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BUSCANDO LA MATERIA OSCURA DEL UNIVERSO EN FORMA DE PARTÍCULAS ELEMENTALES DÉBILES

Discurso leído en el acto de su
recepción como *Académico de Honor* por el

Dr. D. Blas Cabrera Navarro

el día 7 de julio de 2003

Discursos Académicos
3

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DEL UNIVERSO
EN FORMA DE PARTICULAS
ELEMENTALES DEBILIES

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BUSCANDO LA MATERIA OSCURA DEL UNIVERSO EN FORMA DE PARTICULAS ELEMENTALES DEBILIES*

Discurso leído en el acto de su recepción como *Académico de Honor* por el Prof. Dr. D. **Blas Cabrera Navarro** el 7 de julio de 2003

Arrecife (Lanzarote), Centro Científico-cultural Blas Cabrera

* Based on invited talk and honorary membership in the newly formed "Academia de Ciencias e Ingenierias de Lanzarote" of at opening of "VII Cursos Universitarios de Verano en Canarias, Lanzatorte 2003" held at the "Centro Cientifico-Cultural – Blas Cabrera" in Arrecife, Lanzarote in the Canary Islands, Spain, July 7, 2003. This paper will appear in the proceedings.

PREFACIO

Es un honor enorme ser nombrado Académico de Honor en la Academia de Ciencias e Ingenierías de Lanzarote, que ha nacido en el contexto del Centro Científico-Cultural Blas Cabrera. En particular, quiero dar las gracias al Profesores Francisco González de Posada y Dominga Trujillo Jacinto del Castillo por sus esfuerzos , ya que gracias a ellos tenemos desde hace muchos años este Centro en Arrecife. Así no nos olvidamos de las importantes obras científicas de mi abuelo Blas Cabrera Felipe y de la tradición científica en Lanzarote, Canarias y España. También quiero dar las gracias a mi tío José Cabrera Ramírez por ser el único que mantiene contacto con los que estamos a mucha distancia física, pero que nos acordamos de nuestra familia y de nuestros antepasados.

Fig 1: Sixth Solvay Conference in 1930 held in Munich.

Ustedes me perdonaran las faltas de gramática y de pronunciación, pero aunque tengo la sangre española de mis padres y abuelos, nunca he vivido en un país de habla hispana, aunque California hoy día es casi de habla hispana.

No tuve la oportunidad de conocer a mi abuelo, murió en México el año antes de que yo nací en Paris. Pero de pequeño mi padre me contaba de sus trabajos y durante mi carrera de físico siempre he sentido orgullo viendo las fotografías de las conferencias Solvay de los años 1930 y 1933 con mi abuelo sentado con Einstien, Heisenberg, Dirac y muchos otros grandes físicos de esa época tan importante para la física moderna. Mi abuelo formo un grupo experimental importante en España en los años 1910 a 1936, y este grupo participo con los otros centros científicos de Europa y de los Estados Unidos en desarrollar la mecánica quántica. A los principios de la Guerra Civil, mi abuelo y su familia fueron exiliados al extranjero, y mi abuelo murió en la cuidad de México en 1945.

En el año 1969, mi padre, el físico Nicolás Cabrera Sánchez, volvió de los Estados Unidos y de México a España y ayudó a reestablecer los contactos con el mundo científico extranjero, dirigiendo el Departamento de Física de la entonces nueva Universidad Autónoma de Madrid.

Como sabían mi abuelo y mi padre, todas las ciencias, en particular la física, son fundamentalmente experimentales. A mi me gusta mas la física cuando estamos tomando datos en algún experimento. Los aparatos e instrumentos son como extensiones de nuestros sentidos, dejándonos ver y tocar a los átomos y a todo el mundo microscópico de las partículas elementales. Es un mundo a la vez raro y magnifico. No hubiera sido posible averiguar las leyes fundamentales de este mundo sin los experimentos. Y no es posible mantener un grupo de investigación a nivel mundial sin las interacciones de un programa activo experimental y el desarrollo de ideas teóricas.

Yo estoy seguro de que mi abuelo, el canario Blas Cabrera Felipe, tenia los mismos sentimientos, y se los enseñó a mi padre, el madrileño Nicolás Cabrera Sánchez, en ese famoso laboratorio Instituto Nacional de Física y Química en los años 30 antes de la Guerra Civil. Hoy, yo soy físico porque mi padre me lo enseño ha mi. Lanzarote y las Islas Canarias deben de tener un orgullo enorme sobre sus antepasados tan importante para la física en España y en el mundo entero.

1. Motivation for Dark Matter Search

Over the last 10 years, we have made remarkable progress in our understanding of the composition of the universe. Radically different experiments are providing a consistent picture of the constituents of the cosmos. As we will discuss in a moment, the experiments include detailed measurements of the anisotropy of cosmic microwave background, new measurements which use the light given off by Type 1a supernova as standard candles, and weak

lensing of background galaxies by the largest superclusters in the universe. These measurements all point to an accounting of the constituents of the universe where 73% of the energy density of the universe is in an unknown form called dark energy, 23% is in an unknown form called dark matter, 3% is made up of free hydrogen and helium, 0.5% makes up all the light we see in the night sky including the stars and the gas that makes up the stars in our galaxy and in the distant galaxies, 0.3% is in neutrinos which are now known to have a non zero mass, and finally 0.03% in the heavier nuclei of which the sun, the earth and ourselves are made. In a very real sense, we have the ultimate Copernican revolution - not only are we not at the center of our solar system, nor is our solar system at the center of our galaxy, nor is our galaxy a particularly distinguished galaxy, but in fact we are made of particles that are way down the list of the constituents of the cosmos.

Today, I will describe in a little bit more detailed this exciting new standard model for cosmology and for the universe, and then I will describe in general terms the experiments that we are undertaking at Stanford University in collaboration with 10 other institutions to search for the dark matter in the form of weakly interacting massive particles or WIMPs. Not only are the goals of the research exciting and interesting, but in addition the technological breakthroughs which allow exploration of this new regime are also exciting and interesting. We utilize superconductivity where metals lose all electrical resistance, we operate at temperatures only 0.1 K away from the absolute zero, and have developed the world's most sensitive fast thermometers for detecting elementary particles better than ever before possible.

The best way to understand the dark matter problem is to look at photographs of galaxies in our night sky. For example in Fig 2, NGC2903 is a spiral galaxy about 50 million light years away from our own Milky Way. It has a similar mass and structure to our own Milky Way and you can see its rotation from the pinwheel shape of the arms. It is natural to think of our galaxy and other galaxies in analogy with our solar system. Our solar system has a central massive Sun with nine major planets circling it in roughly circular orbits. The velocity of the planets around the sun is a balance between the gravitational attraction of the sun and the centripetal acceleration required to produce a circular orbit. That balance was first determined by Kepler's third law which tells us that the velocity of planets falls off as one over the square root of their distance from the sun. Thus, a planet that is four times further from the sun in a circular orbit moves around its orbit only half as fast, so that the period is eight times longer. Looking at the photograph of NGC2903, one would expect that for objects orbiting outside of the region where we see light, that the further the objects were from the center of the galaxy the slower they should propagate in their circular orbits. In fact, as is represented schematically with the arrows in the picture, we find that the velocity of objects in circular orbit around NGC2903 become go to a constant value independent of their distance from the center of the galaxy. The only way we have found to understand this tremendous surprise is that NGC2903 and all other galaxies contain at least 10 times more gravitating mass then we can account for in the stars and the gas that make up the stars in galaxies. We call this additional mass dark matter because it neither absorbs or emits light. We only know of its existence through its gravitational attraction with objects that do emit light. So one of the most interesting and important unresolved questions for physics and for astrophysics is - what is the nature of this dark matter?

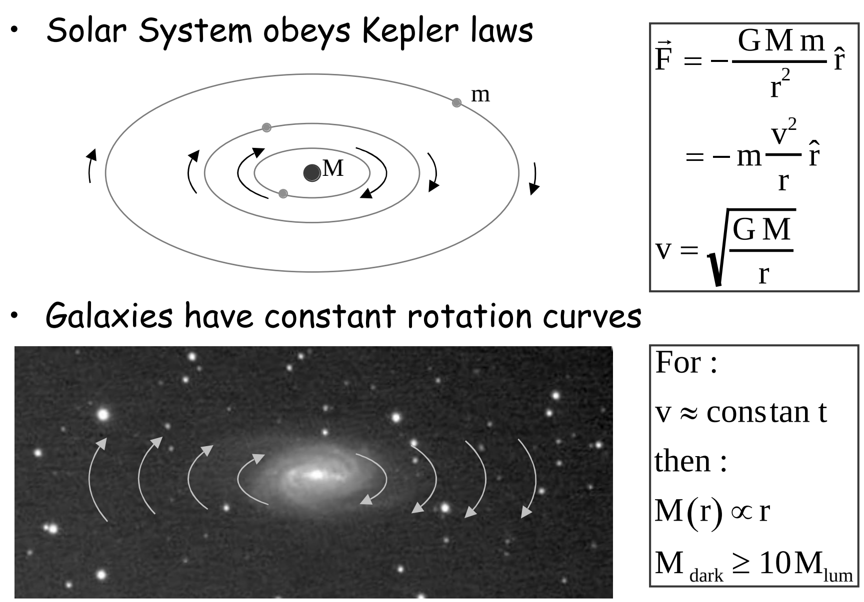

Fig 2: Dark matter is seen because of its effect on galaxy rotation velocities.

In fact, as I mentioned in the introduction, there are many experiments and observations that relate to this dark matter and dark energy. With higher and higher precision, the cosmic microwave background measurements have confirmed that the universe as whole is very close to its critical density. The critical density, which we often described through parameter omega which equals one for critical density, corresponds to the boundary between a universe

that would continue expanding forever and one that would eventually stop its expansion in the future and then begin to contract into a collapse, something like an inverse big bang – or big crunch. The fraction of the universe that makes up gravitating matter, that is all constituents that attract each other to form clumps, is limited to between 0.3 and 0.4 of the total energy density. The most precise measurements are through the distortion of distant galaxies by foreground superclusters of galaxies - so-called weak lensing.

However, there is a surprise from Nuclear Physics which provides limits for the portion of the universe that can is made up of normal matter - the electrons, protons and neutrons that make up all of the atoms in the sun and the planets and in ourselves. This matter is often described by physicists as baryons. Because we have performed almost 60 years worth of experiments with protons, neutrons and electrons, we understand them very well. In particular, in the early universe when the universe was just cooling enough to allow nuclei to form, we can calculate what fraction of the nuclei should form hydrogen, what fraction deuterium, what fraction helium, and what fraction of lithium. These nucleosynthesis calculations have been refined over the past 30 years, and today it is inescapable that our universe must have no more than 6% and no less than 2% of its energy density in the form of baryons.

This reliable conclusion actually presents us with two dark matter problems. First, there is a baryonic dark matter problem, because the stars we see in the sky and in our galaxy and all the planets around them and us make up only about 0.7% of the energy density of the universe. But I just told you it at least 2% of the energy density in the universe must be in baryons. Thus something like a factor of three more normal baryonic material must exist then we have found so far. We suspect this is in the form of cold gas clouds which did not ignited star formation, or compact objects like Jupiter's or old neutron stars which do not shine in the night sky. These objects are called MACHOs (massive compact halo objects – in contrast to WIMPs) have been looked for by several experiments looking for microlensing of objects between us and the stars in the Large Magellantic Clould.

The second dark matter problem is the focus of my talk today, and stems from the difference between the 6% maximum amount of baryonic material in the universe and the measurements showing that 27% of the universe is in the form of gravitating matter. The conclusion is that about 23% of the energy density of the universe must be in a nonbaryonic form. We strongly suspect that the dark matter accounting for the behavior of galaxies is in fact nonbaryonic matter.

So what is this nonbaryonic dark matter? Elementary particle physics provides us with a number of interesting candidates for this dark matter. Several types of particles which are hypothesized for reasons within particle physics and having nothing to do with cosmology, make good candidates for nonbaryonic matter. We will briefly consider four types of particles – axions, neutrinos, magnetic monopoles and supersymmetric WIMPs. The axion is a very funny type of particle which was proposed to solve the problem of why protons and neutrons, which are made of quarks, obey charge-parity conservation, while neutrinos and the W and Z bosons which interact only through the weak force violate charge-parity conservation. In fact before the discovery of the weak force it was thought that charge-parity conservation was a law of nature. It was only after the discovery of the violation of charge-parity conservation in the 1950's, that it was realized there must be a specific reason for its conservation in strong or nuclear forces because it was clearly violated in the weak force. There is one major experiment searching for axions as the dark matter in the universe, but here, I will not describe it further.

The second particle which we consider is the neutrino. It has a major advantage over other particles on our list because it is the only one that is known to exist. One might suspect this would give it a leg up with respect to the other candidates for dark matter, but in fact, because neutrinos have an exceedingly small mass, and they do not clump sufficiently to help form galaxies in the early universe. They would be a form of what we call hot dark matter, meaning that at the time of galaxy formation they move at velocities close to the speed of light. Computer simulations with hot dark matter are not successful at replicating the structure we see in the night sky. On the other hand, cold dark matter, particles which move slowly under gravitational attractions at the time of galaxy formation, is very successful in replicating that structure that we observe.

Axions, magnetic monopoles and WIMPs are all excellent cold dark matter candidates. At Stanford, we began our search for dark matter in the form of elementary particles in the early 1980's with the search for magnetically charged particles in the cosmic rays. Today, magnetic monopoles are considered an unlikely candidate for the dark matter because to obtain the correct density in the universe requires extreme fine-tuning of the temperatures in the early universe. There's no particular reason why the reheating temperature at the end of the inflationary epoch would have come exactly to a value which has to be accurate to many significant figures, so that magnetic monopoles are considered an unlikely candidate for dark matter.

2. WIMPs as Dark Matter Candidates

On the other hand, a subclass of WIMPs called neutralinos, which arise from a theory called supersymmetry, have exactly the right properties. These particles are neutral since they carry no electric charge and they interact only

through the weak force. When one calculates the density they would have today, as a relic from their formation in the hot early universe, one finds a density very close to that needed amount for dark matter. We consider this to be an extremely interesting coincidence and it may well be a hint that supersymmetric neutrinos may in fact be the dark matter around our galaxy and in our universe.

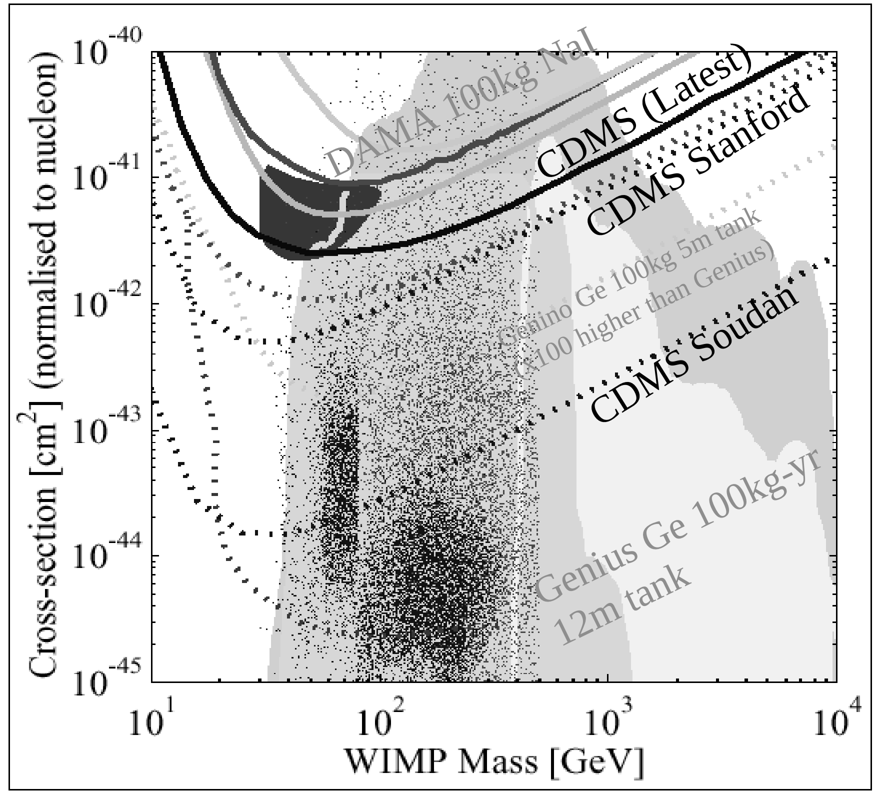

Fig 3: Goals for CDMS-I at Stanford site (0.01 events/(keV kg day) with 2 keV threshold for Ge), for CDMS-II at Soudan (0.0003 events/(keV kg day) with 2 keV threshold for Ge), and for CRESST at Gran Sasso (0.2 events/(keV kg day) with 0.5 keV threshold for sapphire). The best current limits are shown for comparison along with the envelope of possible SUSY model predictions (the peak corresponds to 3 events/(kg day) for Ge). Also shown are new DAMA and CDMS results.

We represent the results of many different experimental searches for neutralino WIMP dark matter in Fig 3. The horizontal axis represents the mass of this neutral heavy particle and it is in units of GeV/c^2, roughly the mass of the proton. So the region of interest extends from about 10 times the mass of the proton to over a thousand times the mass of the proton. Along the vertical axis we represent the interaction of these particles with the protons or neutrons in normal matter. These particles have only weak interactions so that interactions are very rarely, but they do occur at a very similar rate to the interactions of neutrinos with normal matter. Each of the curves in Fig 3 represents an experimental sensitivity meaning that interaction rates and masses located above the line have been ruled out by that experiment, and those interaction rates and masses below the line have not been ruled out and are still possible. The solid lines represent completed experiments with published results, and the dotted lines represent planned experiments or experiments under construction. In addition, there is a hart shaped region with a mass around 70 times the mass of the proton and an interaction strength of 10^{-41} cm^2, which represents a claimed detected signal by the DAMA collaboration in Italy and China. For four years they have claimed a positive signal coming from a carefully controlled experiment in the Gran Sasso National Underground Laboratory. Their experiment looks for a change in the rate of events in a sodium iodide detector array between the summer and winter months. A change in rate is expected for WIMPs, because our solar system circles around our galaxy at about 220 km/s and is moving through a cloud of WIMPs. When the earth’s rotation velocity around the sun adds to the direction of the solar system around the galaxy then more particles will hit a detector per unit time, much as a bicycle rider writing into the wind in the rain gets wetter than one riding with the wind. Their experiment does in fact see such a modulation and the modulation has been repeated for four years. Unfortunately, the maximum and minumum velocity of Earth's orbit around the galaxy is synchronized with the winter and summer as well. There are a number of radioactive backgrounds which are known to vary with season. As you can see, our experiment and several others have now largely ruled out the claim from the DAMA group.

3. The CDMS Experiment

Our experiment is called CDMS which stands for the cryogenic dark matter search experiment, and is designed to search for nonbaryonic dark matter in the form of supersymmetric WIMPs or neutralinos. The detectors, shown in Fig 4, are 1 cm thick crystals of germanium and of silicon, and have a 7.6 cm

diameter. The Ge detectors weigh 0.25 kg and the Si detectors weigh 0.1 kg, and are operated near the absolute zero of temperature below 0.1 K. The idea behind these detectors is to simultaneously measure two independent quantities from each particle interaction with the crystals. The first is the charge or ionization production and the second is the heat or phonon production. By simultaneously measuring both of these quantities, we can determine whether the energy was absorbed in the crystal by an electron or by a nucleus. The actual recoil energy is determined through the phonon signal, and the ionization signal distinguishes electron recoils which have nearly three times the charge production verses nuclear recoils. This discrimination allows rejection of nearly all of the backgrounds occurring in the laboratory. These backgrounds are due to gamma rays and produce recoiling electrons in the crystals. Recoiling nuclei would be produced by WIMPs passing through our laboratory as part of galactic dark matter, but also from neutrons. Since neutrons produce the same indistinguishable signal believe as WIMPs, it is important to suppress the neutron background as much as possible.

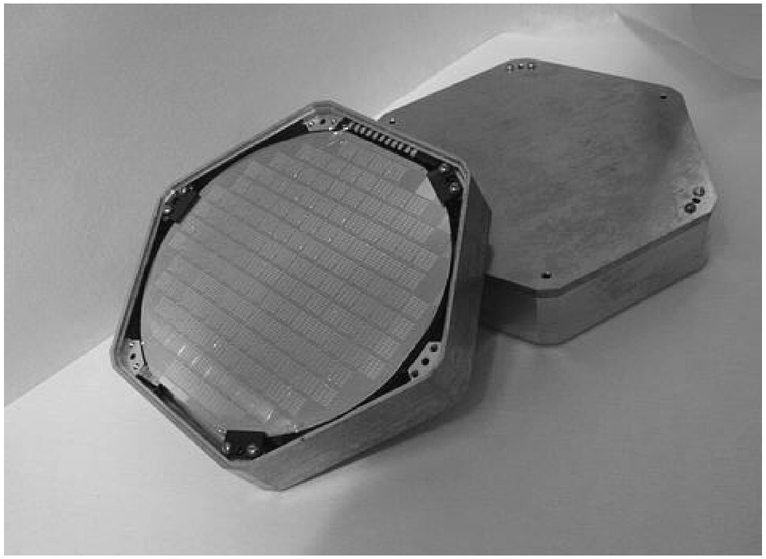

Fig 4: Germanium detector of CDMS experiment, which measure both charge and heat deposited by each elementary particle interaction, allowing identification of electron recoils versus nuclear recoils in the detector.

The charge sensor technology is similar to that used in commercially available germanium and silicon diode particle detectors. However, the reason for going to such incredibly low temperatures, is the ability to measure the heat produced by an elementary particle interaction. The thermal sensors are based on a novel new detector technology which utilizes superconducting transition-edge sensors. Thin film lines of tungsten, a superconductor with a transition at around 0.08 K, are maintained in the middle of their superconducting to normal transition where there is a rapid change in resistance with temperature. By monitoring the resistance of these films using superconducting amplifier's called SQUIDs, we're able to measure tiny energy depositions in the crystal. Fig 5 shows a calibration run both with gamma rays and with neutrons. The upper band along the 45 degree axis of the figure corresponds to electron recoil's produced by gamma rays interacting with the crystal. The lower band at a shallower angle corresponds to nuclear recoils produced by calibration neutrons. In low background operation with our neutron shielding in place, we look carefully to see whether there are events along the nuclear recoil band, and if there are, we would make sure that they behave like WIMPs rather than neutrons.

We operate both silicon and germanium detectors, because neutrons interact with silicon and germanium at about the same rate, but supersymmetric WIMPs interact with germanium at about six times the rate that they interact with silicon. In addition, roughly 30 percent of neutron interactions occur in more than one detector simultaneously, whereas supersymmetry wimps have a negligibly small probability of occurring in more than one detector. The combination of the ratio of single detector events to multiple detector events as well as the ratio of silicon events to germanium events give us the strong ability to differentiate a new supersymmetric WIMP signal from a leakage neutron background. We have the only detectors in the world capable of this type of discrimination.

To develop this new type of detector technology, we decided to build an underground facility at a shallow site on the Stanford campus. The facility, known as the Stanford Underground Facility (SUF) is 10.5 m underground, which is sufficient to reduce the neutrons and protons from cosmic rays to insignificant levels and to reduce the muon rate by about a factor of five. Since muons produce neutrons in the laboratory, we enclose the detectors inside of carefully chosen passive shielding surrounded by an active muon veto made of plastics scintillator. Thus, each time a muon passes through the active veto we detect it and we reject events in our cryogenic detectors coincidence with those events. These detectors, operated at the shallow site using the muon veto, have allowed us to obtain the best limits for supersymmetric WIMPs in the world. Even today, our results remain the best for WIMP masses of less than 50 times a proton mass. In the run lasting nearly one year and completed in September,

2002, we began to see a residual neutron flux corresponding to one neutron event per detector per week in a six detector array. These neutrons originate from high energy muons interacting with the rock and dirt away from the muon veto and producing a sufficiently energetic neutron to punch through our shielding and interact with our detectors. Our best limits include a statistical subtraction of this neutron background. Once we began to see this background at roughly the expected level, we knew it was time to build a facility deep underground where the muon flux would be reduced by many orders of magnitude.

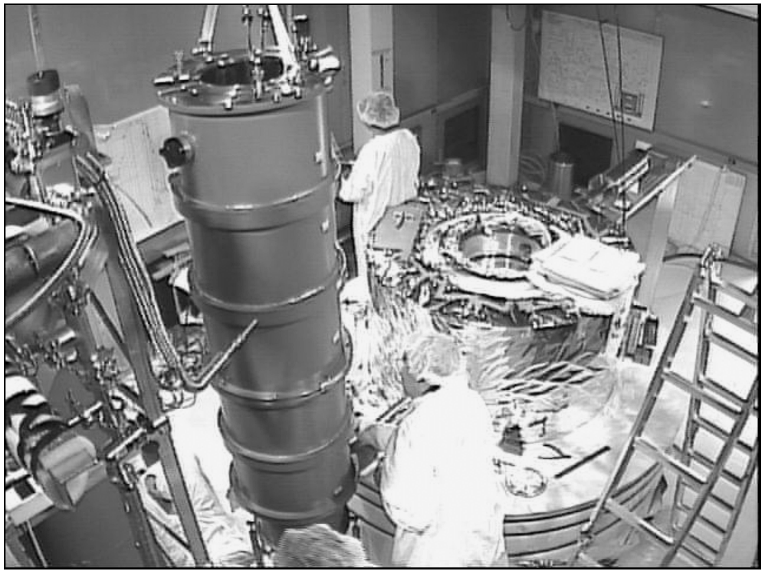

Fig 5: Assembly of the CDMS apparatus in the Soudan mine during 2002. The system is now fully operational and is starting to take data.

We have built such a facility in the Soudan mine in northern Minnesota. The facility is nearly 800 m underground. The muon flux in this facility is 10,000 times lower than at Stanford Underground Facility. As shown in Fig 6, we have recently begun operations in the Soudan mine, and we have twelve CDMS detectors, six made of germanium and six of silicon, operating at base temperature. We expect to begin low background running within the next several months. One month of low background operation in the lower background environment using the same detectors operated at SUF, will improve our sensitivities by a factor of 10. Over the next year and a half we will operatw a total of 30 detectors, and we expect to improve our sensitivity by an additional order of magnitude, thus providing a net improvement of a factor of 100 over the Stanford Underground Facility results.

4. Conclusions and Acknowledgments

These are particularly interesting times because the sensitivities that we will obtained in the Soudan mine experiment are well within the suggested region for supersymmetry WIMPs. Over the next several years, we may indeed identify the dark matter in and around our galaxy and in fact the dominant matter in our universe. For references see website at http://hep.stanford.edu/~cabrera/indexcdms.html.

The CDMS collaboration has over forty members from eleven institutions – Stanford Univesity, UC Berkeley, UC Santa Barbara, Fermilab, Santa Clara University, Case Western Reserve University, NIST Boulder, University of Colorado at Denver, Princeton, Brown University, and University of Minnesota.

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COLECCIÓN:
DISCURSOS ACADÉMICOS

1.- *La Academia de Ciencias e Ingenierías de Lanzarote en el contexto histórico del movimiento académico.* (Académico de Número).
Francisco González de Posada. 20 de mayo de 2003.
Excmo. Ayuntamiento de Arrecife.

2.- *D. Blas Cabrera Topham y sus hijos.* (Académico de Número).
José E. Cabrera Ramírez. 21 de mayo de 2003.
Excmo. Ayuntamiento de Arrecife.

3.- *Buscando la materia oscura del Universo en forma de partículas elementales débiles.* (Académico de Honor).
Blas Cabrera Navarro. 7 de julio de 2003.
Amigos de la Cultura Científica.