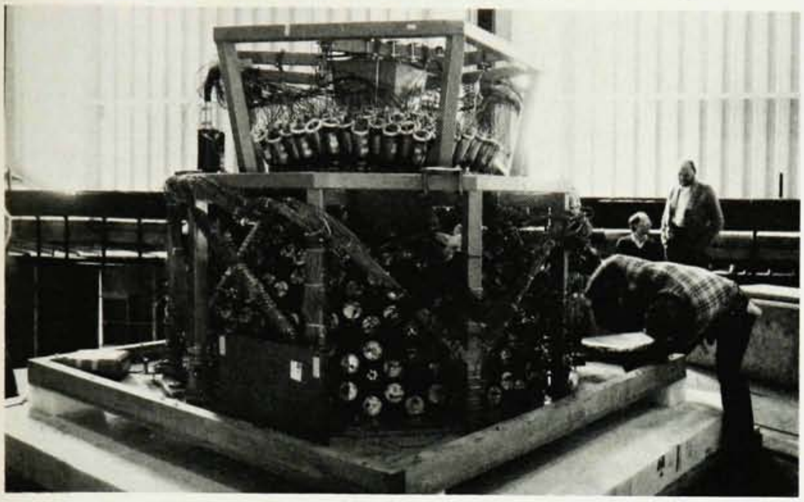
Plastic Ball flies to CERN—and higher energies



At the Lawrence Berkeley Lab's Bevalac in February, the Plastic Ball nuclear particle detector was being carefully crated for its jumbo-jet flight to CERN—and higher heavy-ion energies. For the past four years, this hollow, faceted ball of 814 plastic/CaF_2 scintillation modules has been monitoring the fragments coming off high-energy heavy-ion collisions at the Bevalac, which can accelerate heavy-ion beams to 2 GeV/nucleon. From the outside, we see mostly the cabled ends of photomultiplier tubes. The Plastic Ball, built at LBL in collaboration with the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, was the first nuclear-physics detector capable of simultaneously identifying and measuring essentially all of the charged particles produced in a high-energy heavy-ion collision. Among the Plastic Ball's successes has been the first observation of "collective flow" in compressed nuclear matter.

In its new incarnation at the CERN Super Proton Synchrotron, the Plastic Ball will be looking at the debris from 200-GeV/nucleon collisions. SPS is primarily a proton–antiproton storage-ring collider nowadays, but for several weeks in November and again next May it will be devoted to heavy-ion physics. With a heavy-ion source (built at GSI) and a new rf-quadrupole injection system (built at LBL), SPS will be able to accelerate nuclei as heavy as calcium for fixed-target experiments. The fond hope, in these extraordinarily high-energy collisions between heavy ions, is to carry the compression of nuclear matter so far that one will see the transition to a quark–gluon plasma. Starting at about the same time next fall will be the heavy-ion program at the Brookhaven AGS accelerator, which will provide fixed-target experiments with 15-GeV/nucleon beams.

resonant density be wide enough that the process is adiabatic. That is to say, the Hamiltonian experienced by the neutrino must vary slowly enough that the neutrino remains in an eigenstate, adjusting its mass smoothly to the local density as it goes. This adiabatic condition requires that the oscillation length l_m in the resonant density region be much smaller than its width.

Bethe's rederivation of the Mikheyev–Smirnov resonance stresses its kinship to adiabatic level-crossing transition, a phenomenon well known in atomic physics. In the absence of mixing, Bethe points out, the square of the effective ν_e mass in the presence of the charged-current potential in matter would grow linearly with density, while the effective ν_μ mass would remain independent of density. Where the two m^2 curves would cross is precisely the resonant density of Mikheyev and Smirnov (see figure on page 17). But when mixing is introduced, coupling the two neutrino flavors, the actual m^2 eigenvalue curves move smoothly from one straight line to the other near the crossing point; the eigenvalue curves never actually cross. If the density change is adiabatically slow, the neutrino will stay on the same eigenvalue curve, its state vector turning slowly from the $|\nu_e\rangle$ direction toward $|\nu_\mu\rangle$ as it traverses the resonant density.

Mikheyev and Smirnov apply the theory to the solar-neutrino problem by formulating and numerically solving the differential equations for a neutrino traveling outward from the high-density region at the center of the Sun. Bethe undertook to get essentially the same result by a simple hand calculation "that would not require reproducing their computer programs to confirm it. Any physicist can immediately understand and confirm my argument," he told us.

Bethe argues that all the lost neutrinos come from B^8 decay. Neutrinos from all other solar sources have energies less than 2.8 MeV, too small to fulfill the resonance condition at any density in the Sun. The B^8 neutrino spectrum extends out to 14 MeV. All these boron neutrinos are presumed to originate in a small central region of the Sun with a mean density of about 130 g/cm^3. Thus, Bethe points out, there will be a critical energy (depending on the as yet unknown neutrino mass splitting and mixing angle) above which all neutrinos coming from this small core will pass through a region of resonant density, emerging as undetectable muon neutrinos. The higher the neutrino energy, the lower (and further from the center) is the density at which resonance occurs.

Attributing all the lost neutrinos to the B^8 and taking straightforward analytic expressions for the B^8 decay spectrum and the energy dependence of the Brookhaven detector's response, Bethe obtains a simple integral that immediately gives a critical energy of about 8 MeV, well above the upper limit for all the other solar neutrino spectra. This critical energy plus the central solar density of 130 g/cm^3, taken from Bahcall's standard solar model, immediately yields a value of 1×10^{-4} eV^2 for $(m_2^2 - m_1^2)\cos 2\theta$. Making the reasonable assumption that the mixing angle is small and ν_e is much lighter than ν_μ, Bethe gets an estimate of 0.01 eV for the mass of the muon neutrino.

It will be very difficult to confirm so small a mass splitting by laboratory experiment. "Observation of solar neutrinos with a gallium detector," Bethe suggests, "would be the best confirmation—or disproof—of our theory." Detectors exploiting the conversion of Ga^{71} to Ge^{71} by neutrino capture have an energy threshold of only 0.23 MeV, permitting one to see much of the proton–proton neutrino spectrum. With resonant neutrino conversion in the Sun removing only neutrinos more energetic than 8 MeV (exclusively from B^8 decay), the fractional suppression would be much smaller in a detector sensitive to lower-energy neutrinos. Whereas the chlorine detector seems to be losing ⅔ of its signal to neutrino conversion, the Mikheyev–Smirnov theory expects that a gallium detector would come up only about 10% short. Subtracting the resonant-conversion loss of 88% of the B^8 signal from Bahcall's standard-model calculation for gallium detectors, Bethe predicts that the gallium detectors will see about 110 SNU if it's really resonant conversion that's causing the ν_e shortfall.

Not only will this be a crucial test of the Mikheyev–Smirnov conversion mechanism; it will also shift the responsibility for testing the standard solar model from the very peripheral B^8 decay to the p–p and C–N–O sequences that are firmly believed to be