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Inverse β^- decay of ^{40}Ar: A new approach for observing MeV neutrinos from laboratory and astrophysical sources

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Inverse β^- decay of ^{40}Ar to its isobaric analog state in ^{40}K should occur with a large cross section (σ) for neutrino (ν_e) capture above a threshold of $E_{\rm th}=5.885$ MeV. The ν_e capture is distinguished by a characteristic γ-ray coincidence signature. With a σ typically larger than that for (e,ν_e) scattering, the new capture mode of detection should significantly enhance the sensitivity and usefulness of liquid-Ar chambers as ν_e spectrometers at meson factories and for astrophysical sources such as the Sun, cosmic rays, and collapsing stars.

Neutrinos in the energy range 5—30 MeV are characteristic of some important laboratory and astrophysical sources and their real-time observation by energy-resolved methods is of great interest to several questions in particle physics and astrophysics. These include the study of "low"-energy neutrino reactions at meson factories, the solar-neutrino problem, the observation of neutrino bursts during the gravitational collapse of massive stars, the study of cosmic-ray-produced neutrinos of energy <50 MeV, etc. For direct, real-time neutrino (ν) spectrometry at these energies, three processes have been considered so far. One is elastic (e,ν_e) scattering: $e+\nu_e \rightarrow e+\nu_e$ with detection of the scattered electron in light or heavy water by Cherenkov methods or in liquid-Ar chambers using ionization methods. The process does not have a stringent signature. Another method is (ν_e,d) capture:[1] $d+\nu_e \rightarrow 2p+e$, using Cherenkov detection of the electron in heavy water. It also lacks a unique signature, but its cross section is significantly larger than that for (e,ν_e) scattering. Recently, a third method based on the neutral-current reaction $\nu+d \rightarrow n+p+\nu$ has been considered, involving Cherenkov detection of the Compton electrons of a 6.25-MeV γ ray from the capture of the released neutron by another deuteron.[2]

In this article I propose a new approach. It is based on the inverse β^- decay of ^{40}Ar to the excited $T=2$ isobaric analog state at 4.38 MeV in ^{40}K (Ref. 3). The threshold of this reaction is at 5.885 MeV and is thus tailored to ν spectrometry in the problems cited above. Features which make this a specially attractive approach are the following. (1) The detection can be accomplished by a distinctive γ-ray (delayed) coincidence signature which is a powerful aid for background suppression. The methods listed above do not have this advantage and require extremely careful study of background sources. (2) It is a direct-counting approach yielding the energy spectrum of the incident neutrinos. (3) The ν_e capture cross section σ is typically larger than for (e,ν_e) scattering (even allowing for the 18 times as many electrons as Ar) and comparable to that for (ν_e,d) capture. (4) The cross section is known with high ($<1\%$) precision; the mode of detection via the γ-ray coincidence and the details of the level scheme of ^{40}K ensure that ν detection is accomplished by capture to a single level at 4.38 MeV. (5) Finally, and most importantly, the reaction target is ^{40}Ar, the dominant (99.64%) isotope of Ar which is abundant, easily prepared as liquid Ar (LAr) and thus economically available in large quantities. It is also the preferred material for large detector chambers whose technology is very advanced.[4] Energy resolution as good as several percent has been demonstrated for 600-keV electrons.[5] Very good position resolution has been shown for LAr time-projection chambers.[6] Their use for ν spectrometry based on (e,ν_e) scattering, has been discussed for many years.[7] The additional availability of a powerful new detection mode such as the one described here should thus significantly enhance the usefulness of LAr chambers for ν spectrometry.

The isobaric analog of the ground state of ^{40}Ar of spin and isospin $(I;T)=(0^+;2)$ is the state at 4.38 MeV $(0^+;2)$ in ^{40}K (Ref. 8). Driven by a superallowed $0^+ \rightarrow 0^+$ Fermi (F) $(\Delta T=0)$ matrix element, neutrino capture in ^{40}Ar is dominated by capture to the 4.38-MeV analog state with a threshold at 5.885 MeV. The analog state decays by γ-ray cascades (see Fig. 1), partly promptly, and partly delayed through the state at 1.644 MeV which is *isomeric* with a mean life $\tau=480$ nsec. Allowed Gamow-Teller (GT) captures to $I=1^+$, $T=1$ states (at 2.29 and 2.73 MeV) are also possible. Captures to all other known bound states in ^{40}K are negligible.

The coincidence signature for the capture of, say, a 10-MeV neutrino in ^{40}Ar is as follows. For F capture, a prompt 4.115-MeV recoil electron e_1 is always accompanied by γ rays of total energy $E_{\gamma t}=4.38$ MeV. In 65% of the events, it is emitted in coincidence with a photon cascade of total energy $E_{\gamma 1}=2.74$ MeV followed in delayed coincidence by a single photon of energy $E_{\gamma 2}=1.644$ MeV. The energy of the prompt recoil electron e_1 yields the neutrino energy. In most cases, the photons would produce a cluster of Compton tracks well removed from that of the recoil electron e_1, yielding the electron energy without ambiguity. In rare cases, however, this separation may be small, and unique identification of the prompt electron track among those of the Compton electron tracks ambiguous, especially if e_1 needs to be measured with very good energy resolution. However, Fig. 1 shows that the maximum energy of a Compton

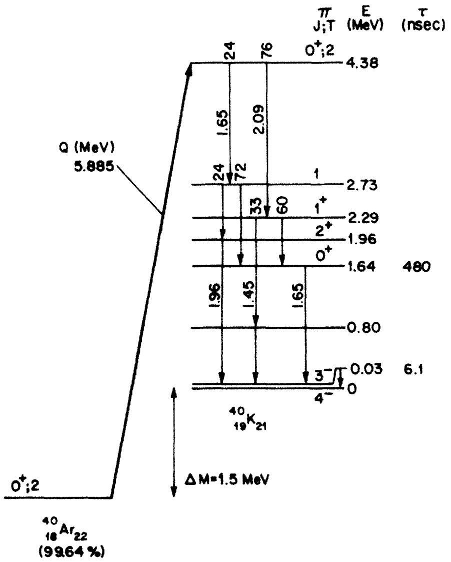

FIG. 1. Level scheme of ^{40}Ar-^{40}K relevant to ν_e capture in argon.

track from any one of the γ rays can only be less than 2 MeV. Unambiguous identification of the prompt electron track and extraction of the value of E_{ν_e} from F captures, is thus safely assured for $E_{\nu_e} > 8$ MeV. A modest degree of spatial resolution (and if necessary, time resolution of ≈ 100 nsec) is thus sufficient to completely define the coincidence (or delayed) events, separate them from background, characterize the ν_e capture, and measure the energy of the incident neutrino.

The cross section for the Fermi ν_e capture is given by

$$\sigma(0^+0^+) = \sigma_0 W_e (W_e{}^2 - 1)^{1/2} F(W_e)/ft(0^+ - 0^+) ,$$

where $\sigma_0 = 2.628 \times 10^{-41}$ cm^2, W_e, the energy of the prompt electron, is $W_e = (E_{\nu_e} - Q + 1)$, the excess of the neutrino energy E_{ν_e} over the threshold of $Q = 11.517$ (energies in units of m_0c^2), and $F(W_e)$ is the Fermi function.[9] The value of ft between two 0^+ states within a $T=2$ isospin multiplet, the present case, is simply given by $ft(0^+ - 0^+; T=2) = \frac{1}{2} ft(0^+ - 0^+; T=1)$ (Ref. 10). The latter is available with great precision as $ft(0^+ - 0^+; T=1) = 3086.6(3.5)$ sec, independent of A or Z (Ref. 11). Thus $ft(0^+ - 0^+; T=2) = 1543(2)$ sec. Experience with $T=1$ decays shows that effects of isospin impurities are typically $\ll 1\%$ and are included in the quoted errors. Thus we obtain

$$\sigma(0^+0^+) = 1.702(4) \times 10^{-44} W_e (W_e{}^2 - 1)^{1/2} F(W_e) \text{ cm}^2 .$$

Between 0.5 and 20 MeV, the shorthand formula $\sigma(0^+0^+) \approx 2.655 \times 10^{-44} (E_{\nu_e} - 10.5)^2$ cm^2 (E_{ν_e} in m_0c^2 units) is useful. Cross sections for the GT captures to $I = 1^+$ $T=1$ states are less certain at present but could be obtained from a measurement of the lifetime of the 4.38-MeV state since this transition is the analog of the GT capture, via 0° (p,n) reactions, or directly with neutrino beams from meson factories (see below). Since the F captures can be measured separately from the GT captures (the accompanying γ rays differ by 1.65—2.09 MeV in the two cases) we shall base further discussion only on the F capture rates.

Compare the sensitivities of ν_e reactions for a typical ν_e energy of 10 MeV: $\sigma(0^+0^+;\text{Ar}) = 2.2 \times 10^{-42}$ cm^2; $\sigma(\nu_e, d) = 2.2 \times 10^{-42}$ cm^2; $\sigma(e, \nu_e) \approx 18 \times 2.4 \times 10^{-44} = 0.43 \times 10^{-42}$ cm^2 $[N(e)/N(\text{Ar}) = 18; E_{\text{th}} = 7$ MeV]; $\sigma(\nu + d \rightarrow n + p + \nu) = 1 \times 10^{-42}$ cm^2. Thus, the 0^+0^+ ν_e capture in ^{40}Ar compares favorably with other ν_e-detecting reactions.

It is well known that at these energies, the (e, ν_e) scattering is highly directional. Inverse β reactions in principle, are anisotropic; but the $(\nu_e - e)$ anisotropy[12] is small, typically $\frac{1}{3}$. However, the Ar(0^+0^+), being a pure Fermi transition, has the highest possible anisotropy of 100%; i.e., twice as many prompt electrons are emitted along the ν direction as at 90° to it. While this is less direction specific than (e, ν_e) the high rates of Ar(0^+0^+) could render it more than equivalent in directionality.[13] I shall now consider typical investigations for which the present approach could be valuable.

Neutrino experiments at meson factories. The ν_e beam at LAMPF has a maximum energy $E_\nu^{\max} = 53$ MeV. The time-averaged ν_e flux at target is $\approx 3 \times 10^7$/cm^2 sec. Using the function $F(x) = x^2(1-x)$ for the energy spectrum with $x = E_\nu / E_\nu^{\max}$, the integrated capture rate in a 10-ton Ar detector is obtained as $N_{\text{sig}} = 30$/day. 99.5% of these events occur with prompt electron energies e_1 between 10 and 47 MeV.

This suggests that with a live time of a few weeks, a number of calibration tests can be carried out on the nature of inverse β events in a LAr chamber. The contributions of GT captures could be measured relative to F captures to some 5% of $\sigma(0^+0^+)$ and compared with GT strengths derived from (p,n) reactions. This would be the first *direct* test of the principles underlying the widespread use of (p,n) results[14] for deriving inverse β strengths. Other applications could include ν oscillation experiments to search for variation of the ν_e spectrum with distance similar to reactor experiments on antineutrinos, the use of LAr(0^+0^+) as a live monitor of the ν_e profile for other investigations such as that of (ν_e, e) scattering, etc.

Solar Neutrinos. The precise knowledge of the capture cross section $\sigma(0^+0^+)$ and the availability of a γ-ray coincidence signature for suppressing background suggest the application LAr chambers to the *spectrometry* of neutrinos from the Sun. The operative threshold of $E_{\text{th}} \approx 8$ MeV yields $\approx 95\%$ of the ν events expected from solar ^{8}B decay, at a rate of about 4.2 events/(day) (kiloton Ar). With comparable cross sections (see above), the ν-capture rates per unit target mass in LAr would be somewhat smaller than in D$_2$O but with the vital advantage of a less critical role of the background. However, the utility of the neutral-current reaction[2] $\nu + d \rightarrow n + p + \nu$ is unavailable in the LAr approach.

One of the most elusive quests in solar-neutrino science is ν spectrometry of the region $E_\nu = 0.5$—2 MeV, containing vital solar structure information from the decays of

^{7}Be, ^{15}O, ^{13}N, and the (*pep*) reaction.[15] New surprises if any, such as *Q* nuclear burning in the Sun,[16] are most likely to appear here. The recent discovery of the concept of resonant enhancement of ν oscillations in solar matter implies, even for very small flavor-mixing angles, the possibility of drastic distortions at all ν_e energies of the standard solar ν spectrum.[17] The strong energy dependence typical of resonant ν oscillations necessitates spectral data over a very wide ν_e energy range, say from 0.5 to 15 MeV for meaningful interpretation of solar ν results in terms of models of neutrino mixing.

An opportunity to accomplish solar ν spectrometry below 5.885 MeV arises by amalgamating the indium ν_e capture approach[18] into a large LAr detector. In such a low-background ambience, the In ν_e detector can be operated with good signal-to-noise ratio at ν_e energies above 0.65 MeV using the delayed coincidence ($\tau=4.7$ μsec) of the recoil electron e_1 ($E_{e_1}=E_\nu-120$ keV) with a 620-keV γ-ray cascade. (The β decay of ^{115}In with $E_{\beta_{\max}}=0.5$ MeV offers no interference.) Events of such energies have been observed with good resolution in LAr chambers.[5] If In in the form of thin strips is incorporated in the central 10% volume of a large (1 kiloton) LAr chamber, this enclave of low-energy ν spectrometry will be well shielded by the bulk of the LAr detector surrounding it, where high-energy ν spectrometry using Ar(0^+0^+) can be carried out.

"Low"-energy neutrinos from cosmic rays. Recently an examination of the yearly average yield of ^{37}Ar in the ^{37}Cl ν_e detector at Homestake has revealed an apparent anticorrelation with sunspot occurrences and a suggestive correlation with cosmic-ray protons below 5.8 GeV (Ref. 19). These data hint at either a link between surface solar activity and ν production in the core, or that a good part of the ^{37}Ar yield is due to an unknown ν_2 flux above 20 MeV, both of which are extremely intriguing. Independent of this, it has been suggested[20] that monopole catalysis of proton decay in the Sun should result in emission of ν_e characteristic of μ decay, with $E_\nu^{\max}=53$ MeV. If nothing else, these questions indicate the importance of data on neutrinos in the 20—50-MeV range,[21] above the highest solar ν energies predicted by any solar model. These energies lie near the detection threshold of the most sensitive, large proton decay detector at Kamioka. A large LAr detector, on the other hand, would operate almost ideally, both from the Ar(0^+0^+) and the (ν_e,e) scattering detection modes, to examine the spectral as well as directional characteristics of neutrinos in this range. At a minimum, it would provide hard data on cosmic-ray-produced neutrinos in this "low"-energy region.

Neutrinos from supernova collapse. The collapse of massive stars into very compact objects such as neutron stars and the pivotal role of neutrino emission in these catastrophic events have recently been reviewed.[22] It is believed that in the neutronization phase of the collapse, a burst of ν_e with a total energy of $\approx 3\times10^{53}$ ergs is generated, lasting a few msec and with ν_e energies between 15 and 20 MeV. Several msec later, a thermalization burst occurs with an intensity several percent of the initial burst and with a similar time structure and ν energy distribution. The after-burst involves pair emission of neutrinos of all kinds and also contains the bulk of the electron antineutrino $\bar{\nu}_e$ flux. It has been estimated that a stellar collapse might occur every 10—20 years in our Galaxy. Such an event at the center of the Galaxy would produce on Earth a primary burst $\phi_{\nu_e}=10^{12}/\text{cm}^2$ and an after-burst $\phi_{\bar{\nu}_e}=10^{11}/\text{cm}^2$, both occurring on a total time scale of several tens of msec.

The event response of an LAr detector to this transient source can be readily computed and compared to existing light-water (H_2O) Cherenkov detectors operating in this energy range via the (e,ν_e) scattering mode or by ($\bar{\nu}_e$,p) capture on proton. For a 1-kiloton mass of each, using the burst fluxes and cross sections given above, $\sigma(\bar{\nu}_e)=2.44\times10^{-44}\times(E_{\bar{\nu}_e}-2.53)^2$ and $E_{\nu_e}=E_{\bar{\nu}_e}=29.4$ (15 MeV), the H_2O detector would observe 31 (e,ν_e) and 114 ($\bar{\nu}_e$,p) events. The LAr detector would observe 130 Ar(0^+0^+)+31(e,ν_e)=161 ν_e events. A few (3) ($\bar{\nu}_e$,e) events will also occur in both. Thus the H_2O detector is sensitive mostly to the secondary $\bar{\nu}_e$ burst while the LAr detector observes only the primary ν_e burst. The msec transience of the event effectively eliminates background from consideration.

At present, the only large detectors operating at these ν energies are H_2O Cherenkov devices at Homestake (U.S.) (Ref. 23) and Kamioka (Japan) (Ref. 24). A 1-kiloton D_2O Cherenkov detector has been proposed at Sudbury (Canada) (Ref. 2). A 1-kiloton LAr chamber at a suitable location would thus make an ideal network of detectors at widely separated points, observing supernova events with the full complement of ν and $\bar{\nu}$ reaction modes available now. They will be well equipped to characterize in great detail, the progressive development of the collapse on a msec time scale. In addition, the use of a synchronous network of detectors for pinpointing the celestial location of the collapse as well as the possibility of detecting a possible neutrino mass,[25] are well known.

In summary, a large state-of-the-art LAr chamber with its high ν_e capture sensitivity and the relatively less critical role of background sources in its operation, appears to be a potentially powerful and versatile instrument for medium energy neutrino astronomy of steady and transient sources. Combined with the In approach, it should also have an extraordinarily wide energy range reaching from 0.5 to 50 MeV.

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