Delayed coincidence in electron-neutrino capture on gallium for neutrino spectroscopy

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This work explains a delayed-coincidence method to perform MeV-scale neutrino spectroscopy with electron-neutrino capture on gallium. An electron-neutrino possessing energy greater than 407.6 keV can be captured on gallium and produce a daughter germanium nucleus at its first excited state with a mean lifetime of 114 ns. The released electron and gammas before the first excited state of Ge can generate a prompt signal representing the solar neutrino energy and the gamma from the deexcitation of the first excited state, 175 keV, can give a delayed signal. The cross-section of this electron-neutrino capture process is evaluated and is comparable with electron-neutrino capture on chlorine. A possible implementation with a liquid scintillator is discussed to exploit the delayed coincidence. The detection scheme is more feasible than using $^{115}$In, etc, but need a larger target. The proposed method can be helpful for the MeV-scale solar neutrino spectroscopy and for solving the gallium anomaly.

I. INTRODUCTION

The early works by J. Bahcall [1] and R. Davis [2], and many results achieved later by other experiments such as GALLEX [3], GNO [4], SAGE [5], SNO [6], Super Kamiokande [7], KamLAND [8], and Borexino [9] mark the legend of modern studies of solar neutrino. The standard solar model and neutrino oscillations are the most noteworthy achievements.

However, several theoretical and experimental puzzles continue to exist. The “upturn” effect, which is the increase in solar electron-neutrino survival probability from matter dominant region to vacuum region, is still poorly constrained by experiments [10–13]. Moreover, in the source tests with helioseismic prediction and the standard-solar-model prediction of the Sun, a conflict exists between the expected solar-electron neutrino flux and the standard solar model and neutrino oscillations. The carbon-nitrogen-oxygen (CNO) fusion neutrinos from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9]. For the metal-element abundance from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9]. For the metal-element abundance from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9]. For the metal-element abundance from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9]. For the metal-element abundance from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9]. For the metal-element abundance from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9]. For the metal-element abundance from the Sun, which are dominant of the fueling processes of high-temperature massive stars, have not been observed [9].

Electron-neutrino capture on a nucleus,

$$\nu_e + (A, Z) \rightarrow (A, Z + 1) + e^-,$$  \hspace{1cm} (1)

provides a detection channel of the pure weak charged-current (CC) interaction for MeV-scale neutrino spectroscopy, in which the energies of the neutrino and the emitted electron simply differ by an energy threshold [10]. Neutrino-electron scattering also provides a detection channel of the charged current together with the energy of the recoiled electron is a complicated function of the neutrino energy and the electron emission angle, for example, as shown in [20]. Comparing these two types of detection channels, a large number of target electrons are easier to collect in water or an organic liquid scintillator, but the $\nu_e$-nucleus capture is more convenient to extract the physics depending on the neutrino energy, such as the upturn effect and the structure of CNO neutrinos.

The SNO experiment measured the $e^-$ kinetic energy spectrum above 3.5 MeV [6] using the CC process $\nu_e + d \rightarrow p + p + e^-$ which has a reaction threshold 1.44 MeV. All the rest $\nu_e$-nucleus capture measurements have only chemically detected the final state nuclei and no energy measurement of the emitted electrons is available so far. None of them has effectively addressed the upturn feature and CNO neutrinos.

The delayed-coincidence technique for $\nu_e$-nucleus capture has been actively discussed for nuclei, such as $^{115}$In, $^{190}$Mo, $^{176}$Yb, $^{116}$Cd, etc. [21–24] because it can greatly decrease the demand for the radioactive purity of the detection material and distinguish the signal from the background $\nu_e$-electron scattering. The experimental efforts are still in progress, and facing a lot of technical challenges [25], for example, the high radioactivity of $^{115}$In.

II. DELAYED COINCIDENCE IN $\nu_e$ CAPTURE ON GALLIUM

In this work, we propose a delayed-coincidence method to use gallium to perform a study on solar neutrino spectroscopy. An energy level plot of the Ga-Ge system is presented in Fig. 1 for a few relevant states. The process is described in detail below,

$$\nu_e + ^{71}_{31} \text{Ga} \rightarrow ^{71}_{32} \text{Ge} + e^- \rightarrow ^{71}_{32} \text{Ge}^{\text{ex}} + e^- (\gamma), (2)$$

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which is followed by

$$71_{32}^{71} \text{Ge}_{\text{int}} \rightarrow 71_{32}^{71} \text{Ge}_{\text{gs}} + \gamma (174.94 \text{ keV}), \, \tau = 114 \text{ ns}. \quad (3)$$

Through the charge-current reaction an electron-neutrino is captured on $^{71}\text{Ga}$ and emits an electron and a $71\text{Ge}$ nucleus at an excited state. The direct nucleus product can be the first excited state of $^{71}\text{Ge}$ at 175 keV ($5/2^-$) or other higher levels, which can subsequently decay to the first excited state through one or a few gamma decays with certain probabilities. The first excited state has a mean lifetime of 114 ns $[26,28]$. The electron and deexcitation gammas in Eq. 2 form a prompt signal. The neutrino energy, $E_\nu$, is the sum of the prompt energy, $E_\text{prompt}$, and the reaction threshold $[24,30]$,

$$E_\nu = E_\text{prompt} + 407.63 \text{ keV}. \quad (4)$$

The deexcitation of the first excited state in Eq. 3 results in a delayed signal and coincidence. Note that there is a level at 198 keV with a lifetime of 29.45 ms and must be taken into consideration (Fig. 1). The gallium can be dissolved in a liquid scintillator and the delay-coincidence signals can be detected with a photomultiplier tube (PMT) array and a modern fast electronic readout system.

![Figure 1](image)

**FIG. 1.** The relevant energy levels of $^{71}\text{Ga}$-$^{71}\text{Ge}$ system. The energy level, spin, and parity are labeled. The mean lifetime of the ground, first, and second excited states of $^{71}\text{Ge}$ are also labeled. The deexcitation of the first excited state of $^{71}\text{Ge}$ can be used as a delayed coincidence in the experiment.

### III. CROSS-SECTION

The differential capture cross-sections of each $^{71}\text{Ge}$ energy level, $l$, can be calculated with the approach described in [31][34],

$$\sigma_l(\omega_e) = \sigma_0 \frac{B(\text{GT})_l}{B(\text{GT})_{\text{gs}}} \frac{\omega_e p_e}{2\pi\alpha Z} F(Z, \omega_e) \quad (5)$$

where $B(\text{GT})_l$ are the Gamow-Teller strengths for each level, $\sigma_0$ was introduced in [31][32] in which the ground state transition strength was considered, $\omega_e$ and $p_e$ are the energy and momentum of the electron, respectively, $\alpha$ is the fine-structure constant, and $F$ is the Fermi function with $Z = 32$ and $\omega_e$, which can be calculated according to [31][33]. The $B(\text{GT})$ values were measured through the $^{71}\text{Ga}^{(3}\text{He},t)^{71}\text{Ge}$ charge-exchange reaction in [36] and are listed in Table I. For a conservative cross-section estimation, we didn’t take the shell-model calculation result for $B(\text{GT})$ of the $5/2^-$ level, which is five times larger [37].

To evaluate the total cross section, $\sigma$, the incident neutrino energy spectrum $\phi(E_\nu)$, all the allowed excited energy levels, and their branching ratios to the first excited state, $\text{BR}_l$, are considered

$$\sigma = \int_{E_{\text{min}}}^{E_{\text{max}}} \sum_l \sigma_l(\omega_e) \text{BR}_l \phi(E_\nu) dE_\nu, \quad (6)$$

where the energy integral region $[E_{\text{min}}, E_{\text{max}}]$ is limited by the $E_\text{prompt}$ of interest for detection and the contributions through the 198 keV level are excluded. The branching ratios of the excited states to the first excited state can be calculated based on the information given in ENSDF [29]. However, only the data up to approximately 2 MeV are available for this estimation. Table I summarizes the branching fractions.

With Eq. 5 and 6 and the input in Table I the capture cross-sections of solar neutrino components, $\nu_\text{p}$, $\nu_\text{e}$, and $\text{CNO}$, are calculated and listed in Table II with the solar neutrino spectrum input from [1].

### IV. GALLIUM-LOADED LIQUID SCINTILLATOR DETECTOR

One measurement scheme is a Ga-loaded liquid scintillator. The Ga-loaded liquid scintillator is contained in a spherical transparent container. The scintillation and Cherenkov lights emitted by the prompt and delayed signals are detected by PMTs, and subsequently read out with fast electronics.

There are several applications to load different elements into organic liquid scintillator. The Te-loaded liquid scintillator [38], In-loaded liquid scintillator [39],...
Gd-loaded liquid scintillator \cite{25}, and Li-loaded liquid scintillator \cite{40} are some examples. A method to load other elements into water-based liquid scintillators also exists \cite{41}.

The timing feature of the PMT and electronics is suitable for such a method. The rising time of the large diameter PMTs (\geq 8 inches) \cite{42} is less than 10 ns and their transition time spread is 2-4 ns. Fast waveform digitizers can be found \cite{43} with a sampling rate of 1 Giga samples per second and no dead time.

The random coincident background from natural radioactivities is negligible for a 342 ns coincident window (3 \times lifetime) according to the calculation method in \cite{21, 22}.

The late pulse of the PMTs should be considered. Actual PMT time residual distributions in a large detector are presented by the SNO experiment (Fig. 5 of \cite{44} and Fig. 3 of \cite{45}), where the late pulse rate is approximately 1\% of the major pulse height per 0.33 ns from 10 to 80 ns because of the PMT’s, electronics and reflections, and only 0.2\% per 0.33 ns after 80 ns. Considering a light yield of 500 photoelectrons (PE) per MeV in a liquid scintillator detector and a prompt 2 MeV signal, the number of PE for the prompt and delayed signals are 1000 and 88, respectively. After 80 ns, the number of PE for the late pulse in a 20 ns window is approximately 4, so that identifying the 175-keV delayed signal is not a concern.

V. DISCUSSION AND CONCLUSION

In this work we explained the delayed-coincidence method in \( \nu_e \) capture on \( ^{71}\text{Ga} \) and evaluated the cross-sections below 2 MeV.

Naturally, gallium has only two stable isotopes and the natural abundance of \( ^{71}\text{Ga} \) is 39.9\%. This overcomes the difficulty of intrinsic background in \(^{115}\text{In} \) \cite{21} and \(^{100}\text{Mo} \) \cite{22}. The coincident time of \(^{71}\text{Ga} \) is the shortest among \(^{115}\text{In} \), \(^{100}\text{Mo} \), and \(^{116}\text{Cd} \) \cite{21} and is just over the limitation of PMT system. The delayed energy is higher than \(^{176}\text{Yb} \) \cite{22} and is also higher than the endpoint of \(^{14}\text{C} \), which is contained in organic detection material. Experimentally it is easier to implement.

The cross-section going through the first excited state of \(^{71}\text{Ga} \) is 2\%-3\% of that going through the ground state and much smaller than \(^{115}\text{In} \): however it is comparable with that of \(^{37}\text{Cl} \) \cite{51} which was used by R. Davis. If we take the B(BG) for the 5/2- level of shell-model prediction \cite{57}, the cross-section is five times larger. This is the largest uncertainty and at this moment, we cannot exclude one or the other. The cross-section beyond 2 MeV can be measured using a neutrino source on a spallation neutron facility \cite{46, 47} with a known \( \nu_e \) spectrum from the muon decay.

The application of loading Ga into a liquid scintillator is also discussed. The delayed signal is well detectable by a modern PMT-digitizer array. The background situation is promising except for some efficiency loss due to the late PMT pulses.

For the gallium anomaly, the method could be very interesting, because considerable focus of the cause is on the neutrino capture cross-section prediction for the first excited state of \(^{71}\text{Ge} \) \cite{33, 36, 37}. This method will give key insights of the popular speculation on the systematic uncertainty of the first excited state of \(^{71}\text{Ge} \). In the search of the upturn and CNO neutrinos, this method is clear of the unfolding complexity of the electron targets and can be useful for directly measuring the solar \( \nu_e \) energy spectrum.

In summary, the delayed-coincidence in \(^{71}\text{Ga}(\nu_e,e^-)^{71}\text{Ge} \) reaction involving the the first excited state of \(^{71}\text{Ge} \) could be technically applicable for solar neutrino spectroscopy. For the studies of gallium anomaly, upturn, and CNO neutrinos, it is an approach to consider.

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