Constraining neutrinoless double $\beta$ decay matrix elements in $^{130}$Te

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Abstract. If a reliable measurement of a neutrinoless double beta decay ($0\nu2\beta$) rate is made, the effective neutrino masses can be determined from the nuclear matrix element. Theoretical calculations of nuclear matrix elements, however, show some disagreement. To test the suitability of various theoretical models, they should be benchmarked against experimentally measured nuclear properties, such as the ground-state distribution of nucleons in the parent-daughter nuclei, and how they change as a result of the decay process. Single neutron-adding reactions have been performed on the $0\nu2\beta$ candidate nucleus, $^{130}$Te. The Macfarlane-French sum rules have then been used to determine the single-particle vacancies. Some quasi-random phase approximations (QRPA) can greatly simplify theoretical calculations by describing the ground state of even-even nuclei using a BCS wavefunction. This assumption has been tested using two-neutron removal, ($p,t$) reactions. The BCS wavefunction appeared to be a valid approximation for valence neutrons.

1. Introduction

There has been considerable scientific effort to observe the neutrinoless double $\beta$ decay ($0\nu2\beta$) process [1, 2, 3]. Half-lives for the process are expected to be large ($10^{26}$yr), and a clear result has thus far proven difficult. The process involves lepton symmetry breaking and could be supported by the existence of a massive Majorana neutrino, however, in the current standard model lepton number is always conserved and the neutrino has zero mass. Recent observations of neutrino oscillations though, do suggest the neutrino has a finite mass [4]. One major consequence a definite observation would have, is that the mass of the neutrino ($m_\nu$) could be determined from the decay rate ($\tau_{1/2}$) by the expression,

$$[\tau_{1/2}^{0\nu}]^{-1} = G_{0\nu}(m_\nu)^2 |M_{if}|^2,$$

where $G_{0\nu}$ is the phase space factor. However, the nuclear matrix elements for the process, $|M_{if}|$, often differ depending on the model being used and even if all models were to agree, this would not automatically imply that they were accurate.
Although there is still considerable discussion as to the best theoretical approach to employ, what undoubtedly must matter is the nuclear valence occupation of protons and neutrons and how they change from parent to daughter nucleus in the decay. The particles in these orbitals and how they are distributed will be vitally important when constructing the initial and final ground-state wavefunctions.

A promising candidate for the decay is $^{130}\text{Te}$, which is the current focus of the CUORE experiment [3]. This report outlines a set of measurements taken on $^{128}\text{Te}$ and $^{130}\text{Te}$ to determine the vacancy of the low-lying single-particle neutron orbitals using single-neutron transfer reactions. The strength of nucleon-adding reactions to a particular set of quantum numbers, $\ell$ and $j$, will be proportional to the vacancy of the corresponding single-particle orbital, and the strength of nucleon removal reactions to the occupancy. The single-neutron adding $^{128,130}\text{Te}(d,p)$ and $(\alpha,^3\text{He})$ reactions have been carried out to determine the vacancy of the nuclear valence orbitals. If confidence is to be obtained from any theoretical model used to determine nuclear matrix elements, it should be able to reproduce these data.

Some QRPAAs assume the ground state of even-even nuclei to be a simple Bardeen-Cooper-Schrieffer (BCS) wavefunction. If this is to be considered a reasonable approximation, pair transfer should only strongly populate the ground-state $\ell=0$ transition [5]. Significant two-nucleon transfer to excited $0^+$ configurations are not consistent with this assumption [6] and would represent a pair vibration. This would raise problems for the QRPA and question its suitability in constructing reliable nuclear matrix elements. To test for the presence of any pair vibrations the two-nucleon removal $^{128,130}\text{Te}(p,t)$ reactions have also been performed on $^{128}\text{Te}$ and $^{130}\text{Te}$. If transfer to any excited $0^+$ configurations is observed that would constitute $\gtrsim 10\%$ of that to the ground state, the simple BCS wavefunction is likely to be fragmented and the consequence for any QRPA calculations is unknown.

2. Experiment

The experiments outlined in this report were carried out at the A.W. Wright Nuclear Structure Laboratory at Yale University. Beams of protons, deuterons, $^3\text{He}$ and $\alpha$ were produced by the ESTU tandem Van de Graaf accelerator and incident on isotopically enriched $^{128,130}\text{Te}$ targets. The reaction products were analysed by an Enge split-pole spectrometer and light reaction products were delivered to the focal plane for detection. The focal plane consisted of a position-sensitive ionisation drift chamber (PIDC) backed by a plastic scintillator.

The product of target thickness and spectrometer entrance aperture was determined using Rutherford scattering. 15-MeV $\alpha$ particles were scattered from both targets and analysed at $20^\circ$. These energies and angles were chosen as calculations using several optical potentials showed deviation from Rutherford scattering to be less than 1%. The spectrometer entrance aperture was then maintained throughout the experiment to reduce systematic errors. This product was used along with the measured beam dose to normalise the reaction yield and obtain absolute differential cross sections.

A 15-MeV deuteron beam was chosen for the $(d,p)$ reactions and measurements were taken at 7, 18, 31 and 42. This energy was chosen to ensure that both incoming deuterons and outgoing protons were well above the Coulomb barrier. The angles correspond to the theoretically calculated peaks in the angular distribution for $\ell = 0, 2, 4$ and 5, corresponding to the angular momentum transfers to single-particle states expected in this mass region. The shape of the cross section distribution would allow for $\ell$ values to be assigned. Previous studies [7, 8] had however, already assigned $\ell$ values to the observed states and our distributions acted as a check.

To better determine the strength of any $\ell = 5$ transfer from the $1h_{11/2}$ orbital, the $(^3\text{He},\alpha)$ and $(\alpha,^3\text{He})$ reactions were performed. A 50-MeV $\alpha$ beam was used for the $(\alpha,^3\text{He})$ reactions and a 40 MeV $^3\text{He}$ beam was chosen for the $(^3\text{He},\alpha)$ reactions. The reaction was measured at
the forward angle of 5\(^\circ\) with another measurement taken at 22.5\(^\circ\). The spectroscopic factors of the \(1h_{11/2}\) orbital are considered more reliable for these reactions due to the better momentum matching for higher \(\ell\) as compared to the (d,p) reactions.

A 23-MeV proton beam was used for the \((p,t)\) reactions and reaction products were analysed at 5\(^\circ\) and 17\(^\circ\). These angles were chosen to roughly correspond to the first maximum and minimum of the angular distribution for \(\ell = 0\). To differentiate between \(\ell = 0\) transfer of 0\(^+\) correlated pairs and all others, an order of magnitude difference in the cross section at these two angles is taken as the key discriminator. Once \(\ell = 0\) states are found, the magnitude of their cross section in comparison to the ground state is considered.

3. Analysis
To determine absolute differential cross sections, a least squares minimisation routine was used. Spectroscopic factors and angular distributions were then found using the Distorted-Wave Born Approximation (DWBA). Optical potentials from a study by An and Cai et al [9] were used for deuterons, and proton potentials were taken from surveys by Bechetti and Greenlees [10]. For \(^3\)He and \(\alpha\), potentials are taken from Reference [11]. Spectroscopic factors are then determined by taking the ratio of the experimentally measured cross section to the theoretical DWBA calculation. Using the Macfarlane-French sum rules [12], a common normalisation is sought that can reproduce the single-particle approximation. Transfer was also carried out on the \(^{128}\)Te nucleus to ensure there is consistency. The summed spectroscopic strength for nucleon adding, using the (d,p) and \((\alpha,^3\)He) reaction, is normalised to reproduce the known total vacancy within the shell in question; for \(^{128}\)Te and \(^{130}\)Te this is 6 and 4, respectively.

4. Preliminary Results
Relative spectroscopic factors have been obtained for states populated in the (d,p) reactions. Once the spectroscopic factors are summed for all states populated and normalised to reproduce the total known vacancy a normalisation of 1.31 is required in the case of \(^{128}\)Te and 1.23 for \(^{130}\)Te. This is consistent across both isotopes to within 6\%. A global normalisation is then applied to the summed strength from each individual orbital that is a mean value of these two. The \(\ell=5\) transfer from the \(1h_{11/2}\) orbital has been considered separately using the \((\alpha,^3\)He) and \((^3\)He,\(\alpha\)) reactions. Only the lowest-lying state was seen in these reactions implying little or no fragmentation of the single-particle strength. The normalisations in this case of 1.76 and 1.77 are consistent to well within the statistical errors of \(\approx 1\%\). Figure 1 shows the results of the preliminary analysis. This analysis is, however, incomplete as data are required from \(^{130},^{132}\)Xe, the (0\(\nu\)2\(\beta\)) daughter nuclei of the decay process.

The analysis of the (p,t) reactions has been completed and the results have been published in Reference [13]. No pair vibrations were found in either the \(^{128}\)Te or the \(^{130}\)Te(p,t) reactions suggesting the the BCS wavefunction is a reasonable approximation for neutrons in the ground state. It has however been noted that in a previous study by Alford et al [14] using the \((^3\)He,n) reactions, large peaks were observed as a the result of \(\ell = 0\) transfer. It is suggested this is the likely consequence a proton subshell which develops at Z=64. As was noted in Reference [13], this is a classic case of a proton pair vibration and suggests potential difficulties for some QRPA matrix elements.

5. Conclusion and outlook
Considering systematic errors (\(\approx 6\%) attributable to the apparatus and the choice of optical model used for the DWBA analysis, the common normalisations obtained are consistent across both isotopes. The same experiments carried out on \(^{128}\)Te and \(^{128}\)Te here have been recently performed on \(^{132}\)Xe and \(^{130}\)Xe, the daughter nucleus of the decay. Once data from this is
analysed it should be combined with this work to create a fuller picture and to give a greater global normalisation.

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