Development of Highly Efficient Composite Cryogenic Detectors for the Implementation in a Radiochemical Solar Neutrino Experiment

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The main focus of this work was the realization of a cryogenic detection concept for radiochemical solar neutrino experiments like GNO and SAGE which use gallium as target material. Via the reaction ^{71}Ga + $\nu_e \rightarrow ^{71}$Ge + e^- gallium experiments measure the capture rate of electron neutrinos on ^{71}Ga nuclei, ^{71}Ge is unstable and decays back to ^{71}Ga (half-life: 11.43d). A highly efficient and highly resolved detection of the ^{71}Ge decay signature consisting of X-rays and Auger-electrons (0.16 to 10.37keV) is required to further improve the sensitivity of gallium experiments essentially. Also in the context of a more precise determination of the electron neutrino capture cross section on ^{71}Ga, using an artificial neutrino source (e.g. ^{37}Ar or ^{51}Cr), highly efficient cryodetectors could enhance the accuracy considerably.

Gallium experiments like GNO and SAGE have been of great importance to obtain insight into a stellar interior and, in particular, they are the only ones capable of probing the predominant low-energy pp-neutrino branch of the solar fusion cycles. Both experiments measured a deficit in the expected total ν_e interaction rate on gallium. The neutrino deficit can now be explained as a consequence of massive neutrinos undergoing flavour transitions, via so-called neutrino oscillations. Gallium measurements have provided up to now the only experimental data from which a limit for the CNO-cycle contribution to the overall energy production in the sun can be derived. The continuation of gallium measurements is also essentially important for further analysis of time dependencies regarding the solar pp-neutrino flux.

The introduction of cryogenic ^{71}Ge detection in gallium experiments necessitated the development of a composite detector concept. Commonly used Ir/Au Transition Edge Sensors (TESs) are destroyed during chemical vapour deposition (at $\sim$400C) of germane gas (GeH_4) onto the sapphire absorber (Al_2O_3; 10x20x1mm^3) of the cryodetector. The separate fabrication of the TES on a smaller silicon substrate (Si; 5x5x0.25mm^3) and the deposition of the metallic germanium layer containing the ^{71}Ge activity was successfully realized. It was demonstrated that an energy resolution, mainly limited by the size of the dielectric sapphire absorber, of 187eV at 6keV and an energy threshold of 100eV can be reached, thus increasing the detection efficiency due to the detectability of the M-capture process, which was previously not possible with the miniaturized proportional counters utilized in GNO. Concerning a reproducible fabrication of composite detectors a particularly critical issue is the glueing of the two detector components, where the amount and shape of the glue drop (two-component epoxy-resin) plays an important role for the detector's eventual performance.

Since the detection of ^{71}Ge has to be highly efficient, the detection geometry must cover the full (4π) solid angle. This is realized by using the information provided by two individual detectors. Detector A bears the metallic germanium layer containing the ^{71}Ge activity and detector B is placed above. The separation between the two detectors is $\leq$1mm. Thus a detection efficiency close to 100% has been reached, which is only limited by the detector's energy threshold, determining the detectability of the M-capture at 160eV.

To operate this double (4π) detector a special holder had to be designed taking into account aspects like: fast handling, redundancy, shielding capability for creating low background conditions, radiopurity, temperature cyclability from room temperature to $\sim$10mK and longterm stability. In order to reduce the intrinsic radioactive background the selection of materials for the construction of the holder was based on low-level γ-spectroscopy indicating the quality of materials in terms of radiopurity like copper, antique lead, or the sapphire and silicon substrates themselves. The 4π detector housing made from copper with a minimum thickness of 5mm all around the detectors acts also as part of the internal shielding inside a ^{3}He/^{4}He dilution refrigerator. The holder can be attached to a $\sim$70mm thick, segmented copper and lead shielding below the mixing chamber of the cryostat. Thus the detectors are shielded from radioimpurites originating from the parts of the refrigerator itself.

To investigate the feasibility of cryodetectors for gallium experiments, a ^{3}He/^{4}He dilution refrigerator was set up in the underground laboratory (15m.w.e.) in Garching. The cryostat is located in a $\sim$15cm lead shielding which itself is surrounded by a plastic scintillator based muon-veto that can be operated in anticoincidence to the cryodetector. Together with the muon-veto the background rate was lowered to $\sim$5 cts/keV/d in the energy region between 8 and 12keV. Using this experimental setup and the double (4π) detector of the composite type Al_2O_3/Si + Ir/Au TES, a successful 35d longterm measurement was performed to prove the feasibility of cryodetectors for gallium experiments by recording the decay curve of ^{71}Ge. The longterm stability of the measurement was excellent.

In addition to the Al_2O_3/Si-type also different versions of composite detectors have been investigated. First measurements with a composite detector of the microcalorimeter type consisting of a 0.43x0.43x0.25μm^3 Sn absorber and a silicon substrate with the TES were extremely successful. An energy resolution of 5.9eV (FWHM) at 5.9keV was achievd; this result is to the day the best obtained with Ir/Au TESs worldwide.