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Study of the β decay of Tz=-1 nuclei for nuclear structure and astrophysics and to test the CVC hypothesis

Study of the β-decay of $T_z = -1$ nuclei for nuclear structure and astrophysics and to test the CVC hypothesis

We propose to measure the β-decay of the $T_z = -1$ member of the $T = 1$ triplets, in particular the $T_z = -1$ nuclei ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni, using the Total Absorption Gamma-ray Spectroscopy (TAGS) technique. These measurements are of profound interest for both nuclear structure and nuclear astrophysics.

These nuclei play a critical role in nucleosynthesis pathways in stellar environments, particularly the rp-process (rapid proton-capture process) occurring in supernova explosions and Type-I X-ray bursts [Bla08,Par09]. The β-decay rates of these isotopes, such as ^{42}Ti, influence the flow of nucleosynthesis and determine how matter is transformed into heavier isotopes. Small changes in these rates can significantly alter the final abundance patterns and the rise time of X-ray bursts [Hou23]. These measurements are critical to allow tests of theories that will be used to calculate nuclear properties in stellar explosive conditions.

The decay of these nuclei probes Gamow–Teller (GT) strength distributions. This provides critical data to constrain GT quenching and improve shell-model weak-rate extrapolations used in astrophysical networks. On the other hand, the comparison of these β decays with charge-exchange (CE) reactions carried on the mirror stable nuclei can be used to investigate isospin-symmetry-breaking effects.

Furthermore, the superallowed $0^+ \to 0^+$ Fermi transitions in these nuclei provide stringent tests of the Conserved Vector Current (CVC) hypothesis, contributing to the high-precision determination of the V_{ud} element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix which is a fundamental requirement for testing the Standard Model.

Hardy and Towner presented a comprehensive review of superallowed β decays of 23 nuclei, including ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni, using the experimental results of refs [Mol15,Kur09]. Currently, while ^{46}Cr, ^{50}Fe, and ^{54}Ni have been added to survey tables, their results are not yet precise enough for V_{ud} extraction, and ^{42}Ti still requires more precise half-life and branching-ratio data [Har15,Har20]. Both Hardy and Towner, and Hou et al [Hou23], who have recently measured the Q values of these decays with greater precision, believe that improved measurements of the half-lives and $B(\mathrm{GT})$ distributions should allow them to be included in the determination of V_{ud} and thus contribute to precision tests of the CKM matrix.

The β-decay properties of the nuclei we propose to measure are summarized below.
Parent nucleus ^{42}Ti ($T_{1/2}$ (ms)= 208.34 ± 0.57, Q_β (keV)= 7016.48 ± 0.22)
Daughter nucleus ^{42}Sc ($T_{1/2}$ (ms) = 680.79 ± 0.28, Q_β (keV) = 3751.22)
Parent nucleus ^{46}Cr ($T_{1/2}$ (ms) = 244.3 ± 1.3, Q_β (keV) = 7603 ± 20)
Daughter nucleus ^{46}V ($T_{1/2}$ (ms)= 422.62 ± 0.05, Q_β (keV) = 4882 ± 22)
Parent nucleus ^{50}Fe ($T_{1/2}$ (ms) = 152 ± 6, Q_β (keV) = 8151 ± 8)
Daughter nucleus ^{50}Mn ($T_{1/2}$ = 283.19 ± 0.08, Q_β (keV) = 4583.5 ± 2.2)
Parent nucleus ^{54}Ni ($T_{1/2}$ (ms) = 114.2 ± 0.3, Q_β (keV) = 8790 ± 5)
Daughter nucleus ^{54}Co ($T_{1/2}$ = 193.27 ± 0.04, Q_β (keV) =4351.6 ± 1.6)

We intend to use the TAGS technique to investigate these decays. As indicated above, the primary objective is to measure the β-intensity distribution (I_β) and the β-decay strength $B(\mathrm{GT})$ free from the "Pandemonium" systematic error [Har77], ensuring that high-energy, low-intensity γ-ray cascades are not missed, which is essential for accurate I_β and $B(\mathrm{GT})$ determinations. We also aim to provide additional validation to the technique in the high-energy range through comparisons with CE reaction data in mirror nuclei, and to supply high-precision data on branching-ratios, which currently dominate the experimental uncertainties for these $T_z = -1$ parent decays.

The measurements will be made with the upgraded hybrid Total Absorption Spectrometer (TAS) array which has been developed in the framework of the $(NA)^2$STARS project and will be installed at DESIR. This new hybrid TAS spectrometer will be composed of either DTAS [Tai15,Gua18] or Rocinante [Val17], which was refurbished recently [Orr25], and new $LaBr_3$(Ce) modules arranged in a star configuration.

The proposed beams (^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni) will require beam development. The number of UTs is based on the number of implantations of the parent nucleus required to obtain 10^6 counts in the β-gated TAS spectrum, which represents the optimal goal. A minimum of 10^5 counts in the β-gated TAS spectrum could also be considered for cases where production is more difficult. To estimate counting rates, we assume a 40% detection efficiency for β particles, a total efficiency of 70% for single-γ detection in TAS, and approximately 100% efficiency for γ cascades. Provided that 10 pps are available, 20 UTs should be considered for each nucleus under study. If the beam intensities are higher, the corresponding number of UTs will be scaled down accordingly.

As the daughter nuclei (^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co, respectively) subsequently decay via superallowed Fermi transitions, with half-lives comparable to those of the parent nuclei, the tape cycle cannot be used either to purify the nucleus of interest or to collect the daughter under sufficiently clean conditions. Therefore, to subtract the background arising from the decay of the daughter nuclei, beam time to measure the daughter nuclei, has to be included in the total number of requested UTs and is not yet accounted for.

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