to longer wavelengths it is relatively free of fiber attenuation. Clad with a low index non-absorbing optical layer, the fiber traps part of the wave-shifted fluorescence and guides it to its output ends. This fluorescence conversion of light from a localized event in the tank occurs in both members of the nearest pairs of crossed fibers resulting in a 4-fold coincidence of fiber signals. This can pinpoint the 3 coordinates of the event in a digital fashion. The central idea of a sensing grid of fluorescing fibers immersed in a scintillation medium is the generation of position information by sharing the *optical* radiation from the event between the crossed sensor fibers thus circumventing the problem of direct activation of the pair by *ionizing* radiation of short range. By inserting diffuse reflecting baffles between the fibers and dividing the tank into resolution elements Δv each sensed by one fiber cross, the light from an element several times larger than the enclosed fiber cross can be collected, thus requiring only a loosely spaced sensor grid. This serves two purposes: i) the light from the resolution element is converted into only one fiber pair, ii) because of the loose spacing the total length and luminous area of the fibers necessary to observe the tank -- the two parameters of most relevance to the cost of the detector -- could be significantly less than those in the close-packed array of Fig. 3. The well known method of light collection[11] by fluorescence conversion is thus available as a natural by-product of the central idea of this chamber. Notice that with fewer phototubes, which contribute much to the γ-background, the figure of merit equation could also become more favorable than indicated in #4. This new concept of a 'fluorescence chamber' could thus provide a global solution to the problems discussed in #4.

Fig. 4 shows, as an example, a resolution element of the In neutrino chamber. The elements are defined by a lattice of 2X2 mm square cells with 0.5 mm high walls of ~0.1 mm thickness, made of polyethylene or similar material. Structural strength is provided by 2mm thick ribs running at 15 cm intervals. The cell walls are coated with a highly reflecting layer. This framework can be wrapped around a drum and the fibers wound on it, their alignment and spacing being maintained by guide notches on the cell walls (see Fig. 4) and especially on the support ribs where the fibers can be firmly glued down. The sensor



Total detector mass = 20 tons
Fiber diameter d = 0.5 mm
Luminous area = 40 m^2
C = 5
m = 140 mg
S/N = 0.028

Fig.3. Schematic of the close-packed fiber bundle design. The thickness of the In-coating on the fibers is $\sim$3 mg/cm^2.



Total detector mass = 66 tons
Fiber diameter d = ½ mm
Luminous area = 8 m^2
C = 16.5
m = 0.72 mg
S/N = 1.7

Fig.4. Schematic of fluorescence chamber design. a) Resolution element (Δv = 2x2x1 mm) showing principle of fluorescence chamber. Thickness of interleaved In layer is $\sim$6 mg/cm^2. b) Schematic of $1m^3$ module illustrating the reduction of fiber luminous area. The exact braiding arrangement of the fiber ends will depend on the position-sensitive phototube array and the fiber coding scheme adopted.

grid is then assembled simply by stacking these 1 m^2 fiber planes alternately crosswise and interleaving In-plated plastic film between every crossed pair of planes. It can then be placed inside a tank and filled in with the scintillating liquid.

Such a design would have a luminous area only one fifth that of Fig. 3 and yield a S/N $\cong$ 2 not including the effect of the reduced tube γ-background. Closer packing of the In layers which reduces the detector mass and enhances S/N or the use of thinner fibers (e.g. fibers of 0.125 mm in the geometry of Fig. 4 would have the luminous area equivalent to only 2000 2" phototubes) indicate trends for further optimization. Clearly, the fluorescence chamber approach thus offers the unprecedented combination of powers required to bring the In neutrino detector into the practical regime.

6. DEVELOPMENT OF SCINTILLATING FIBERS

The success of these ideas depends critically on the development of high quality scintillation fibers[12] with high scintillation and light trapping efficiencies and low fiber attenuation. Two different approaches have been pursued in this laboratory:

i) *Plastic fibers:* Plastics such as PVT (polyvinyltoluene) have a high scintillation efficiency and a high refractive index ($n = 1.59$). For high trapping efficiency, the technically compatible cladding material with the lowest index is a silicone resin with $n = 1.41$. A copolymerized PVT scintillator with a higher than usual melting point was used and fibers of $d = 0.5$ mm fabricated[13]. The light yield of these fibers was found to be consistent with the expected trapping efficiency. However, the transmission length was only ~35 cm well below our goal of >1 m. While these fibers are already useful for small scale detectors, specific development of the fiber technology of these plastics is thus necessary before they could be applied to neutrino experiments. Progress is expected to be slow due to the difficulty in optimizing the many intercoupled parameters.

ii) *Liquid core quartz fibers:* As an alternate approach, quartz fibers in capillary form filled with a suitable scintillating liquid offer several advantages. Quartz fiber technology is highly developed and geared for mass production due to the impact of light-wave communications. The fiber fabrication is entirely decoupled from the core liquid which can thus be in-house optimized independently. The surface quality routinely available is very high. The small (<1 ppm) potassium levels in quartz add negligibly to the γ-ray background assumed in §4. The fiber sizes easily available are of 50-500μ bores and wall thickness ~10% of the bore. Despite the presence of the quartz walls this attractive technology is open to us because a principal virtue of the fluorescence chamber concept is that the electrons do not directly activate the fiber. The foreseeable trend towards thinner fibers also fits well into this program. The practical feasibility of low loss liquid cored capillary fibers of $\cong$100μ bore has been demonstrated in our laboratory and transmission lengths ~40 m for He-Ne laser light achieved.[14]

Most of the known organic liquid scintillators have an index of only $n = 1.5$ (n(quartz) = 1.466; n(cladding) = 1.41). Therefore a new high index liquid scintillator with $n = 1.62$, excellent scintillation efficiency (~35% better than the best plastic) and bulk absorption length >2 m has been developed. Quartz capillary fibers of different bore sizes have been fabricated and further development is now in progress.

7. ^{8}B NEUTRINOS AND (ν,e) SCATTERING

The problem of background suppression is severe only for pp neutrinos since their e_ν spectrum (e_ν<300 keV) overlaps with the In β-spectrum. For e_ν>500 keV the end point of the In β-decay, S/N improves by some two orders of magnitude. This is the case for ^{7}Be solar neutrinos which produce a line feature at e_ν = 730 keV which can be distinguished without difficulty from the pp ν-group. Neutrinos from solar ^{8}B decay (E_ν = 5−14 MeV) are quite rare, with a flux only 10^{-4} that of the pp group. A detector dimensioned for ~1 pp ν-capture/d contains too few In atoms (~ 2×10^{28}) for a reasonable capture rate of ^{8}B neutrinos (<1/year). Nevertheless its total mass of ~50 tons contains ~2×10^{31} *electrons* which can thus generate a much higher rate of (ν,e) scattering events. The interesting possibility of observing (ν,e) scattering of ^{8}B neutrinos in our detector arises from the track visualization capability of the fluorescence chamber. Unlike inverse β-decay in In, the sole observable signal in a (ν,e) event is the scattered electron, the identification of which is feasible, even at high energies (~5 MeV), only if discrimination of charged particles and γ-rays is possible. Thus a measurement of the orientation of the electron track, the specific energy loss along the track and the total track energy are of paramount importance for particle and multiple event (γ-ray) discrimination[15]. The resolution of 1-2 mm^3 in a 5 MeV electron track (~25 mm) possible in the fluorescence chamber, is superior to that in the most advanced proposal to date for observing solar (ν,e) scattering[15]. This and the smaller initial track disorientation from multiple scattering in our chamber could better exploit the kinematics of the (ν,e) process which confines the electron tracks (>5 MeV) to a cone ~20° around the axis of the ν-direction. Besides providing additional background discrimination, this directionality offers the important feature of directly correlating the observed (ν,e) events to the sun.

The information output that can be expected from the operation of a full-scale In neutrino chamber may now be summarized: 1) The relative intensities of the pp and the ^{7}Be neutrino groups measured by the In reaction bears directly on solar models independent of effects such as neutrino oscillations; 2) The ^{8}B neutrino flux measured by the (ν,e) scattering extends this type of information to cover the pp chain to completion; 3) The (ν,e) process directionally correlates the observed events to the sun; 4) The intensity of the pp ν-group is an extremely sensitive measure of long-range neutrino oscillation phenomena independent of astrophysical models. Results of such scope and compelling significance justify the considerable undertaking that this experiment represents.

8. SOLAR PROTOTYPE AND REACTOR $\bar{\nu}$ EXPERIMENTS

Our objective for the immediate future is the construction of a prototype neutrino chamber ~1% of the size of the solar detector. It would be extremely attractive if this prototype chamber is useful not only towards the long-range development of the solar detector but can be applied, in its own right, to new physical research. The above discussion on solar (ν,e) scattering points to such an application. Experiments with reactor produced antineutrinos have detected ($\bar{\nu}$, e) scattering and the cross section estimated within wide errors[16]. This purely leptonic reaction is of fundamental interest to particle physics and astrophysics and needs to be measured as precisely as possible. The application of the solar prototype fluorescence chamber to this purpose could be of substantial value due to two major new improvements it can effect: a) the introduction of electron track observability which can enhance background rejection by particle and γ-ray discrimination as well as by the use of the forward peaked ($\bar{\nu}$,e) correlation; and b) the use of a much more massive target enhancing the reaction yield. The reaction $\bar{\nu}$(p,n)e^+ which could be observed simultaneously (with interposed ^{3}He counters for neutron detection) can be utilized as an internal flux calibrator. Thus a well motivated program which could investigate a fundamental physical process while providing development experience for solar neutrino astronomy could be mounted.

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REFERENCES

1. F. Reines, Proc. Roy. Soc. *A301*, 159 (1967).
2. R. Davis, "*Direct Counting-Some History and Some Ideas*", in Proc. Irvine Confce. Solar Neutrinos, Ed. F. Reines and V. Trimble, 1972 (unpublished).
3. R. S. Raghavan, Phys. Rev. Lett. *37*, 259 (1976).
4. M. Deutsch, "*Proposal to Develop a Detector for Solar Neutrinos*", to the U. S. Department of Energy (M.I.T. 1979).
5. R. S. Raghavan, Proc. Confce. Status and Future of Solar Neutrinos, Brookhaven, Ed. G. Friedlander, BNL-50879, vol. II, p. 1 (1979).
6. F. Reines et al., Phys. Rev. *117*, 159 (1960).
7. L. Pfeiffer et al., Phys. Rev. Lett. *41*, 63 (1978).
8. R. S. Raghavan, Bell Labs report TM-79-1131-38 (1979) (unpublished).
9. Analog methods such as pulse-height ratios or relative time delays are inefficient because of the low light levels and result in $\Delta z \cong 50$ cm, which does not justify their added complexity.
10. K. Lande et al., Rev. Sci. Instr. *30*, 496 (1959); G. T. Reynolds, I. R. E. Trans. Nuc. Sci. *NS-7*, 115 (1960).
11. W. A. Schurcliff, J. Opt. Soc. Am. *41*, 209 (1951).
12. The fiber sensors in the fluorescence chamber need not scintillate, but only fluoresce. However, for the In chamber the total energy measurement of γ_2 requires minimizing non-active materials. The relaxation of this requirement of the sensing fibers may be useful for other experiments.
13. Plastic scintillator type NE-161 produced by Nuclear Enterprises Inc. The fibers (both plastic and quartz) were fabricated by Galileo Electro-Optic Inc., Sturbridge, Ma.
14. J. Stone, J. Quantum Elec. *QE-8*, 386 (1972).
15. H. Chen, see ref. 5, Vol. II, p. 55 (1979).
16. F. Reines, H. Gurr and H. Sobel, Phys. Rev. Lett. *37*, 315 (1976).

Anomalous Showers Deep Underground

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Several studies of high energy interactions using particle telescopes placed deep underground have been carried out. Some have operated in various arrangements for as much as ten years (Kolar Gold Field detectors in India[1-4]; Chase-Wits-Irvine detectors in South Africa[5]). Others have come into operation recently (The Baksan telescope in the Caucasus, USSR[6], the Homestake Mine detector, S. Dakota, USA[7,8]. These detectors, in general, have capabilities which can include, (a) multiple track recording and reconstruction; (b) determining the direction of the primary giving rise to the event; and (c) particle identification: whether a given track or tracks imply a muon, a hadron or an electromagnetic shower (e or γ). They are in general relatively large, either in acceptance or in their "mass" or both, and are located at great depths under rock (greater than 850 hg/cm^2 or about > 1 TeV equivalent muon energy needed to penetrate the depth). A variety of detector elements have been used, including crossed flash tube arrays; proportional chambers; and scintillator counters, generally interspersed with absorbing material to form a crude calorimeter as well as a directional hodoscope.

In what follows we discuss some interesting events that have been collected in the Kolar Gold Field (KGF) experiment. The more recent experiments (Homestake and Baksan) have yet to report on their "unusual" events if any. We summarize KGF observations on anomalous cascades deep underground.

These consist of steeply inclined showers traversing detectors placed at depths of 3375, and 7000 hg/cm^2. The telescopes have vertical detector planes of crossed proportional counters, flash tubes and/or scintillators with lead or iron absorbers interspersed. In figure 1 an edge on view of the detector is shown. At 3375 g/cm^2, in a total exposure of 1.68×10^9 m^2 sec and an angular range from 30° to greater than 90° (upwards), four events have been observed. The visible energy of these events is greater than several hundred GeV. The observed spectrum of bursts, when extrapolated to the energy range of these anomalous events gives a flux which is at least an order of magnitude less than that implied by these four events. Two of the four events were obtained prior to 1977 and two have been observed recently 1979 with improved apparatus in about one-third as much running time as the first run.