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Abstract

The β-decay of ^{40}Ti was studied. The Fermi and Gamow-Teller strength function was deduced from the observed β-delayed emission of protons and γ-rays and from the measured half-life of 55(2) ms. The results are compared to shell-model predictions and are used to estimate the neutrino-capture rate of the solar-neutrino detector ICARUS.

23.40.-s, 23.50.+z, 27.40.+z, 96.60.Kx

In the recently proposed ICARUS solar neutrino detector [1], neutrinos interact with ^{40}Ar via scattering and absorption reactions. The ratio between the rates relates to the fraction of non-electron neutrinos from the sun. While neutrino scattering can be described with standard electroweak theory, the situation for absorption is more complex. In principle, the Fermi and Gamow-Teller (GT) contributions to the neutrino-capture rate can be obtained from shell-model considerations, from ^{40}Ar(p,n)^{40}K data, or from the mirror β-decay of ^{40}Ti assuming isospin symmetry. A study of the reaction ^{40}Ar(p,n) [2] has been performed, but the relation between forward-angle (p,n) data and transition strength has been put into question [3]. The attractive feature of the ^{40}Ti β-decay is that its large energy release of (Q_{EC} = 11.68(16) MeV) [4] enables one to extract all GT strength relevant to the solar neutrino detection [5]. Apart from the need for "calibration" of the ^{40}Ar neutrino absorption rate, a study of the ^{40}Ti decay can also provide information on high-energy release β-decay at the beginning of the *fp* shell. Such data can help address the evident discrepancy between β-decay results on the one hand and shell-model calculations and/or charge-exchange reaction data on the other (see e.g. [6]). In a previous study of the ^{40}Ti β-decay, Détraz *et al.* [7] measured β-delayed proton (βp) emission. However, the accuracy of their results was severely limited due to low statistics (only 190 ^{40}Ti ions implanted) and a high proton detection threshold. This motivated us to re-investigate this decay following the "complete spectroscopy" approach [6].

A ^{40}Ti beam was produced by the fragmentation of a ^{58}Ni beam (550 MeV/u, 1×10^9 ions s^{-1}) in a 4 g/cm^2 ^{9}Be target and isotopically separated by means of the projectile fragment separator FRS of GSI Darmstadt. Unambiguous particle identification was achieved by using standard ΔE-TOF techniques and information from position sensitive multi-wire counters. The ^{40}Ti beam was slowed down in a 0.7 g/cm^2 aluminium degrader before being implanted in a stack of eight 300 μm thick, ϕ30 mm silicon detectors at the final focal plane. The number of ^{40}Ti ions identified by their ΔE and TOF was corrected for secondary reaction losses in this degrader. This correction was determined by ΔE-E information from the stack as 13(3)%, in good agreement with a value of 10% calculated with the EPAX code [8]. In total, $1.09(3)\times10^4$ ^{40}Ti ions were implanted during five days of measurement. About 90% of these ions stopped in the central three detectors. The stack was surrounded by 14 Crystal Ball [9] NaI(Tl) γ-ray detectors mounted in close geometry, achieving an overall photopeak efficiency of 15(2)% at 1.33 MeV.

The energy calibration of the silicon detectors was performed by using the known βp radiation of ^{41}Ti [10] implanted as a beam from the FRS. Full proton-absorption spectra were obtained for ^{41}Ti and ^{40}Ti by considering the events recorded in the individual silicon detectors and requiring anti-coincidence with the adjacent stack members. The latter condition rejects penetrating light particles as well as protons which scattered out of the detectors before depositing their full energy. Fig. 1 shows the proton spectrum of ^{40}Ti, obtained under these conditions from the three central detectors, the resultant proton energy resolution being 140 keV FWHM at 3.7 MeV. The βp intensities for ^{40}Ti were determined from this spectrum by using the line-shape parameters deduced from the ^{41}Ti βp data. By comparing the intensities of strong ^{41}Ti βp lines, determined from the full proton absorption spectrum, to the corresponding numbers obtained for the coincidence operation of all silicon detectors, the efficiency for full proton absorption was determined to be, e.g., 82(3) % for a proton energy of 3.7 MeV.

From a one-component fit to the time distribution (relative to the implantation time) of ^{40}Ti-associated βp events (see Fig. 1) , the half-life of ^{40}Ti was deduced to be $T_{1/2}(^{40}\mathrm{Ti})$ = 55(2) ms. This result is in good agreement with, but considerably more accurate than the previously obtained value of 56^{+18}_{-12} ms [7].

A significant (70 events) coincidence relation was observed between 2.5(1) MeV γ-rays, recorded in the NaI(Tl) detectors, and 1.33(2) MeV protons detected in the stack. We interpret this as evidence for a 23(3)% proton branch from the 0^+ ^{40}Sc Isobaric Analog State (IAS) to the $J^\pi = 1/2^+$ excited state at 2.47 MeV in the daughter ^{39}Ca. The proposed levels in ^{40}Sc populated in the β-decay of ^{40}Ti are shown in Fig. 2 together with experimental β branching ratios I_β and the corresponding strengths. Apart from the Fermi transition to the IAS at 4.37 MeV, all other transitions are assumed to be of GT character, feeding 1^+

states. All excited levels of ^{40}Sc decay via proton emission to the ground state of ^{39}Ca and, in the case of the IAS, also to the state at 2.47 MeV. The resulting transition strengths B(F) and B(GT) for Fermi and GT β-decay were deduced for each level i, using the formula [11]

$$[B(F) + B(GT)]_i = 6127(9)s/ft_{1/2}(i),$$

where f is the phase-space factor [12] and $t_{1/2}(i) = \mathrm{T}_{1/2}(^{40}\mathrm{Ti})/I_\beta(i)$.

The sum of the experimental B(GT) values (see Fig. 2), extended up to ^{40}Sc excitation energies of 7.7 MeV, amounts to 3.78(38) compared to the shell-model prediction of 5.62 [5]. This discrepancy is almost entirely due to the fact that the shell-model calculation yields considerably more B(GT) strength at higher ^{40}Sc excitation energies, i.e. above the IAS.

Following a procedure similar to that proposed by Ormand *et al.* [5], we use the data from the present work to calculate the ^{40}Ar neutrino absorption cross section as 6.8(26) SNU. This value agrees with that deduced from the shell-model calculations in spite of the discrepancies mentioned above. Our result, which is the first one based entirely on experimental data, is about 3 times larger than the previously used value of 2.2(7) SNU [13], which only took the Fermi transition into account.

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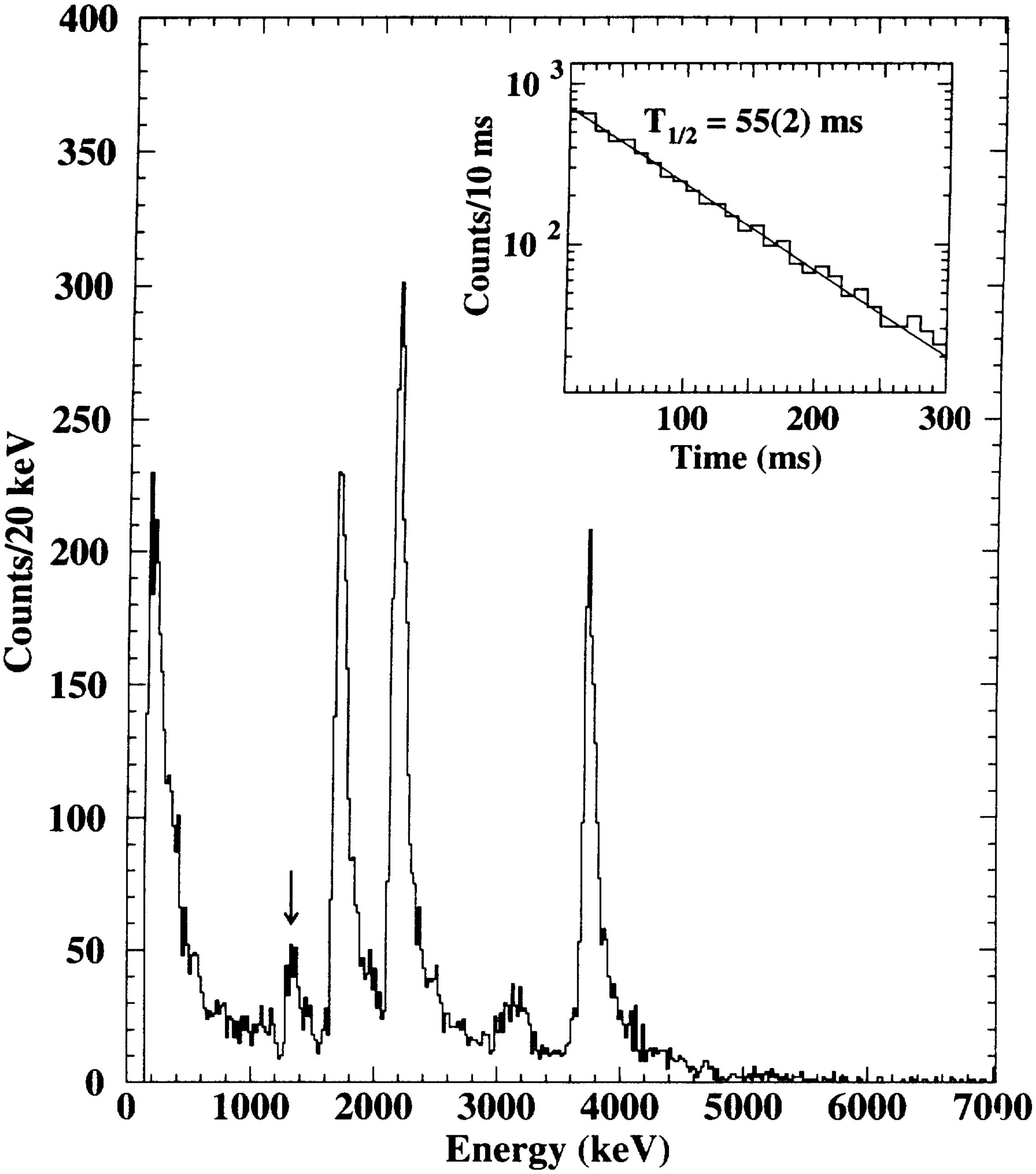
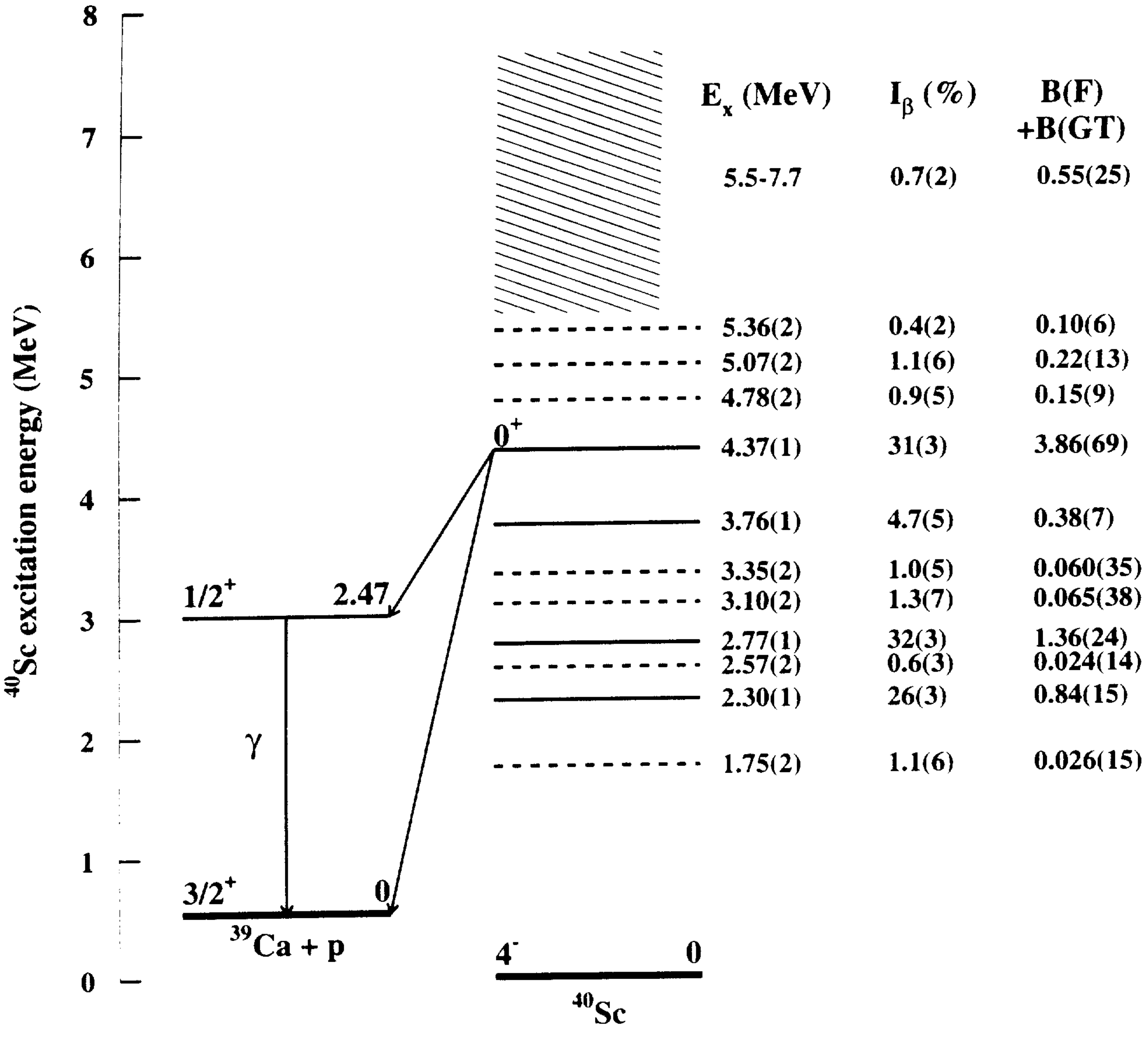


FIG. 1. ^{40}Ti β-delayed proton energy spectrum. The proton peak characterized by coincidences with 2.5 MeV γ-rays is marked by an arrow. The insert shows the time distribution of proton events with energies above 1.5 MeV.



E_x (MeV)	I_β (%)	B(F) +B(GT)
5.5-7.7	0.7(2)	0.55(25)
5.36(2)	0.4(2)	0.10(6)
5.07(2)	1.1(6)	0.22(13)
4.78(2)	0.9(5)	0.15(9)
4.37(1)	31(3)	3.86(69)
3.76(1)	4.7(5)	0.38(7)
3.35(2)	1.0(5)	0.060(35)
3.10(2)	1.3(7)	0.065(38)
2.77(1)	32(3)	1.36(24)
2.57(2)	0.6(3)	0.024(14)
2.30(1)	26(3)	0.84(15)
1.75(2)	1.1(6)	0.026(15)

FIG. 2. Excited levels in ^{40}Sc fed in ^{40}Ti β-decay. J^π assignments are 1^+ except where otherwise indicated. The levels given as solid lines indicate strong βp transitions ($I_\beta \geq 5$ %), whereas those indicated as dashed lines are weak transitions.