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Anomalies and Sterile Neutrinos – Implications of New Theoretical Results

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Abstract.
The reactor antineutrino and the gallium anomalies have been long unexplained. Possible explanations for both of these anomalies include new physics, such as the existence of one or more eV-scale sterile neutrino. However, the previous theoretical calculations, which do not replicate the experimental results, rely on many simplifying approximations. We have performed shell model calculations in order to gain insights into these issues. In the reactor-antineutrino analysis the beta decays contributing to the cumulative electron spectrum are usually assumed to have allowed spectral shapes. However, many of these decays are actually first-forbidden. Moreover, these decays dominate the experimentally observable region. Based on the recent results, the use of this allowed approximation can at least partially explain the so called reactor antineurtino anomaly. Our new large-scale shell model calculations regarding the neutrino-nucleus scattering cross section off ^{71}Ga decreases the gap between theory and the experimental results of GALLEX and SAGE experiments. Conflict between charge-exchange BGTs and the neutrino-nucleus cross sections can to some extent be explained by destructive interference between Gamow-Teller and tensor contributions.

INTRODUCTION

The reactor antineutrino and the gallium anomalies have been long unexplained. Possible explanations for both of these anomalies include new physics, such as the existence of one or more eV-scale sterile neutrino [1]. Both of these anomalies refer to small discrepancies between theoretical predictions and experimental results. However, the previous theoretical calculations rely on many simplifying approximations [2, 3]. The uncertainties related to these choices is hard to quantify, and thus a reasonable way to proceed is to do new theoretical calculations which do not rely on these approximations.

Reactor antineutrino anomaly refers to the observed 6% deficit in detected antineutrino flux with respect to the theoretical predictions [4, 5, 6] . In addition, precision antineutrino spectra in the 4–6 MeV region seem to show some disagreement in the spectral shape [7, 8, 9]. This bump, or spectral shoulder, has so far been unexplained. The problem with the previous theoretical analyses is all the decays contributing to the cumulative spectra are assumed to be either allowed or forbidden unique decays. However, in the region of interest, 4–6 MeV, the cumulative spectrum is actually dominated by non-unique forbidden decays [10], which can have spectral shapes that are quite different from the allowed and unique decays. In order to treat these decays properly we have performed calculations of these spectral shapes employing the interacting shell model.

The so-called gallium anomaly relates to the findings of the solar neutrino detectors GALLEX [11, 12, 13] and SAGE [14]. The detection efficiency of these detectors was tested using ^{37}Ar and ^{51}Cr radioactive sources. These sources emit discrete-energy electron neutrinos ($E_\nu < 1$ MeV) as they decay via electron capture(EC). The detection of neutrinos is based on the charged-current neutrino-nucleus scattering reaction

$$\nu_e + {}^{71}\mathrm{Ga}(3/2^-)_{\mathrm{g.s.}} \rightarrow {}^{71}\mathrm{Ge}(J^\pi) + e^- \quad (1)$$

to the lowest four (flux from the ^{51}Cr source) or five (flux from the ^{37}Ar source) nuclear states in ^{71}Ge. Gallium anomaly refers to the fact that the experimental total neutrino-nucleus cross section as measured by the GALLEX and SAGE experiments is lower than the theoretical predictions, such as the one given by Bahcall [2]. The issue with the cross-section calculation relates to the use of results from charge-exchange reaction experiments. In order to address these issues, we have performed shell model calculations which give us important insights to the issue.

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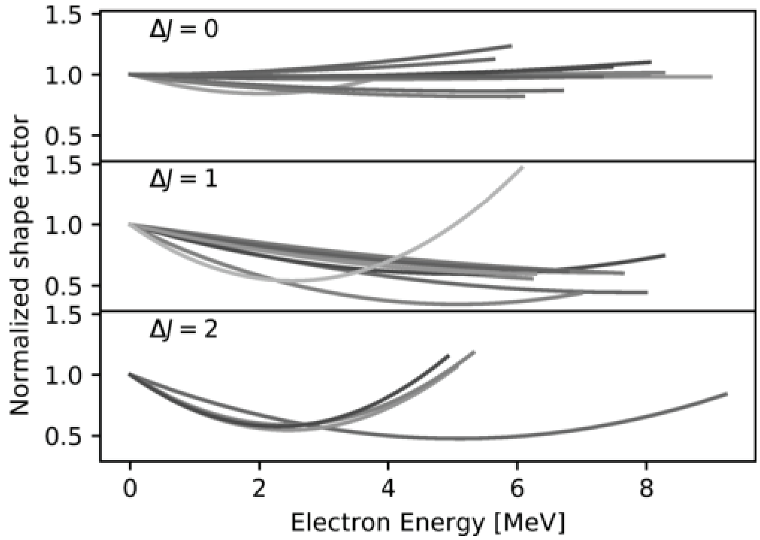

FIGURE 1. The shell model calculated shape factors C as a function of the electron kinetic energy, categorized according the spin-parity change of the transition. For allowed transitions $C = 1$, i.e. the shape factor is constant. Each shape factor was normalized to its value at electron kinetic energy 0 MeV. Results correspond to $g_A = 0.9$ and $\varepsilon_{MEC} = 1.4$ (the latter is meaningful only for $\Delta J = 0$ decays).

REACTOR ANTINEUTRINO ANOMALY

The shape factor for forbidden non-unique beta decays is complicated and depends on the nuclear structure of the initial and final nuclear states which we describe here using the nuclear shell model. We considered in our analysis 29 of the most contributing forbidden decays (see details [3]). The shell model calculations were performed using the computer code NUSHELLX@MSU [15]. For nuclei with $A < 100$ the effective interaction glepn [16] was adopted in a full model space consisting of the proton orbitals $0f_{5/2}$–$1p$–$0g_{9/2}$ and the neutron orbitals $1d$–$2s$. The problematic lighter cases ^{86}Br and ^{89}Br were calculated using the interaction jj45pna [17, 18], in the full model space spanned by the proton orbitals $0f_{5/2}$–$1p$–$0g_{9/2}$ and the neutron orbitals $0g_{7/2}$–$2s$–$1d$–$0h_{11/2}$. For the nuclei with $A = 133$–142 the Hamiltonian jj56pnb [19] was used in the full model space spanned by the proton orbitals $0g_{7/2}$–$2s$–$1d$–$0h_{11/2}$ and neutron orbitals $0h_{9/2}$–$1f$–$2p$–$0i_{13/2}$ for $A < 139$, while for the heavier nuclei the proton orbital $0h_{11/2}$ and the neutron orbital $0i_{13/2}$ were kept empty in order to reduce the computational burden to manageable levels.

The results from the calculations are presented in Fig. 1. It is clear that the allowed approximation is not a good description for almost all the decays. Interestingly, the unique approximation turns out to be even worse for the dominant contributions which are of $\Delta J = 0, 1$ type. When these shape factors are included in reactor antineutrino flux analysis, we see that the uncertainties related to the neutrino flux in the region 4–6 MeV are significantly increased, thus lowering the statistical significance of the reactor antineutrino anomaly. We also see a mitigation of the spectral shoulder. As a conclusion we can say that the forbidden beta decays must be taken into account with out using heavy approximations in order to make strong statements regarding the reactor anomaly.

GALLIUM ANOMALY

The most referenced theoretical calculations for the full ^{71}Ga cross section have been based on the reduced Gamow-Teller transition densities (BGTs) extracted from charge-exchange reactions [2, 20]. In order to get another estimate of this cross section we performed a large-scale shell model calculation for the BGT-values. The Hamiltonian we adopted was JUN45 [21] in the full $0f_{5/2}$–$1p$–$0g_{9/2}$ model space for both protons and neutrons. The reason for this choice was the Hamiltonian's ability to reproduce well nuclear observables such as the energy spectra, magnetic dipole moments, electric quadrupole moments as well as the β-decay half-life of ^{71}Ge. With these wave functions we get the neutrino-nucleus cross sections

$$(5.67 \pm 0.10) \times \text{ cm}^2 \qquad (^{51}\text{Cr source}), \tag{2}$$

$$(6.80 \pm 0.12) \times \text{ cm}^2 \qquad (^{37}\text{Ar source}). \tag{3}$$

These cross sections are 2.5–3% lower than those reported by Bahcall [2], which is enough to reduce the statistical significance of the gallium anomaly from 3σ to 2.3σ. However, the disagreement with the shell model results and the charge-exchange reactions must be still addressed. One well known problem with the charge-exchange reactions are $L = 2$ tensor contributions, which cannot be removed from the data by fitting angular distributions corresponding to different angular momentum combinations of the target and the projectile (the removing of the other components might not be trivial either since large-scale shell model calculations are usually involved). The interference between the Gamow-Teller (GT) and $L = 2$ tensor (T) NMEs can be described by the linear combination

$$\langle f||O_{(p,n)}||i\rangle = \langle f||O_{\text{GT}}||i\rangle + \delta\langle f||O_{L=2}||i\rangle\ , \tag{4}$$

where i (f) is the initial (final) nuclear state and δ is the mixing parameter, which is usually considered to be about 0.1 [22]. The results for the nuclear matrix elements are shown in Table I. The large destructive interference for the $5/2^-$ state is well known [22], making the charge-exchange reaction method problematic for scattering to the $5/2^-$ state. For the ground state the interference is destructive while for the $3/2^-$ state it is constructive. This means that the ratio $\text{BGT}_{5/2}/\text{BGT}_{\text{g.s.}}$ which the charge-exchange reaction analysis uses to determine cross-section for the scattering to the $3/2^-$ state is systematically overestimated (see details [23]). However, this alone is not enough to explain the difference as it stands but it is a step towards explaining the charge-exchange results and ultimately the gallium anomaly.

TABLE I. Results for ^{71}Ga with $\delta = 0.097$ in Eq. (4).

State	$\langle f\|\|O_{\text{GT}}\|\|i\rangle$	$\langle f\|\|O_{L=2}\|\|i\rangle$	$\text{BGT}^{\text{SM}}_{\beta}$	$\text{BGT}^{\text{SM}}_{(\text{p,n})}$
$1/2^-_{\text{g.s.}}$	-0.795	0.465	0.158	0.141
$5/2^-_1$	0.144	-1.902	0.0052	0.0004
$3/2^-_1$	0.100	0.0482	0.0025	0.0027

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