NUCLEAR STRUCTURE STUDIED WITH DIRECT REACTIONS FOR FUNDAMENTAL SYMMETRY TESTS*

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Direct reaction studies provide crucial information on nuclear structure for nuclei that are used in weak interaction and fundamental symmetry tests. Motivated by the superallowed Fermi β-decay studies, we have investigated the structure of ^{50}Cr and ^{62}Zn, the daughters of the superallowed β^+/EC emitters ^{50}Mn and ^{62}Ga, with (p,t) reactions. For both nuclei, we reassigned the location of the first excited 0^+ state. The data for these reassignments are reviewed and limits on the possible $L=0$ transfer to the previously assigned 0^+_2 states are determined. For ^{50}Cr, we find no evidence for the presence of a 0^+ state at 3695 keV. For ^{62}Zn, the data allow for a possible contribution of $L=0$ and $L=2$, indicating a possible

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$0^+/2^+$ doublet of states at 2342 keV. However, this relies on an enhanced cross section at only one data point, and thus the existence of a 0^+ state at this energy is not clear. A preliminary result from a γ–γ angular correlation measurement following the β^+/EC decay of ^{62}Ga weakly favours the existence of a 0^+ state, but requires further study with increased statistics.

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1. Introduction

The structures of nuclei are interesting not only in their own right, but are critical for investigations of fundamental symmetries and searches for physics beyond the Standard Model. Often, it is detailed knowledge of the nuclear wave functions that is required, especially the microscopic configurations involved. Direct reactions are an ideal probe since the extremely-short time scales of the process implies that, ideally, only one interaction with the nucleus takes place. Inelastic scattering, one- and two-nucleon transfer reactions, *etc.*, all provide transition matrix elements that are difficult, if not impossible, to obtain by other means.

We have been carrying out a program of in-depth studies, using direct reactions, of nuclei important for tests of fundamental symmetries and searches for physics beyond the Standard Model. For example, we have performed one- and two-neutron transfer measurements on ^{52}Cr [1] and ^{64}Zn [2, 3] related to the superallowed Fermi β decays of ^{50}Mn and ^{62}Ga, respectively, with the aim to locate the non-analogue 0^+ states, and to provide information on the nuclear wave functions.

2. Superallowed Fermi β decay

Data from superallowed Fermi β decay establishes the most precise determination of the Cabibbo–Kobayashi–Maskawa (CKM) up–down matrix element of $V_{ud} = 0.97417 \pm 0.00021$ [4]. This value is obtained from $V_{ud} = G_{\rm V}/G_{\rm F}$, the ratio of the vector to Fermi coupling strength for weak interactions, where $G_{\rm F}$ is determined from the purely leptonic decay of the muon. The value for $G_{\rm V}$ can be obtained in a number of ways, but most precisely from the $0^+ \to 0^+$ superallowed decays in isospin $T = 1$ triplets via

$$\mathcal{F}t = ft\,(1+\delta_{\rm R})\,(1-\delta_{\rm C}) = \frac{2\pi^3\hbar^7 \ln 2}{2G_{\rm V}^2 m_e^5 c^4\,(1+\Delta_{\rm R})}\,, \tag{1}$$

where $\delta_{\rm R}$ is a transition-dependent radiative correction, $\Delta_{\rm R}$ is a transition-independent radiative correction, and $\delta_{\rm C}$ is a nucleus-dependent isospin-symmetry-breaking (ISB) correction. Although relatively small (a few percent), these corrections are crucial due to the very precise (relative uncertainty of the order of 0.1% or better) experimental ft values [4] that result from a multitude of high-precision half life, branching ratio, and mass/Q-value measurements over the decades [4]. The current limit on the uncertainty on $G_{\rm V}$ is, in fact, dominated by the precision of these theoretical corrections. Consequently, both the precision and accuracy of the corrections have come under scrutiny.

One of the more demanding tests of the accuracy of the calculated corrections (see, *e.g.* Refs. [5–11]) can be conducted for the $\delta_{\rm C}$ values, which can be divided into a part due to the mixing of states with different isospin $\delta_{\rm C1}$ and the mis-match of the overlap in the radial wave functions for the proton and neutron $\delta_{\rm C2}$ such that $\delta_{\rm C} \approx \delta_{\rm C1} + \delta_{\rm C2}$. The isospin mixing correction $\delta_{\rm C1}$ can be approximated as $\delta_{\rm C1} \approx \sum_n \delta^n_{\rm C1}$, where the sum is extended over all non-analogue 0^+ states n. The $\delta^n_{\rm C1}$ values can be deduced by measuring the branching ratios for decay to the non-analogue 0^+ states. This requires knowledge of the location of excited 0^+ states in the daughter nuclei, especially, as is often the case, no discrete γ rays can be observed and only upper limits on their intensity, and hence a limit on the $\delta^n_{\rm C1}$ value, can be established.

3. The ^{52}Cr(p,t) and ^{64}Zn(p,t) two-neutron-transfer reactions

One of the best tools to locate excited 0^+ states in nuclei is the two-nucleon-transfer, *e.g.* (p,t), reaction. Due to the strong preference for the pair of transferred neutrons (or protons in the case of the $(^3{\rm He},n)$ reaction) to couple to spin $S = 0$, a selection rule of $J = L$ is imposed and thus the reaction populates preferentially natural parity states. Excited 0^+ states are usually easily identified due to their unique $L = 0$ angular distribution for the outgoing tritons.

In order to seek excited 0^+ states in the daughter nuclei of the superallowed β^+/EC-emitters ^{50}Mn and ^{62}Ga, we have employed the ^{52}Cr(p,t) and ^{64}Zn(p,t) reactions. The experiments were performed at the Maier–Leibnitz Laboratory of the Technische Universität and Ludwig-Maximilians Universität München. Beams of 24 MeV protons with up to 2 μA current were provided by the tandem accelerator, and bombarded targets of enriched ^{52}Cr and ^{64}Zn. The reaction ejectiles were momentum analysed using the Q3D magnetic spectrograph. Further details are given in Refs. [1, 2]. In the present contribution, we re-examine the assignments made in Refs. [1, 2] regarding the location of the 0^+_2 states. Specifically, we consider limits for inclusion of an $L = 0$ transfer to the angular distributions of the peaks in the triton spectra corresponding to the previously identified 0^+ states at 3694 keV in ^{50}Cr, and 2342 keV in ^{62}Zr.

In both studies, the first excited 0^+ states were reassigned to observed levels at higher energies. In ^{50}Cr, the previous assignment of the 0^+_2 level at 3694 ± 8 keV was based on the result of a (p,t) reaction study performed at a beam energy of 31.4 MeV [12], but was not observed in another study using the same reaction at 27 MeV [13]. The energy of 3694 ± 8 coincides with an assigned state at 3697.6 ± 0.6 keV [14]. Figure 1 displays a portion of the observed triton spectrum at 10° centred near the 3698 keV peak; the typical full-width-at-half-maximum resolution achieved is 8 keV. In our

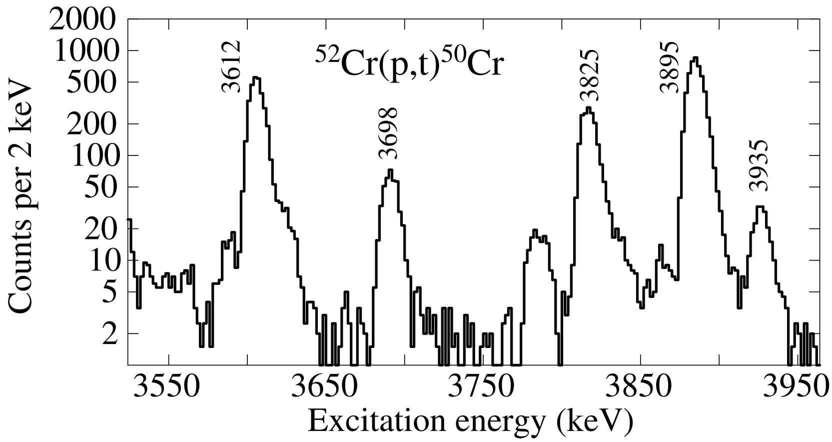

Fig. 1. Portion of the triton spectrum observed at 10° following the $^{52}\mathrm{Cr}(p,t)^{50}\mathrm{Cr}$ reaction using 24 MeV protons. The more prominent peaks are labelled with the corresponding excitation energies in keV.

measurement [1], the observed angular distribution of the 3698 keV peak has the character of an $L = 2$ angular distribution, as shown in the left-hand panel of Fig. 2. Also shown in the figure are fits using theoretical angular distributions, the calculations which are described in Ref. [1], using the FRESCO code and two-neutron amplitudes from a shell-model calculation. The calculations take both the direct di-neutron transfer and the sequential (p,d)–(d,t) processes into account. The curve in black/blue is a single-L fit to the data, whereas that in grey/dark green is the sum of two components, $L = 0$ and $L = 2$, obtained by a least-squares fit with the individual components shown in dotted/red and dashed/red. The normalisation factors required for the $L = 2$ fits are 4.1 and 3.9, respectively. Both fits underestimate the data at the largest angles. The reduced χ^2 values are $\chi^2_\nu = 18.2$ for the one-component fit, and 20.4 for the two-component fit, where the major contribution results from the data point at 40°. While the large value of the χ^2_ν indicates that the model angular distribution does not accurately reproduce the observed cross sections, qualitatively, one can see that there is no substantial improvement in the reproduction of the experimental data adopting a two-component fit, and there is no evidence for an $L = 0$ component. This is confirmed by the $F(\chi^2)$ test, defined as [16]

$$F\left(\chi^2\right) = \frac{\chi^2(n-1) - \chi^2(n)}{\chi^2(n)/(N-n)}\,, \tag{2}$$

where N is the number of data points, and n the maximum number of parameters used (in this case, $n = 2$). The value from the data is $F(\chi^2) = 0.43$, and for the two-component fit to be meaningful at the 95% confidence level, it should exceed 3.4 [16]. Further, no evidence for a possible doublet of states was noted in fits of the peak at 3698 keV.

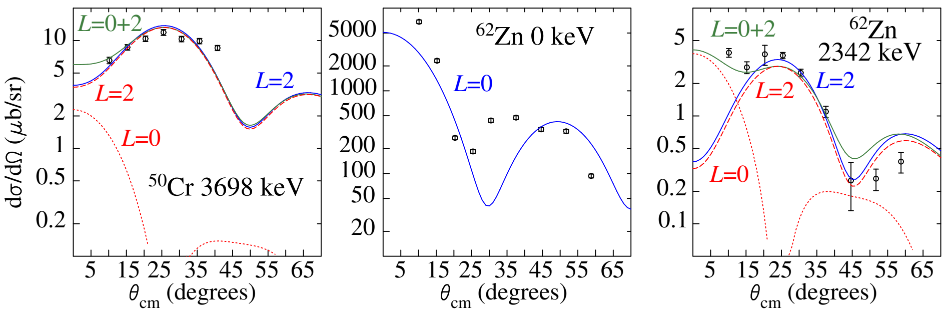

Fig. 2. (Colour on-line) Angular distribution obtained with the ^{52}Cr$(p,t)^{50}$Cr reaction for the 3698 keV level in ^{50}Cr compared with FRESCO calculations (left), those for the ^{64}Zn(p,t) for population of the ground state (centre) and the 2342 keV level in ^{62}Zn (right). The black/blue solid curves show least-squares fits to the data with a single L transfer as indicated, whereas those in grey/dark green are two-component $L = 0+2$ fits, where the individual contributions are shown as dotted lines ($L = 0$) and dashed line ($L = 2$) in red.

The case for the first-excited 0^+ state in ^{62}Zr is more difficult to understand. The level at 2342 keV was assigned by angular correlation analysis of the $0^+ \to 2^+ \to 0^+$ γ-ray cascade following a $(^3\text{He}, 2n\gamma)$ reaction [15]. Our data, however, clearly favoured the presence of an $L = 2$ transition as the major component to the angular distribution. The centre panel of Fig. 2 displays the angular distribution data for the $L = 0$ transition to the ground state, with the right-hand panel data for the 2342 keV peak. While the FRESCO calculations do not provide an exact match to the ground-state data, the data possess a minimum in the cross section at 25°; at this angle, we see a maximum in the data for the 2342 keV level. The two-component $L = 0+2$ fit for the 2342 keV level reproduces the data much better than the fit with $L = 2$ only. This is reflected in the χ^2_ν values of 12.5 and 8.8 for the $L = 2$ and $L = 0+2$ fits, respectively, and the resulting $F(\chi^2) = 4.9$ greatly exceeds the value of 2.62 required for the 95% confidence level for a meaningful improvement of the fit with two components. We note, however, that this improvement is driven exclusively by the datum at 10°; the omission of that point results in χ^2_ν values of 4.6 and 5.0, with $F(\chi^2) = 0.29$, much less than the value of 3.4 required [16]. Figure 3 displays a portion of the triton spectrum containing the 2342 keV peak observed at 10°. There are no indications for the presence of a doublet of states, nor any contaminants that would lead to an excess of counts in the peak.

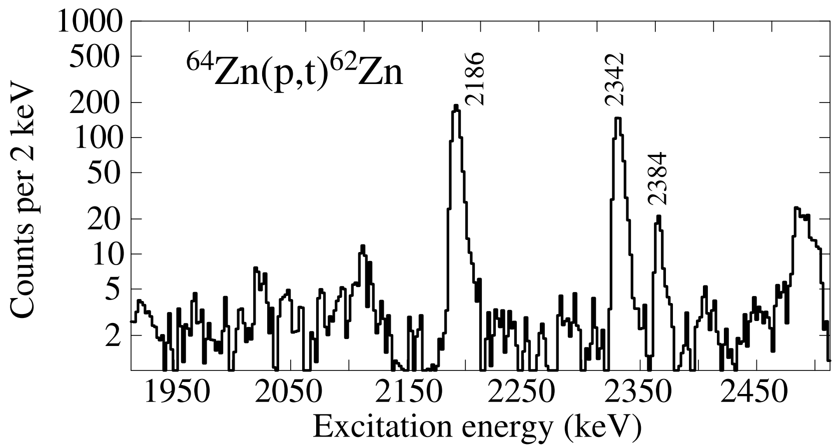

Fig. 3. Portion of the triton spectrum observed at 10° following the ^{64}Zn$(p,t)^{62}$Zn reaction using 24 MeV protons. The more prominent peaks are labelled with the corresponding excitation energies in keV.

An excellent tool to firmly establish spins is via γ–γ angular correlations following β decay. The GRIFFIN spectrometer, consisting of 16 large-volume clover HPGe detectors, located at TRIUMF has demonstrated its sensitivity for γ–γ angular correlations utilizing each Ge crystal independently (see Ref. [17]). Given the uncertainty regarding the spin of the 2342 keV level in ^{62}Zn, a measurement of the decay of ^{62}Ga was performed using GRIFFIN; the results of 1389 keV $\to$ 954 keV angular correlation is shown in Fig. 4. Unfortunately, the rate of the ^{62}Ga beam was much less than expected, with the result that the statistics achieved were insufficient to make a definite assignment, but this early result slightly favours a $0^+ \to 2^+ \to 0^+$ cascade. If this is confirmed in an upcoming re-measurement at TRIUMF, it may imply the existence of a doublet of states at 2342 keV with spins 0^+ and 2^+. One of the more puzzling aspects, however, would be understanding why the $(^3\mathrm{He}, 2n\gamma)$ compound nucleus reaction [15] was insensitive to the decay of the 2^+ state at 2342 keV, but detected the 0^+ state at that energy; experience with such reactions would suggest the opposite situation should have occurred.

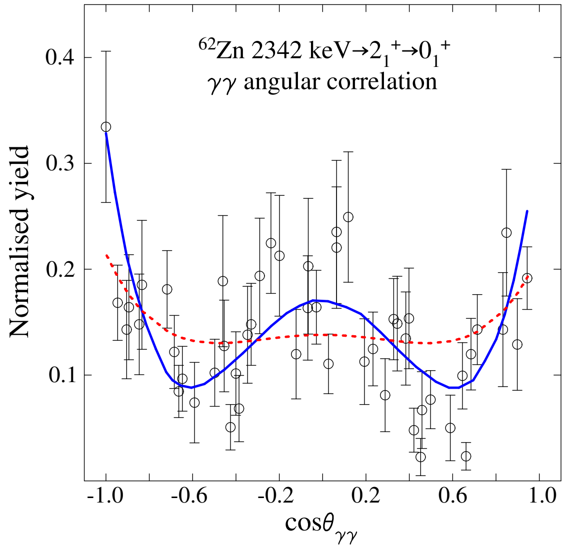

Fig. 4. (Colour on-line) Preliminary results of an angular correlation measurement of the 1389–954 keV γ–γ cascade in ^{62}Zn following the β^+/EC decay of ^{62}Ga performed with the GRIFFIN spectrometer at TRIUMF-ISAC. The curves are results of Geant4 simulations for a hypothetical $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade (solid blue), and a $2^+ \rightarrow 2^+ \rightarrow 0^+$ cascade (dashed red), and not fits to the data except for overall magnitudes.

4. Summary

We have used the (p,t) reaction on targets of ^{52}Cr and ^{64}Zr to seek and identify 0^+ states in the daughters of the Fermi superallowed β^+/EC emitters ^{50}Mn and ^{62}Ga. In both nuclei, we have assigned the 0_2^+ states elsewhere [1, 2]. There is no evidence for the existence of the previously assigned 0_2^+ level in ^{50}Cr; however, the data for ^{62}Zn cannot exclude the possibility of a doublet of states, with 0^+ and 2^+, at 2342 keV. The presence of such a doublet could reconcile the (p,t) data with previous studies. An upcoming ^{62}Ga decay experiment using GRIFFIN at TRIUMF should provide a definitive resolution to this open question.

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