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UNDERGROUND SCIENCE INITIATIVES AT LOS ALAMOS

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Abstract

Recently, the Los Alamos National Laboratory has proposed two major new initiatives in underground science. Following the dissolution of the original gallium solar neutrino collaboration, Los Alamos has formed a new North American collaboration. We briefly review the rationale for solar neutrino research, outline the proposal and new Monte Carlo simulations, and describe the candidate locations for the experiment. Because there is no dedicated deep underground site in North America suitable for a wide range of experiments, Los Alamos has conducted a survey of possible sites and developed a proposal to create a new National Underground Science Facility. This paper also reviews that proposal.

The only source of solar energy adequate to explain the observed lifetime and power output of the sun is the pp-chain of thermonuclear reactions displayed in Table I, which accounts, in the standard model (Bahcall, et al., 1982), for 98.5% of the solar power. The remaining 1.5% of the energy output comes from the CNO cycle displayed in Table II. Six of the reactions in these two cycles produce electron neutrinos with energy spectra and predicted standard fluxes that render them observable, in principle, by terrestrial experiments.

The first practical proposals for such experiments relied upon radiochemical detection. Many detectors have been proposed. For a brief review see (Cowan, et al., 1985) and references therein and the paper by G. Fatsepin, at this conference. In addition, it now seems possible that improvements in the current generation of underground water Cerenkov detectors and the next generation of large underground detection may make possible the detection of the solar neutrino flux in real time by the observation of $\bar{\nu}_e$ and ν_e scattering. Some of these possibilities are discussed in the paper by D. Sinclair, C. Rubbia, A. Zichicki, O. Ryazhskaya, R. Steinberg, E. Wandsand, M. Koshiba at this conference. Table IV displays some of the possible solar neutrino experiments and their sensitivity (in the standard model) to the six neutrino sources in the pp and CNO cycles.

Despite the rich array of proposed solar neutrino detectors, only one experiment has been performed, namely, the chlorine experiment (see, for example, Davis, et al., 1984). Because of the relatively high (0.814 MeV) threshold of the reaction

on which it relies. This experiment is primarily sensitive to the high energy neutrinos from ^8B decay (see Table IV). The standard solar model predicts a neutrino capture rate in the range of 6-8 SNU (the solar neutrino unit, $\text{SNU} = 10^{-36}$ captures/target atom-sec) which is to be compared with the combined average production rate of ^{37}Ar in 59 observations from 1970-1983 in the Davis experiment of 2.1 ± 0.3 SNU (Davis, 1984). This result indicates a substantial reduction in the ^8B neutrino flux and is consistent with a total absence of these high energy neutrinos (see Table IV).

While it is possible that the reason for this discrepancy lies in some terrestrial effect such as incorrect ^{37}Cl capture cross section or difficulties with the ^{37}Ar recovery, the many years of scrutiny that the experiment has withstood make such explanation unlikely. (See Cowan, et al., 1985 for a full discussion.) Most probably the explanation of the discrepancy lies either in a basic flaw in the physics of the standard model of the sun or in neutrino oscillations.

We therefore advocate a broad four-component view of the goals of a full program of solar neutrino research (Cowan, et al., 1985).

(1) The first objective of solar neutrino research is to establish that hydrogen fusion is the current principal source of solar energy. The crucial test is the observation of the distinctive, low-energy pp neutrinos whose production rate is essentially determined by the solar luminosity.

(2) Second, the program seeks to distinguish between two classes of explanations for the ^{37}Cl discrepancy: modifications of the solar model and neutrino oscillations. Nonstandard solar models that reduce the ^8B neutrino flux by, for example, lowering the temperature of the solar core have a negligible effect on the pp neutrino flux. Neutrino oscillations will affect all neutrinos, independently of their sources. Therefore, a

second experiment with a different sensitivity to the solar neutrino spectra can distinguish between these two classes.

(3) To more fully test competing solar models one requires a measure of the relative strengths of the reactions displayed in Tables I and II. This requires a complete neutrino spectroscopy of the sun, that is, a combination of complementary experiments with different sensitivities to the various components of the solar neutrino spectrum.

(4) The fourth objective is a precision test of neutrino oscillations. By a combination of experiments it is possible to isolate the flux of pp neutrinos. This flux is well determined in steady-state models by the luminosity so any significant deviation from the predicted rate would contribute a test of neutrino oscillations sensitive to neutrino mass differences as small as $\delta m \gtrsim 10^{-6}$ eV. (This is discussed in more detail in Cowan et al., 1985 and in the paper by A. Zatsepin and C. Rubbia in this conference.)

The next step in this program, in the view of many, is the GaCl₃ experiment, which relies on the reaction

With a threshold of 0.236 MeV this reaction is sensitive (see Table IV) to all solar neutrinos but predominantly to those from the pp/pap reaction.

The gallium chloride solar neutrino detector was developed in a collaborative effort by Brookhaven National Laboratory, the Max-Planck Institute for Nuclear Physics (Heidelberg), the Weizmann Institute, and the Institute for Advanced Study (R. Davis, et al., 1981). In broad outline, the procedure is as follows.

The target material is a hydrochloric acid solution of gallium chloride contained in an array of specially designed steel tanks with a double fluoracarbon lining. The ^{71}Ge , whose half-life is 11.4 days, is removed from the solution by purging with gas, releasing GeCl_4 , which is removed from the gas stream by a water scrubber column. By straightforward chemical techniques the recovered germanium is converted to the gas GeH_4 which is introduced into miniaturized counters made of ultrapure materials. These counters are operated inside a NaI pure spectrometer used both as an anticoincidence counter and to identify decays of the ^{69}Ge background monitor. The counting technique relies on pulse shape analysis to greatly increase the discrimination power. The entire system was tested on an engineering scale in 1982 by a pilot experiment using 1.3 tons of gallium.

Following the development of this experiment it proved impossible to obtain the necessary funding and in 1983 the collaboration formally disbanded. Since that time the European contingent of the original gallium collaboration has formed a new collaboration, GALLEX, and proposes (Kirstan, 1985) to perform the GaCl_3 experiment in the new Gran Sasso Laboratory. Because of this history the experimental techniques proposed by the US and European teams are substantially identical. The details have been fully described at this conference (Kirstan, 1985) and will not be repeated here. The only differences in the techniques planned by the two teams are in the configuration of the gallium chloride containers and in the plans for the source calibration experiment.

The large entry offered by the Gran Sasso Laboratory makes possible the use of a single large tank of gallium chloride solution in the GALLEX experiment. The Los Alamos experiment will, of necessity, use a location

in a deep mine. The smaller entry will require that an array of 18 glass-lined tanks each of 750 gallons capacity be used. Thus, as in the original 1981 design, the experiment is modular.

A source experiment figures prominently in the original 1981 proposal. At that time the primary motivation was to test neutrino oscillations for $\delta m^2 \gtrsim 0.3 \text{ eV}^2$ and mixing angles $\sin^2 \phi \gtrsim 0.4$. Recent reactor disappearance experiments have now excluded this parameter range with high confidence and thus removed this motivation. Furthermore, the original proposal assumed that the Oak Ridge HFIR reactor could produce a 2-3 megacurie ^{51}Cr source whereas a test irradiation has established that the stringent source that can be produced has an intensity of less than one megacurie. Accordingly, we no longer believe that the source experiment is independently important and we will move immediately to the critical full-scale measurement of the pp solar neutrino flux. The source experiment will be retained as an option to be pursued if the full scale experiment produces results, an indication of neutrino oscillations for example, that demand an additional calibration. Six tanks will be arranged around a central tank with a re-entrant tube to hold the ^{57}Cr source. These tanks will contain a total of 12.5 tons of gallium permitting the production of a readily measurable rate of four ^{71}Ge atoms per day by a one-megacurie source.

The first estimates (Bahcall et al, 1978) of the amount of gallium required for an effective solar neutrino experiment relied on the intuitive argument that one needs approximately one capture per day. In the 1981 proposal to the Department of Energy (Davis, et al., 1981) this implied a 45-ton detector for the standard model pp/pep flux of about 70 SNU. In preparing our new proposal we have expended considerable effort on Monte Carlo simulations that faithfully represent the full sequence of neutrino

capture, chemical extraction, and ^{71}Ge counting, taking into account improvements in the counting techniques. The time at which events are detected due to ^{71}Ge decay and to background counts is subjected to a maximum likelihood statistical analysis (Cleveland, 1983) developed especially for terating ultralow-level counting data. These techniques have been verified by comparison with the ^{37}Cl - ^{37}Ar detector data.

In the simulations we assumed that counting of ^{71}Ge is begun 1.0 days after the end of the extraction and is continued uninterrupted for 60 days. The experimental parameters are given in Table V. The limits that can be placed on measured rates with 90% confidence are shown in Fig. 1 as a function of the true rate in SNU for 15-, 30-, and 45-ton detectors. The production rates and percentage errors for the 30-ton detector and several neutrino capture rates are shown in Table VI.

We have also used Monte Carlo simulations (Robertson and Knapp, 1984) to calculate the spectra as a function of counting time and energy using the parameters in Table V and production rates of 0.36, 0.71, and $1.07\ ^{71}\text{Ge}$ atoms/day corresponding to the 15-, 30-, and 45-ton experiments and the ppI-only capture rate of 79 SNU. An energy independent background was used. These results are displayed in Figs. 2 and 3. It is evident that a decrease in the counting rate with an 11.4-day halflife in the time spectrum and characteristic peaks at 1.2 keV and 10.4 keV in the energy spectrum can be readily discerned in the 30-ton and 45-ton experiments, providing convincing evidence that ^{71}Ge is being produced and counted. Based on these and other studies, the Los Alamos collaboration has planned an experiment involving 30-tons of gallium.

Two deep sites are under consideration for the location of the experiment. The first is the Homestake goldmine in Lead, South Dakota, the current location of the chlorine experiment. There is a possibility that

the chlorine tank could be used or an adjacent room excavated. At a depth of 4850 feet, this level would provide an overburden of 4100 hg/cm^2 and limit the background production of ^{71}Ge by fast muons to less than 1% of that expected by pp neutrinos.

A second promising possibility is the Creighton No. 9 nickel mine at Sudbury, Ontario (Davidson, et al., 1984). This mine extends to 7100 feet and offers a variety of sites at depths of 5600 feet or greater in rock of high strength and density with low uranium and thorium content. The International Nickel Company (INCO) management has expressed considerable interest in hosting scientific experiments (Hanna, 1985; Sinclair, 1985). A suitable room could be excavated at modest cost in about six months.

If the Los Alamos proposal receives a favorable review, we intend to proceed on the following timetable. In late 1985 the pilot tank containing 1.3 tons of gallium will be moved underground, either at Homestake or Sudbury, and an underground experiment will be begun in which the large-scale chemistry and the ^{71}Ge counting will be performed in exactly the same manner as planned for the full 30-ton experiment. This will allow some important background measurements. Site preparation for the full experiment will require approximately six months. Gallium purchase, to be spread over three years, will begin as soon as funds are available and data taking will begin before the completion of gallium deliveries.

Although there has long been a rich program of underground physics research in North America this work has historically been carried on largely in working or abandoned mines, most of which do not offer great depth of cover. Los Alamos National Laboratory began to take an interest in improving this situation in the latter half of 1981 when A. K. Mann pointed out the advantages of a dedicated National Underground Science

(NUSF) Facility. At the time of Mann's proposal, all proposed experiments had an adequate underground site. We quickly came to believe, and the Gram Sasso experience verifies, that the creation of an excellent new facility would stimulate a new generation of proposals. That is, we adopted the premise that a dedicated underground laboratory is needed in North America. It was also recognized that, among the national laboratories in the United States, Los Alamos offers nearly unique capabilities for the creation and management of such a facility because of the presence of a varied program of basic and applied research, pertinent to the facility, experience in geology, mining, and engineering, and a history of supporting technical operations at a distance from the main laboratory site. Moreover, it was thought, and indeed it is true, that most of the likely sites for such a facility in North America lie in the Southwest.

The desirable criteria for a National Underground Science Facility include the following. (1) The depth should be 1100 m or more in dense rock so that the total overburden approximates or exceeds 3,000 meters of water equivalent (mwe). Greater depth is an advantage, funds and geology permitting. (2) The entry should be at least 4 m in diameter and as large as possible to permit the easy introduction of massive equipment. (3) The rock should be capable of supporting large rooms and at least one of approximately 12 m by 14 m cross section and 60 m length should be included in the laboratory. (4) The rock temperature at depth should be modest and groundwater should be controllable so that comfortable working conditions for scientists and apparatus can be maintained in the Laboratory and the background radioactivity should be low. (5) Access to the facility should be controlled by scientific and safety considerations only; that is, associated mining or other operations should not inhibit scientific access

to the facility. (6) There should be surface technical support facilities approximating those of any major laboratory. (7) Ideally, there should be the option to expand the facility if the scientific program warrants it.

With these considerations in mind, Los Alamos began a site survey and evaluation in the fall of 1981 (Sharp, 1982). It was quickly realized that the topography of North America is such that there are no deep highway or railroad tunnels meeting the necessary criteria. Some consideration was given to the construction of the facility by a new horizontal entry and several sites were located where it is fairly certain that this could be done. But an expensive and lengthy exploratory effort would be required to prove these sites and the construction cost would probably be prohibitive.

Some effort was also given to locating suitable sites in existing mines. Could this be done, the savings in cost and time would be quite substantial. To date, no fully satisfactory existing underground opening has been found that could easily accommodate a dedicated permanent laboratory.

The remaining option of a new vertical entry was extensively studied and several suitable sites were identified in or near the Nevada Research and Development Area (NRDA) of the Nevada Test Site (NTS). The NTS, owned by the U.S. Department of Energy, occupies 1,350 square miles of Nye County, Nevada located 65 miles northwest of Las Vegas. The site varies 28-35 miles in width (east-west) and 40-50 miles in length (north-south). The NRDA occupies about 20% of the total area in the southwest corner and is land specifically set aside for unclassified research.

The primary site identified by our study (Sharp, 1982) for a National Underground Science Facility is in Wahmanie Flat, adjacent to the NRDA, at an elevation of approximately 4100 feet. Because the geology, hydrology,

and seismic properties of the entire area are extremely well known, we can save considerable time and expense that might otherwise be required to obtain this information. The site is served by excellent roads and utilities are readily accessible. Several nearby surface buildings are available for shops, laboratories, offices, and housing. The necessary drilling and mining expertise is present at the NTS and a large pool of skilled technical support personnel are employed at the site and would be available to support the NUSF activities. The main NTS base village of Mercury, Nevada is located about twenty minutes by paved road from the Wahmanie site and offers food, housing, medical, and recreational facilities.

We propose (Simmons, 1982; Rosen, 1984) to construct the NUSF by sinking an 8-inch diameter test hole to 6,000 feet. Following this exploratory work a 14-foot diameter vertical shaft will be mined to a depth of 3,600 feet, lined, and two large experimental halls will be excavated at the ends of 70-foot long, 12-foot diameter horizontal drifts connecting to the main shaft. Provision will be made for the construction of additional rooms at this depth and for the sinking of the main shaft deeper (up to 6,000 feet) and for additional rooms at the greater depths.

The nominal dimensions of the two initial chambers are 46 feet high by 40 feet wide by 200 feet long and 25 feet high by 30 feet wide by 50 feet long but the final dimensions and layout will be held flexible as long as possible to accommodate the design of the first approved set of experiments.

The shaft will contain both a main and emergency cage, and will be served by a surface headframe, hoist, and air handling equipment capable of

accommodating an extension to 6,000 feet. Other surface facilities will include machine and electronic shops, office and computer space, and housing.

We note that the constraint of a vertical entry presents certain disadvantages. Among these are the limited size of the entry and rate of access (as compared to the highway entry at Gran Sasso), a probable increase in the operating cost. The vertical entry also offers some distinct advantages that are both scientific, practical, and economic. The chosen site is quite flat at the surfaces which offers the opportunity of coupling one or more deep detectors with extensive surface arrays for the simultaneous study of large air _____. This site would be the only one in the world with the advantages of vertical entry and large flat terrain for complimentary surface experiments. The flat surface implies much easier maintenance of the surface detectors than is the case in rugged mountainous terrain. Moreover, the necessary task of determining the profile of the overburden as a function of direction from the vertical is enormously simplified.

From the economic and practical point of view there are also considerable advantages to our site over a horizontal entry under a mountain. In the latter case the geology is typically quite complex and characterized by numerous faults and fractures. Several exploratory drill holes are likely to be required. The consequences for tunneling in this complex, changing geology and its attendant water flows can be time consuming, dangerous, and expensive. Our site is characterized by comparatively uniform geology, both horizontally and vertically, and there is good reason to believe that the surface geological measurements can be confirmed by a single exploratory drilling.

Following the completion of the preliminary site survey and the draft NUSF proposal, Los Alamos appointed an Advisory Committee chaired by Normal Ramsey to review the rationale and proposed design for NSUF. The Committee unanimously endorsed the concept and general design of NUSF and the specific design recommendations in the Committee's report (Ramsey, 1983) were incorporated in the final proposal.

The Los Alamos proposal for a National Underground Science Facility was submitted to the U.S. Department of Energy which has so far not acted upon it. We note that the lack of suitable deep underground facilities in North America is causing U.S. scientists to move their activities to Japan and Europe in order to participate in the next generation of underground experiments.

TABLE I

	Reactions	Branching %	$E_{\nu}^{\max}(\text{MeV})$	ν flux ($\text{cm}^{-2}\text{sec}^{-1}$)
I _a	$p + p \rightarrow {}^2\text{H} + e^{+} + \nu_e$	99.75	0.42	6.07×10^{10}
or				
I _b	$p + p + e^{-} \rightarrow {}^2\text{H} + \nu_e$	0.25	1.44	1.5×10^8
II	${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$	100		
III _a	${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$	86		
or				
III _b	${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$	14		
IV _a	${}^7\text{Be} + e^{-} \rightarrow {}^7\text{Li} + \nu_e$	99.89	0.86 (90%)	$4.3 \cdot 10^9$
	${}^7\text{Li} + p \rightarrow 2 {}^4\text{He}$			
or				
IV ₆	${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$			
	${}^8\text{B} \rightarrow {}^8\text{Be}^{*} + e^{+} + \nu_e$	0.11	14	5.6×10^6
	${}^8\text{Be}^{*} \rightarrow 2 {}^4\text{He}$			

Table 1. The pp chain. Branching percentages and neutrino fluxes at the earth are taken from the standard model calculations of Bahcall et al. (1982).

TABLE III

Reaction	Max. ν Energy (MeV)	Flux($10^{10}\text{cm}^{-2}\text{sec}^{-1}$)
$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$	0.42	6.1
${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$	0.86 (90%)	4.2×10^{-1}
	0.38 (10%)	
${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_e$	1.20	5×10^{-2}
${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu_e$	1.73	4×10^{-2}
$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$	1.44	1.5×10^{-2}

Table III. Summary of neutrino producing reactions and neutrino spectrum endpoint energies from the pp chain and the CNO cycle ranked according to their total standard model fluxes at the surface of the earth (Bahcall, 1982).

TABLE II

	Reaction	$E_{\nu}^{\text{max}} \text{ (MeV)}$
I.	${}^{12}\text{C} + p \rightarrow {}^{13}\text{N} + \gamma$	
II.	${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_e$	1.20
III.	${}^{13}\text{C} + p \rightarrow {}^{14}\text{N} + \gamma$	
IV.	${}^{14}\text{N} + p \rightarrow {}^{15}\text{O} + \gamma$	
V.	${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu_e$	1.73
VI.	${}^{15}\text{N} + p \rightarrow {}^{12}\text{C} + {}^4\text{He}$	

Table II. The CNO cycle.

TABLE IV

<u>Experiment</u>	<u>Type</u>	<u>pp + pep</u>	<u>${}^7\text{Be}$</u>	<u>${}^8\text{B}$</u>	<u>${}^{13}\text{N} + {}^{15}\text{O}$</u>
${}^2\text{H}(\gamma, e)\text{pp}$	direct counting	0.0	0.0	6.7	0.0
${}^7\text{Li}(\gamma, e){}^7\text{Be}$	radiochemical	9.7	4.1	20.7	11.8
${}^{37}\text{Cl}(\nu_e, e){}^{37}\text{Ar}$	radiochemical	0.23	1.02	6.05	0.34
${}^{71}\text{Ga}(\gamma, e){}^{71}\text{Ge}$	radiochemical	74.1	28.9	1.5	6.7
${}^{81}\text{Br}(\gamma, e){}^{81}\text{Kr}$	radiochemical	1.2	10.6	2.2	2.6
${}^{97}\text{Mo}(\gamma, e){}^{97}\text{Tc}$	geochemical				
${}^{98}\text{Mo}(\nu_e, e){}^{98}\text{Tc}$	geochemical			~13.5	
${}^{115}\text{In}(\nu_e, e){}^{115}\text{Sn}$	direct counting	542	125	5.0	28.5
${}^{205}\text{Tl}(\nu_e, e){}^{205}\text{Pb}$	geochemical				
γ -e scattering	direct counting				

Table IV. Some Possible Solar Neutrino Experiments. This table is taken from (Cowan, et al., 1985). The solar neutrino unit (SNU) is 10^{-36} captures/target atom-sec. The ${}^{97}\text{Mo}/{}^{98}\text{Mo}$ geochemical experiment was proposed by Cowan and Haxton (1982) and is being developed at Los Alamos (Wolfberg, 1984). The sensitivity of the γ e scattering experiments depends on background rates and practical thresholds in the various detectors.

TABLE V

<u>Parameter</u>	<u>Value Used in Simulations</u>
number of runs	70 (4 years)
production rate ($^{71}\text{Ge}/\text{da}$)	variable
decay constant	0.0608 days^{-1}
production time	21 days
extraction efficiency	0.95
counting efficiency	0.74
background rate	0.16 days^{-1}

Table V. Experimental parameters used in the simulations of the experiment.

TABLE VI

<u>Neutrino Capture Rate (SNU)</u>	<u>P</u>	<u>E</u>
(Standard Model) 109	1.00	8.4
(low- z , nonstandard) 85	0.77	9.8
(ppI cycle only) 79.5	0.72	10.2
(Standard with maximal three neutrino mixing) 36	0.33	19

Table VI. Production rates p (in ^{71}Ge atoms/day) and percent errors E after 70 runs (4 years) of 21 days each in a 30-ton gallium experiment for various assumed neutrino capture rates.

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