Spectroscopy of low energy solar neutrinos using CdTe detectors

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The usage of a large amount of CdTe(CdZnTe) semiconductor detectors for solar neutrino spectroscopy in the low energy region is investigated. Several different coincidence signals can be formed on five different isotopes to measure the $^7$Be neutrino line at 862 keV in real-time. The most promising one is the usage of $^{116}$Cd resulting in 89 SNU. The presence of $^{125}$Te permits even the real-time detection of pp-neutrinos. A possible antineutrino flux above 713 keV might be detected by capture on $^{106}$Cd.

Key words: massive neutrinos, solar neutrinos

1 Introduction

Over the last years striking evidence arose for a non-vanishing neutrino rest mass (for reviews see [1,2]). They all come from neutrino oscillations experiments. Among them is the long standing evidence of a solar neutrino deficit also being of fundamental importance for stellar astrophysics. The deficit is seen in radiochemical detectors, namely GALLEX/GNO [3,4] and SAGE [5] using $^{71}$Ga, still the only pp-neutrino detectors available, and the Homestake experiment using $^{37}$Cl [6]. A reduced $^8$B $\nu_e$ flux is measured by two water Cerenkov detectors, namely Super-Kamiokande [7] and SNO [8]. A difference in measured fluxes among the latter resulted in evidence for an active neutrino flavour coming from the sun besides $\nu_e$. This is due to the fact that Super-Kamiokande is using neutrino-electron scattering and SNO inverse $\beta$-decay for detection. Recent SNO results of neutral current reactions on deuterium dramatically confirm the existence of further active neutrinos, being the dominant solar neutrino flux [9]. The solution of the solar neutrino deficit has to
come from particle physics, the scenario discussed most often is neutrino oscillations. Taking all experimental results together the largest effects in the solar neutrino spectrum implied by the various oscillations solutions show up in the region below 1 MeV. Furthermore this region corresponds to 99% of the solar neutrino flux and is still very important for understanding stellar energy generation [10]. An interesting idea to measure such low energy neutrinos in real time is suggested by [11] using coincidence techniques for neutrino capture on nuclei. It is already finding its practical application in the LENS [12], SIREN [13] and MOON projects [14], aiming to measure pp-neutrinos in real time. The technique relies on using either a large amount of double beta isotopes (\(^{176}\text{Yb}\) in case of LENS, \(^{160}\text{Gd}\) in case of SIREN and \(^{100}\text{Mo}\) in case of MOON) or highly forbidden beta decay emitters like \(^{115}\text{In}\) (4-fold forbidden, currently under study in LENS as an alternative to \(^{176}\text{Yb}\)), as target material [15]. Clearly an interesting spin off is the investigation of double beta decay [16].

In this paper the possibility to apply the same technique for CdTe(CdZnTe) semiconductor detectors and their feasibility for solar neutrino detection is explored. CdTe semiconductor detectors have already a wide field of application in \(\gamma\)-ray astronomy and medical physics. The study performed here is motivated by the COBRA project [17], planning to use large amounts of CdTe-detectors for double beta decay searches. The usage of large amounts of semiconductors for solar neutrino detection was also considered in the past for Ge-detectors [18] and GaAs [19] relying largely on the detection of electrons from neutrino-electron scattering. In the case discussed here, we focus on the detection of \(^7\text{Be}\) and pp-neutrinos only. Measurements of higher energetic neutrino flux components are also possible but will not be discussed. Also a possible real-time detection of pp-neutrinos via neutrino-electron scattering as well as contributions from the CNO cycle are not considered.

2 Solar neutrino detection via coincidence measurements

The detection principle for solar neutrinos using coincidences relies on the following two reactions

\[
\nu_e + (A, Z) \rightarrow (A, Z + 1)_{g.s.} + e^- \rightarrow (A, Z + 2) + e^- + \bar{\nu}_e \quad (1)
\]

\[
\nu_e + (A, Z) \rightarrow (A, Z + 1)^* + e^- \rightarrow (A, Z + 1)_{g.s.} + \gamma \quad (2)
\]

Therefore either coincidence between two electrons for the ground state transitions or the coincidence of an electron with the corresponding de-excitation photon(s) is required. The first one is followed by MOON, while the second one is used for LENS. The produced electrons as the first part of the coincidence
have energies of

\[ E_e = E_\nu - (E_f - E_i) \]  

(3)

with \( E_\nu \) as neutrino energy, \( E_f \) and \( E_i \) as the energy of the final and initial nuclear state involved in the transition. In case of \(^7\text{Be}\) neutrinos the electrons will be monoenergetic.

### 2.1 Solar neutrino tags using double beta isotopes

Consider detection with the help of double beta isotopes first. There are 4 (5) \( ^\beta^-\beta^-\) emitters in CdTe (CdZnTe) [17]. Three of them have sensitivity to the \(^7\text{Be}\) line of 862 keV, namely \(^{70}\text{Zn} \), \(^{106}\text{Cd}\) and \(^{130}\text{Te}\) . The corresponding coincidence tags are shown in Fig. 1. \(^{70}\text{Zn}\) and \(^{116}\text{Cd}\) are in the form of ground state transitions (Eq. 1), while for \(^{130}\text{Te}\) an e-\(\gamma\) coincidence (Eq. 2) is required. In case of \(^{70}\text{Zn}\) it is the ground state transition to \(^{70}\text{Ga}\) with a threshold of \( E_\nu = 655 \) keV. \(^{70}\text{Ga}\) will decay via beta decay to the ground state of \(^{70}\text{Ge}\) in 98.9 % of all cases and a half-life of 21.14 min. However because \(^{70}\text{Zn}\) is only present in small amounts (Zn typically replaces 10 % of Cd in CdZnTe detectors) in the detector, the expected rate is rather small. In case of \(^{130}\text{Te}\) it is the transition to the first excited \( 1^+ \) state in \(^{130}\text{I}\) , lying 43.25 keV above ground state. This corresponds to a neutrino energy threshold of \( E_\nu = 494 \) keV. The state de-excites under the emission of a 3.3 keV X-ray. With a half-life of 8.8 mins in 86 % of the cases an IT will happen resulting in a 39.95 keV photon or in 14 % a \( \beta\)-decay to \(^{130}\text{Xe}\) , dominantly inot the first excited \( 2^+ \) state. This is connected with the emission of a 536 keV photon. The analogous \( \beta\)-decay of the \( 5^+ \) ground state of \(^{130}\text{I}\) with a half-life of 12.36 h is probably inadequate to use in the coincidence. Two more \( 1^+ \) states exist at 254.8 keV and 349.6 keV above ground state which can be populated by \(^7\text{Be}\) , corresponding to a neutrino energy threshold of \( E_\nu = 706 \) keV and 801 keV respectively. Furthermore there exist several low-lying states, whose quantum numbers have not been determined yet and it might be worthwhile to do so. Probably the most appropriate isotope for the search is \(^{116}\text{Cd}\) . The coincidence signal will be the two electrons of the neutrino capture to the ground state of \(^{116}\text{In}\) with an energy threshold of \( E_\nu = 464 \) keV together with the \( \beta\)-decay (practically 100 %) of \(^{116}\text{In}\) with a half-life of 14.1 s. The Q-value of the latter is 3.275 MeV. Thus a good coincidence signal can be formed among the two electrons. Such double electron tags can also be performed for detecting the pep-line at 1.445 MeV by using \(^{114}\text{Cd}\) . Here a low energy electron of about 5 keV is in coincidence with a \( \beta\)-decay electron of \(^{114}\text{In}\), having a half-life of 72s and a Q-value of 1.98 MeV.
2.2 The case of $^{113}\text{Cd}$

One might also consider the case of $^{113}\text{Cd}$ as target for a neutrino capture into $^{113}\text{In}$ . $^{113}\text{Cd}$ is one out of only three known 4-fold forbidden beta decay isotopes, besides $^{115}\text{In}$ and $^{50}\text{V}$. Indeed, since quite some time the idea to build an indium solar neutrino detector exists [20], a possible realisation is considered now within the LENS experiment. It is therefore natural to ask, whether $^{113}\text{Cd}$ is also interesting. The possible solar neutrino tag is shown in Fig. 2. As can be seen, also with this isotope $^7\text{Be}$ spectroscopy of the sun is possible. There are two excited $3/2^+$ states at 1029.6 and 1063.9 keV above ground state, resulting in neutrino thresholds of $E_\nu = 709$ and 743 keV respectively. The electron is most of the time accompanied by a 672 or 638 keV photon. The IT of the $1/2^-$ state to the $9/2^+$ ground state of $^{113}\text{In}$ is associated with an additional 391.7 keV photon and a half-life of 1.65 h. Two forbidden transitions exist which in principle would allow a real time-detection of pp-neutrinos with a threshold of $E_\nu = 70$ keV and 330 keV, however the expected smallness of the involved nuclear matrix elements will result in a rather small rate. Possible advantages with respect to $^{115}\text{In}$ are that the beta half-life of $^{113}\text{Cd}$ is more than one order of magnitude higher than for $^{115}\text{In}$, resulting in correspondingly less background from that process (typical background from the $^{115}\text{In} \beta$-decay is 0.24 Bq/g In). Furthermore, the endpoint energy of $^{113}\text{Cd}$ is only about 320 keV compared to 496 keV from $^{115}\text{In}$ . Additionally, its implementation in a semiconductors implies a better energy resolution than scintillators. Disadvantages are the smaller natural abundance with respect to $^{115}\text{In}$, being a factor eight less, and the much higher threshold for allowed transitions. $^{50}\text{V}$ as the third 4-fold forbidden beta-decay emitter is not appropriate for low energy solar neutrino searches because of its low natural abundance and lack of interesting low lying $1^+$ states. A comparison of the three isotopes is shown in Tab. 1.

2.3 Real time pp-detection using of $^{125}\text{Te}$

A chance for real-time pp-neutrino detection exists using two allowed states in $^{125}\text{Te}$ (Fig ??). The first excited $3/2^+$ state in $^{125}\text{I}$ is 188 keV above the ground state allowing pp-detection with a threshold of $E_\nu = 366$ keV. The coincidence will be formed by a double tag of an electron in direct coincidence to the emission of a 188 keV photon or the corresponding cascade. An additional $1/2^+$ state exist with a threshold of $E_\nu = 420$ keV resulting in the emission of a 243 keV photon. Additionally two further $3/2^+$ states can be used for $^7\text{Be}$ detection having thresholds of 549 keV and 631 keV. Associated with them is the emision of 453.8 or 372.1 keV photons respectively.
2.4 Measuring solar antineutrinos

The existence of active flavours coming from the Sun besides $\nu_e$ is established by SNO. However, it is an open question what this new flavour actually is. Therefore a measurement of a possible solar antineutrino flux might be useful. In CdTe (CdZnTe) there are 3 (4) isotopes available of various forms of $\beta^+\beta^+$ decay, allowing for a tag on possible solar antineutrinos. From a principle point of view no antineutrino below 511 keV can be detected via charged current reactions on nuclei because one has to account for the positron mass. Therefore pp-antineutrinos cannot be observed by this method. The most promising candidate in CdTe is $^{106}Cd$, allowing antineutrino detection with a threshold of $E_\nu = 713$ keV. The tag would be a monoenergetic 149 keV positron together with a decay of $^{106}Ag$ via $\beta^+$ or electron capture and a half life of 24 min.

3 Experimental considerations

In the following the detection of the coincidences is discussed close to the design presented in [17]. It is assuming an array of CdTe detectors each of 1cm$^3$ size. Such a design has a large advantage for coincidence searches. The signals containing two electron tags have to rely on the fact, that the same crystal has to fire twice. The individual rates of such a crystal can be small and applying corresponding energy cuts appropriate for the tag will reduce background significantly. Furthermore in case of monoenergetic electrons as expected from $^7Be$ neutrinos the good energy resolution allows to define a rather tight constraint on the coincidence signal. To avoid background from $^{113}Cd$ $\beta$-decay the second electron can be required to have at least 320 keV. This is completely reducing this background, while keeping the efficiency still high, because the interesting $\beta$-decays have Q-values well above 2 MeV (e.g. the $\beta$-decay of $^{116}In$ has a Q-value of 3.27 MeV). None of the $\gamma$-lines to be observed from the signal are in close vicinity of the strongest lines of the natural decay chains. The most dangerous might be an effect of the 46.5 keV line of $^{214}Bi$ on the 39.9 keV IT line occuring in the $^{130}Te$ tag. Also the 672 keV line of the $^{113}Cd$ tag is in vicinity of the 662 keV line of $^{137}Cs$, but both can be significantly reduced by the coincidence techniques and the good energy resolution.

For higher energetic gammas the coincidence of neighbouring crystals has to be used, because no delayed coincidences can be formed. The efficiency of gamma-rays leaving the crystal without further interactions is increasing with energy and is beyond 60 % already at 250 keV as obtained by a GEANT4 Monte Carlo simulation [21]. Another step forward in signal identification would be the usage of pixelised detectors, which would constrain the vertex...
for two electron tags to one pixel and additionally two tracks consistent with electrons have to start from that pixel. Also multiple interactions within a crystal like an electron together with a gamma, can be probed in that way. Even without pixel detectors such a discrimination seems possible by pulse shape analysis.

For calibration purposes several solar neutrino experiments have used MCi $^{51}$Cr source, producing monoenergetic lines of 743 keV (90 %) and 426 keV (10 %) neutrinos [22]. Two more sources of $^{75}$Se with $E_\nu = 451/461$ keV and $^{37}$Ar with $E_\nu = 814$ keV are also under consideration [23,24]. The $^{51}$Cr source would be appropriate here as well, because all nuclear levels discussed as signal levels except one of the excited 1$^+$ states in $^{130}$Te and one of the excited 3/2$^+$ states in $^{113}$Cd can be populated by the source. The latter depends on the precise Q-value of the $^{113}$Cd $\beta$-decay.

### 4 Rates

Observed rates can be determined for the ground state transitions by using the known ft-values of the corresponding $\beta$-decays. The cross-section can be determined via the relation [25]

$$\sigma = \frac{2.64 \cdot 10^{-41} 2I' + 1}{ft} \frac{2I + 1}{2I + 1} p_e E_e F(Z, E_e) \quad (\text{cm}^2) \quad (4)$$

where $I', I$ are the involved nuclear spins, $p_e$ and $E_e$ are the momentum and energy of the outgoing electron in units of the electron mass and $F(E,z)$ is the Coulomb function. The used ft-values of $\beta$-decay are taken from [26,27]. The Gamow-Teller transition matrix elements for $^{116}$Cd were measured recently [28]. The expected rates from $^7$Be only are 89 SNU for $^{116}$Cd and 10 SNU for $^{70}$Zn. For the excited states transitions the GT matrix elements have to be measured or calculated and without their knowledge, rates cannot be seriously predicted. Therefore the above mentioned neutrino sources are very important. Accelerator measurements can be done using charge exchange reaction like (p,n) or $(^3$He,t) [29]. A more sophisticated analysis will also include efficiencies from Monte Carlo simulations and details on the $\gamma$-emission in the nuclear de-excitation.

### 5 Summary and conclusions

The prospects of various isotopes of Cd, Zn and Te for low energy solar neutrino spectroscopy are explored. To obtain a reasonable signal various coinci-
dence tags can be used, as compiled in Tab. 2. It allows the detection of $^7$Be in real time for five isotopes and therefore offers redundancy in the obtained results. The most promising detection signal is the ground state transition of $^{116}$Cd to $^{116}$In resulting in 89 SNU. This has to be seen as a lower limit because CNO contributions are not taken into account. In addition $^{125}$Te allows a real time detection of pp-neutrinos with a threshold of 330 keV. The usage of semiconductors is advantageous for background reduction for $^7$Be detection because the monoenergetic electron forming the first step of the coincidence can be measured with good precision. Rates for excited state transitions cannot be determined reliably because a lack of knowledge in the corresponding GT matrix elements, a problem also known from other low energy solar neutrino experiments. It might be worthwhile to consider an experimental program to measure these matrix elements, which would also be valuable for double beta decay. As common for solar neutrino detection detector sizes of tons have to be considered, this kind of experiment is not feasible in the very near future.

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Fig. 1. Possible $^7$Be neutrino tags using $^{70}\text{Zn}$ (left), $^{116}\text{Cd}$ (middle) and $^{130}\text{Te}$ (right). The most promising one is $^{116}\text{Cd}$, having a threshold of 464 keV for solar neutrinos and a short coincidence time between the two electrons, because the half-life of $^{116}\text{In}$ is only 14.1 s. The metastable $2^+$ state made decay via IT or $\beta$-decay to the first excited $2^+$ state of $^{130}\text{Xe}$.

Fig. 2. Left: The various solar neutrino captures on $^{113}\text{Cd}$. Two allowed transitions exist for $^7$Be neutrinos (solid lines). Two forbidden transition (dashed lines) would allow the detection of pp-neutrinos with a threshold of $E_\nu = 70$ keV only, however the involved GT matrix elements are orders of magnitude lower than for allowed transitions. Right: $^{125}\text{Te}$ allows the detection of pp and $^7$Be neutrinos in real time. The two low lying $1/2^+$ and $3/2^+$ state can be populated by pp-neutrinos. The threshold is 330 keV.
### Table 1
Comparison of the three known 4-fold forbidden $\beta$-decay isotopes and their potential for real time solar neutrino spectroscopy. Shown are the natural abundance, $\beta$-decay half-life, Q-value of the $\beta$-decay and the threshold for solar neutrino detection.

| Isotope | nat. ab. (%) | half-life (yrs) | Q-value (keV) | $E_\nu$ Thr. (keV) |
|---------|--------------|-----------------|---------------|-------------------|
| $^{50}$V | 0.25         | $1.4 \cdot 10^{17}$ | 1038          | 2126              |
| $^{113}$Cd | 12.2        | $9 \cdot 10^{15}$   | 320           | 709               |
| $^{115}$In | 95.7        | $4.4 \cdot 10^{14}$ | 496           | 118               |

### Table 2
Compilation of double beta isotopes in CdZnTe and their sensitivity to various components of the solar neutrino flux. Shown are the natural abundances, the solar neutrino energy threshold and the contributing neutrino fluxes.

| Isotope | nat. ab. (%) | $E_\nu$ Thr. (keV) | solar $\nu$ sources |
|---------|--------------|-------------------|---------------------|
| $^{70}$Zn | 0.62         | 655               | $^7$Be , $^{13}$N , $^{15}$O , $^{17}$F , $^8$B , pep |
| $^{114}$Cd | 28.7        | 1440              | $^{15}$O , $^{17}$F , $^8$B , pep |
| $^{116}$Cd | 7.5         | 464               | $^7$Be , $^{13}$N , $^{15}$O , $^{17}$F , $^8$B , pep |
| $^{128}$Te | 31.7        | 1258              | $^{15}$O , $^{17}$F , $^8$B , pep |
| $^{130}$Te | 33.8        | 494               | $^7$Be , $^{13}$N , $^{15}$O , $^{17}$F , $^8$B , pep |