

1-22-2013

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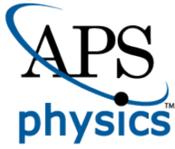
Recommended Citation

Kay, B., Bloxham, T., McAllister, S., Clark, J., Deibel, C., Freedman, S., Freeman, S., Han, K., Howard, A., Mitchell, A., Parker, P., Schiffer, J., Sharp, D., & Thomas, J. (2013). Valence neutron properties relevant to the neutrinoless double- β decay of ^{130}Te . *Physical Review C - Nuclear Physics*, 87 (1) <https://doi.org/10.1103/PhysRevC.87.011302>

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Phys. Rev. C **87**, 011302 — Published 22 January 2013

DOI: [10.1103/PhysRevC.87.011302](https://doi.org/10.1103/PhysRevC.87.011302)

Valence neutron properties relevant to the neutrinoless double β decay of ^{130}Te

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(Dated: December 17, 2012)

The valence neutron composition of the ^{130}Te and ^{130}Xe ground states has been studied with a view to constraining calculations of the nuclear matrix element for the neutrinoless double β decay of ^{130}Te . Single-neutron adding and removing reactions on $^{128,130}\text{Te}$ and $^{130,132}\text{Xe}$ have been used to probe the vacancy of the $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ orbitals. The change in the vacancy of these orbitals, obtained through a self-consistent determination of spectroscopic factors utilizing the Macfarlane-French sum rules, for $^{130}\text{Te} \rightarrow ^{130}\text{Xe}$ is shared only between the d , $s_{1/2}$, and $h_{11/2}$ orbitals, with the $g_{7/2}$ playing no significant role. This is in disagreement with recent calculations within both the QRPA and shell-model frameworks, which show a role for the $g_{7/2}$ orbital that should have been observable. The neutron pairing properties of ^{130}Xe have also been explored through the $^{132}\text{Xe}(p,t)$ reaction showing no evidence for pairing vibrations.

PACS numbers: 23.40.Hc, 25.40.Hs, 21.10.Jx, 27.60.+j

Considerable experimental efforts are being made to observe neutrinoless double β decay ($0\nu 2\beta$). An observation of this process would confirm that the neutrino is indeed its own anti-particle and subsequently yield information on the absolute value of the neutrino mass which no other experiment has done to date. A major obstacle in extracting the neutrino mass from the half-life of this decay is the uncertainty in the nuclear matrix element.

The last decade has seen significant progress in the calculation of nuclear matrix elements for $0\nu 2\beta$ decay. In a 2004 article [1], a summary of matrix element calculations for the $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$ decay showed variation of just over two orders of magnitude. Today the various approaches agree to within a factor of ~ 2 -4 [2]. Obtaining an experimental benchmark for these calculations is not trivial, but there are experimental constraints from other observables that may be placed on the calculations.

There is no *direct* probe which connects the initial and final states of $0\nu 2\beta$ decay, other than the process itself, and so one needs to use other probes to gather the best information possible. Single-nucleon transfer reactions can be used to probe the occupancy and vacancy of valence orbitals which can help characterize the ground-state wave functions. Some aspects of the correlations between nucleons, in particular the BCS-like correlations

between zero-coupled nucleon pairs (which is *assumed* as a starting point in QRPA), can be probed by two-nucleon transfer. The relationship between observable properties of ground states from transfer reactions and the matrix elements has been discussed in Ref. [3] in more detail.

Recent studies of single- and two-nucleon transfer were carried out on isotopes in the $A = 76$ system, where ^{76}Ge is a candidate for $0\nu 2\beta$ decay. Data from neutron-adding and -removing reactions, along with proton-adding reactions, allowed for a detailed description of the energy and vacancy of the ground-state valence orbitals [4, 5]. Neutron pairing correlations were studied at the same time indicating no breaking of the BCS description of the ground state [6]. Within the QRPA framework, subsequent calculations for ^{76}Ge with an adjusted mean field led to a reduction of the matrix element $M^{0\nu}$ by ~ 20 -30% [7-9]. Calculations using the shell model with modified interactions found a 15% increase in the nuclear matrix elements [10]. This reduced the discrepancy between the two approaches by approximately a factor of two. Such approaches have not been applied to other $0\nu 2\beta$ decay candidates. Here we present the first systematic study of neutron transfer reactions on isotopes involved in the $^{130}\text{Te} \rightarrow ^{130}\text{Xe}$ decay. Where possible, reactions on the respective isotones, ^{128}Te and ^{132}Xe , are also studied as cross checks.

The neutron-adding $^{128,130}\text{Te}(d,p)^{129,131}\text{Te}$ reaction has been studied before [11, 12] along with the (t,d) reaction [13]. Neutron-removal reactions have been probed via (p,d) [14], (d,t) [15], and $(^3\text{He},\alpha)$ [16]. Only some of these studies resulted in published cross sections. Further, they were done at different times, using different apparatus and beam energies, and varied prescriptions

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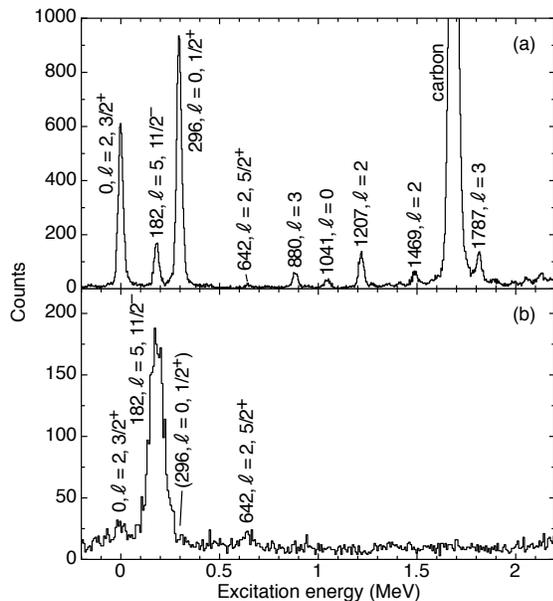


FIG. 1. Spectra from the neutron-adding (d,p) reaction at 15 MeV and $\theta_{\text{lab}} = 34^\circ$ (a) and ($\alpha, {}^3\text{He}$) reaction at 50 MeV and $\theta_{\text{lab}} = 5^\circ$ (b) on the ${}^{130}\text{Te}$ target. States are labeled in keV.

for the analyses, making a systematic consideration of valence occupancies difficult. For the Xe isotopes of interest here, only the neutron-adding (d,p) reaction has been performed on ${}^{132}\text{Xe}$ in inverse kinematics [17]. Given the lack of data for Xe isotopes, and the difficulties in using existing information on the Te isotopes, we carried out a set of consistent, systematic measurements on these targets. The relevant active orbitals between $N = 50$ and $N = 82$ are $0g_{7/2}$, $1d$, $2s_{1/2}$, and $0h_{11/2}$. States are populated through $\ell = 4, 2, 0$, and 5 transfer, respectively. In order to be able to extract reliable information it is important to consider angular-momentum matching conditions. The (d,p) and (p,d) reactions are better matched for $\ell = 0$ and 2 transfer, while the ($\alpha, {}^3\text{He}$) and (${}^3\text{He}, \alpha$) reactions better matched for $\ell = 4$ and 5 transfer.

The measurements were carried out at the A. W. Wright Nuclear Structure Laboratory at Yale University in two separate experiments. The beams were delivered by the Yale tandem accelerator and outgoing ions analyzed by a split-pole spectrograph. A gas-filled position-sensitive detector at the focal plane provided particle identification through ΔE - E measurements and the final momentum of the outgoing ions. Identical approaches to several aspects of the experiments were adopted. These include: a fixed 2.8-msr aperture setting for the spectrograph; beam current integration determined from a Faraday cup at zero degrees; and monitoring of the beam and targets using a Si detector at 30° . The details of each experiment are given below.

The Te isotopes.—The first measurement concerned the properties of the ${}^{128,130}\text{Te}$ isotopes. The targets used were self supporting and of thicknesses 436 and

671 $\mu\text{g}/\text{cm}^2$ for ${}^{128}\text{Te}$ and ${}^{130}\text{Te}$. They were isotopically enriched to 99.2% and 99.4%, respectively. The beam energies were chosen to be well above the Coulomb barrier in both the entrance and exit channels. The (d,p) reaction was carried out at 15 MeV at angles $\theta_{\text{lab}} = 7, 18, 34$, and 42° . The (p,d) reaction was measured at a beam energy of 23 MeV with $\theta_{\text{lab}} = 5, 20, 35$, and 42° . The energies were chosen such that the protons and deuterons from each reaction were at approximately the same energy, allowing a common set of optical-model-potential parameters to be used in the analysis. The angles were chosen to be at the peak of the calculated cross sections for $\ell = 0, 2, 4$, and 5 transfer determined from distorted wave Born approximation (DWBA) calculations. For $\ell = 0$, the maximum cross section is 0° , but 7° was as far forward as practical.

For the high- ℓ states, the ($\alpha, {}^3\text{He}$) reaction was measured at 50 MeV and angles of $\theta_{\text{lab}} = 5$ and 22.5° , and similarly for the (${}^3\text{He}, \alpha$) reaction at 40 MeV at 5 and 22.5° for ${}^{130}\text{Te}$. The ${}^{128,130}\text{Te}(p,t)$ reaction was also measured in the same experiment and the results have been published in Ref. [18]. Typical beam currents of 50-100 nA for protons and 30-60 nA for deuterons were used. For ${}^3,4\text{He}$ beams, the currents were around 10-20 pA. To obtain absolute cross sections, the product of the spectrograph aperture and target thickness was calibrated using α scattering at 15 MeV at a spectrograph angle of 20° . Optical-model calculations show that at this energy and angle, the α -scattering cross section is within 3% of the Rutherford scattering cross section. Typical neutron-adding (d,p) and ($\alpha, {}^3\text{He}$) spectra can be seen in Fig. 1. For these reactions, the Q -value resolution was approximately 30 and 70 keV at FWHM, respectively.

As with previous work [4, 5], detailed angular distributions were not sought. For Te, ℓ values were well known from previous transfer-reaction studies (e.g. [11, 12]), where DWBA calculations reliably reproduced the experimental angular distributions, and for the Xe isotopes the ℓ values of the low-lying states were well known from various studies such as β decay [19]. The ratios of cross sections measured at different angles confirmed previous assignments, as in Ref [4].

The Xe isotopes.—For the Xe isotopes, a cryogenically cooled, solid Xe target was developed for use at the target position of the Yale split-pole spectrograph [20]. Isotopically enriched ${}^{130,132}\text{Xe}$ gas (99.9% for both) was ‘sprayed’ onto a $\sim 360\text{-}\mu\text{g}/\text{cm}^2$ diamond foil where a layer froze. Diamond was chosen because of its high thermal conductivity. The typical thicknesses of Xe layers were from 200-1000 $\mu\text{g}/\text{cm}^2$, determined by scattering measurements for each freezing process as described below. The reactions measured were (d,p) at 15 MeV and angles $\theta_{\text{lab}} = 5, 18$, and 29° along with the ($\alpha, {}^3\text{He}$) reaction at 10° and 50 MeV. The (p,t) reaction was also measured on the ${}^{132}\text{Xe}$ target at 5 and 23° with a proton beam energy of 23 MeV. Typically, the beam currents were 2-10 nA for protons and deuterons and 1-3 nA for α particles—lower than that for the Te targets, in order to minimize

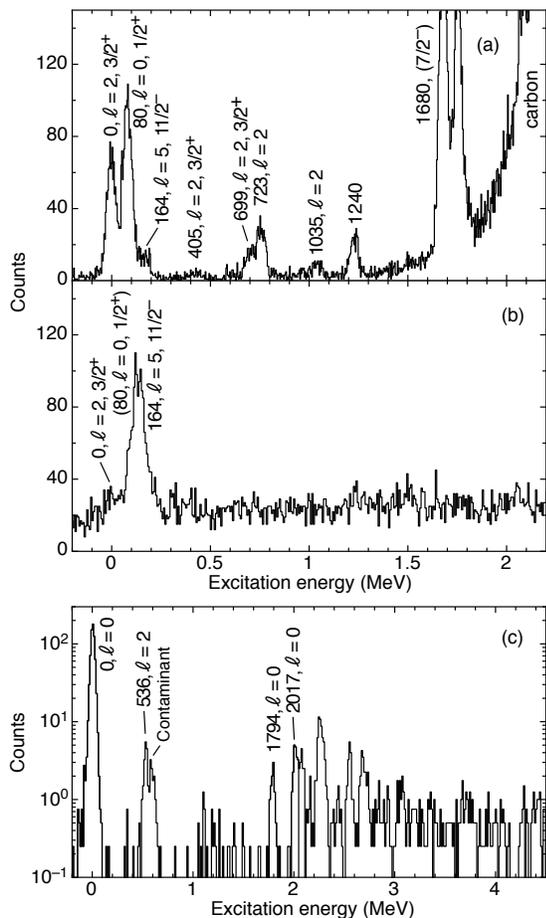


FIG. 2. Spectra from the neutron-adding (d,p) reaction at 15 MeV and $\theta_{\text{lab}} = 29^\circ$ (a) and ($\alpha,^3\text{He}$) reaction at 50 MeV and $\theta_{\text{lab}} = 10^\circ$ (b) on the frozen ^{130}Xe target along with the outgoing triton spectrum from the $^{132}\text{Xe}(p,t)^{130}\text{Xe}$ reaction at 23 MeV and $\theta_{\text{lab}} = 5^\circ$ (c). The 0^+ states following $L = 0$ transfer are labeled. States are labeled in keV.

heat deposition in the frozen Xe, and reduce loss of material. Example neutron-adding (d,p) and ($\alpha,^3\text{He}$) spectra along with the outgoing triton spectrum for the (p,t) reaction are shown in Fig. 2. The Q -value resolution was slightly worse than that for the reactions on Te isotopes due to the diamond foil. For (d,p) and (p,t) reactions, the Q -value resolution was about 60 keV at FWHM and ~ 100 keV for ($\alpha,^3\text{He}$).

Several steps were taken to ensure the Xe target thickness was well calibrated and monitored to account for any loss of material. Rutherford elastic scattering was measured at 8 MeV and 25° , then immediately followed by another measurement of (d,d) scattering at the energy where we ran the (d,p) reaction, 15 MeV, but at the same angle of 25° . This provided a normalization between (d,d) scattering in the Rutherford regime and at higher energies. Simultaneous measurements of scattered deuterons were made at the focal plane of the split-pole spectrograph and in the Si monitor detector. The ra-

tio of the counts in the peak from elastic scattering in the monitor detector to the integrated beam current was determined and scaled to the same data in the (d,p) measurement. A similar procedure was performed for each reaction.

Two-neutron transfer.—A recent publication [18] reported on the two-neutron removal (p,t) reaction on $^{128,130}\text{Te}$. The (p,t) reaction shows particularly large cross sections for transfer to a coherent state in the final nucleus in which BCS-like correlations cause zero-coupled pairs of neutrons to be well localized and have strong overlaps with the singlet s state in the triton, thus providing an excellent probe of pairing correlations. The characterization of the ground state as a simple BCS condensate is a starting point in QRPA calculations, and this assumption may not always reflect reality [3]. Large cross sections for neutron-pair transfer to excited states are evidence of pair vibrations, and a break down of the BCS approximation. For the Te isotopes, the proton-pair adding ($^3\text{He},n$) reaction is clear evidence that for *protons* the simple BCS approximation is not valid in this region of nuclei [21]. However, for neutrons, in the measurement reported here on ^{132}Xe , shown in Fig. 2, and on $^{128,130}\text{Te}$ in [18], essentially *all* the $\ell = 0$ neutron-pair-removal cross section is to the ground state and excited 0^+ states have only a few percent of the ground-state cross section. This is an indication that, for neutrons, the simple BCS approximation is reasonable.

Single-neutron adding and removing.—Spectroscopic factors were extracted from the absolute cross sections at the respective maxima in the angular distributions for a given j^π using the expression $S' \equiv \sigma_{\text{exp}}/\sigma_{\text{DWBA}}$ where S' is the absolute or *unnormalized* spectroscopic factor and σ_{DWBA} is from DWBA calculations carried out using the finite-range code Ptolemy [22]. Absolute spectroscopic factors have to be treated with caution as they are sensitive to reaction-model parameters, particularly the bound-state radii used. However, relative spectroscopic factors are typically more robust. They can be normalized utilizing the Macfarlane-French sum rules [23] such that $N_j \equiv S'/S$ where

$$N_j \equiv [\Sigma(2j+1)C^2 S'_{\text{adding}} + \Sigma C^2 S'_{\text{removing}}]/(2j+1). \quad (1)$$

C^2 is the isospin-coupling Clebsch-Gordan coefficient. This prescription has been demonstrated to yield self-consistent, quantitative nuclear-structure information both in the measurements on Ge and Se [4, 5], and in recent studies with the Ni isotopes [24]. This suggests that while, strictly speaking, spectroscopic factors are not ‘observables’, their properties are reflected in the occupancies and vacancies extracted from experimental data, and satisfy simple consistency checks. For the $j^\pi = 1/2^+$, $3/2^+$, and $5/2^+$ states the spectroscopic factors from the neutron-adding (d,p) reaction and neutron-removing (p,d) reaction on the $^{128,130}\text{Te}$ isotopes were used to calculate the normalization N_j . Due to ambiguities in assigning j^π for the $\ell = 2$ transitions they were analyzed as the sum of both, though they most likely belong to the

$1d_{3/2}$ orbital. For the high- j states, spectroscopic factors from the $(\alpha, {}^3\text{He})$ and $({}^3\text{He}, \alpha)$ reactions on ${}^{130}\text{Te}$ were used for the normalization. The normalizations derived from *both* the adding and removing reactions on the Te isotopes were then applied to the spectroscopic factors extracted from the Xe data using the same bound-state and optical-model parameterizations.

TABLE I. Neutron vacancies.

	$2s_{1/2}$	$1d_{3/2,5/2}$	$0g_{7/2}$	$0h_{11/2}$	Total
${}^{128}\text{Te}$	0.72	2.06	0	3.34	6.13
${}^{130}\text{Te}$	0.50	1.45	0	2.21	4.16
${}^{130}\text{Xe}$	0.56	2.71	0	2.99	6.26
${}^{132}\text{Xe}$	0.26	1.96	0	1.77	3.99

In the DWBA calculations for the (d,p) and (p,d) reactions, the deuteron was characterized by a Reid wave function while for the $(\alpha, {}^3\text{He})$ and $({}^3\text{He}, \alpha)$ reactions, the projectile bound states were calculated using a Woods-Saxon form with $r_0 = 1.2$ and $a_0 = 0.65$. For the wave function in the target, the well depth was varied to reproduce the binding energy using a $r_0 = 1.28$, $a_0 = 0.65$ Woods-Saxon form with an added spin-orbit term with $V_{\text{s.o.}} = 6.20$, $r_{\text{s.o.}} = 1.10$, and $a_{\text{s.o.}} = 0.75$. For the (d,p) and (p,d) reactions, global optical-model parameters were used for the incoming and outgoing channels. For deuterons, those of An and Cai [25] were used and for protons those of Becchetti and Greenlees [26]. Both have smooth E_{beam} , A , and $N - Z$ dependencies. For the ${}^{3,4}\text{He}$ -induced reactions the fixed (non-varying) optical-model parameters of Ref. [27] were used.

The extracted normalization was 0.57(5) for the (p,d) and (d,p) reactions and used to determine the normalized spectroscopic factors for $\ell = 0$ and 2 transitions. For the ${}^{3,4}\text{He}$ -induced reactions the normalization was 0.41(4) as determined from the $h_{11/2}$ strength. The extracted neutron vacancies are shown in Table I and plotted in Fig. 3 and, as before [4, 5], they are self-consistent at the level of a few tenths of a nucleon.

In a recent experiment, data were obtained in a systematic study of neutron-adding on the $N = 50$ isotones [28]. The final states probe the same neutron orbits, but below $Z = 50$ and may be used as a cross check. Using the same DWBA model parameterizations as those in the present study, an independent cross check was made. The normalization for the low- j states was 0.63(3) for both $\ell = 0$ and 2 strength from the (d,p) reaction on $N = 50$ targets, in reasonable agreement with 0.57(5) found here. A similar value of normalization, $N_{\ell=1} = 0.55(2)$, was found in recent work on the Ni isotopes [24] for $\ell = 1$ with the same distorting parameters. These normalization values are reasonably consistent with each other. For ${}^{3,4}\text{He}$ induced reactions, it appears the normalizations vary a little more, perhaps reflecting the fact that there is no energy, A , and $N - Z$ dependence in the optical-model parameters used in this analysis. The work of

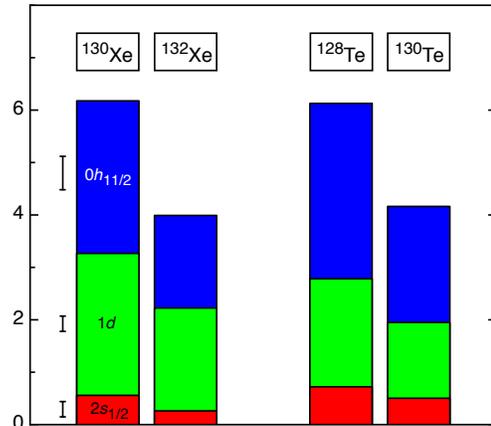


FIG. 3. (Color online) Experimentally determined neutron vacancies for the active orbits in ${}^{130}\text{Te}$ and ${}^{130}\text{Xe}$ along with ${}^{128}\text{Te}$ and ${}^{132}\text{Xe}$, which were used as systematic checks for the normalizations. Estimated uncertainties are shown on the left-hand side of the plot.

Ref. [28] found $N_{7/2} = 0.55(1)$ while $N_{11/2}$ could not be extracted due to significant missing strength. Here, $N_{11/2} = 0.41(4)$. A further test of the $\ell = 5$ normalization would be desirable. If one were to take the difference between 0.41 and 0.55 as representing an uncertainty, it would correspond to a $\sim 30\%$ uncertainty in the absolute values of the $h_{11/2}$ vacancies in Table I, but these would be correlated between the four targets. Thus, it would amount to a change of less than 0.1 neutrons in the $h_{11/2}$ component of the neutron *difference* shown in Fig. 4.

The uncertainties in the extracted neutron vacancies are difficult to estimate. The statistical errors on cross sections extracted from the experimental yields have uncertainties of less than 1% and 3% for strong states, and less than 3% and 5% for weaker ones, for reactions on Te and Xe, respectively. The use of near identical conditions between the two experiments leads us to believe the relative systematic uncertainties between targets is under 10%, and dominated by the instability of the effective thickness of the frozen xenon layers. As to possible missing strength when extracting the normalizations, the reliability of the normalizations, the assumptions inherent in the DWBA and various distorting parameters, these are similar to previous experiments [4, 5, 24]. The summed spectroscopic strength across the four isotopes, seen in Table I, gives some measure of the consistency and reliability. We therefore estimate an uncertainty in the neutron vacancy of approximately ± 0.2 for the $s_{1/2}$ and d orbitals, and ± 0.3 for the $h_{11/2}$ orbital.

In the neutron-adding $(\alpha, {}^3\text{He})$ reaction on both ${}^{128,130}\text{Te}$, no $g_{7/2}$ strength was observed over the measured range (up to about 4 MeV in excitation energy). In the literature [19], there are $7/2^+$ states reported in ${}^{131}\text{Te}$ and ${}^{131}\text{Xe}$ at 943 and 637 keV, respectively. As can be seen in Figs. 1 and 2, there is little evidence of peaks at these energies (an peak with ~ 40 counts in these spectra

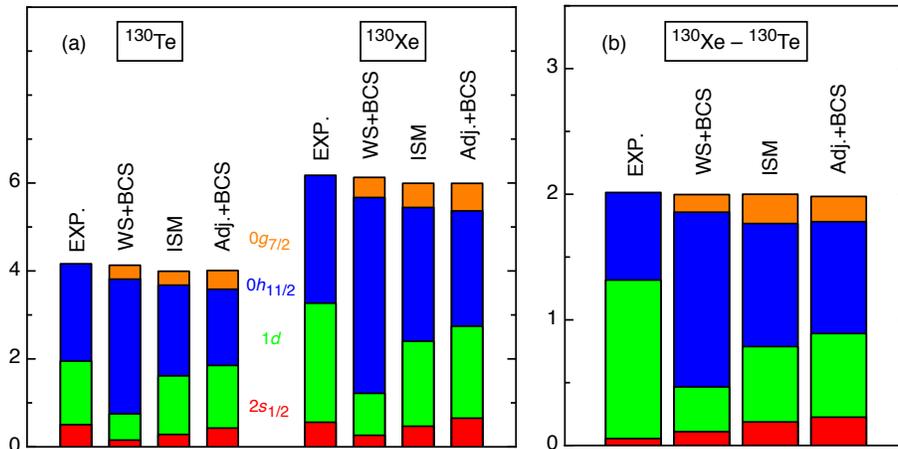


FIG. 4. (Color online) A comparison of experimentally determined neutron vacancies for the active orbits in ^{130}Te and ^{130}Xe with calculations presented in Ref. [29] and labeled as in the reference (a), and the difference between the final and initial ground-state neutron vacancies (b). The experimental uncertainties on the vacancy are approximately ± 0.2 for the $s_{1/2}$ and d orbitals, and ± 0.3 for the $h_{11/2}$ orbital, as discussed in the text.

would amount to less than a tenth of one nucleon in vacancy, which is less than the experimental uncertainty). Similar was true for the ($^3\text{He},\alpha$) reaction, over the measured range of ~ 5 MeV in excitation energy. We estimate that we are sensitive to $\ell = 4$ cross sections down to a few percent of the dominant $h_{11/2}$ state (to ~ 0.1 mb/sr) or about a vacancy of 0.15 nucleons, which is within the estimated uncertainty. As such, the experimental data suggest the neutron $0g_{7/2}$ orbital is fully occupied and is not playing an active role in the difference between the initial and final ground-state wave functions. The only orbitals active are the $1d$ and $0h_{11/2}$ orbitals, and to a lesser extent the $2s_{1/2}$ orbit. Recent theoretical calculations using both QRPA [29] and the shell model [30] suggested that the $g_{7/2}$ plays a non-zero role, and the calculations also appreciably underestimate the role of the d orbitals as shown in Fig. 4. It remains to be seen whether modifying these calculations, to bring them into better agreement with the data, will result in a change in the magnitude of the matrix element similar to that seen in the $^{76}\text{Ge}\rightarrow^{76}\text{Se}$ system.

Proton transfer reactions have not yet been studied, but form part of a future experiment. Previous data from the $^{128,130}\text{Te}(d,^3\text{He})^{127,129}\text{Sb}$ reaction [31] are available. A comparison of these experimental data with the existing calculations show some disagreements with the calculations. No proton $h_{11/2}$ strength is seen experimentally, perhaps a consequence of the $Z = 64$ subshell gap, while this orbital does play a role in the calculation of the nuclear matrix element [29, 30].

In summary, the valence-neutron properties of $^{128,130}\text{Te}$ and $^{130,132}\text{Xe}$ have been studied through single-nucleon transfer, the latter making use of a cryogeni-

cally cooled, frozen-xenon target. The data suggest the change in the ground-state neutron vacancies for the $^{130}\text{Te}\rightarrow^{130}\text{Xe}$ system is dominantly in the d and $h_{11/2}$ orbitals. The $g_{7/2}$ orbital appears not to play a role. For $^{76}\text{Ge}\rightarrow^{76}\text{Se}$ [4, 5] we found significant differences in which the valence orbits participate in the double beta decay process. When the calculations were modified they substantially reduced the uncertainty in the various calculations e.g. [7–10]. In $^{130}\text{Te}\rightarrow^{130}\text{Xe}$, the subject of one of the major experiments under way searching for this exotic decay mode, we again find that the valence orbits participate substantially differently from what is in the existing QRPA and shell-model calculations. The consequences might well be comparable to those found in $^{76}\text{Ge}\rightarrow^{76}\text{Se}$ and could have substantial impact on conclusions drawn from measurements with CUORE [32]. Neutron-pair transfer shows no sign of neutron pair vibrations and thus the assumption that the ground state may be represented by the BCS approximation appears to be reasonable.

The complete dataset is available on the Experimental Unevaluated Nuclear Data List (XUNDL) database [33].

The authors would like to thank the Yale operations staff and J. P. Greene for the fabrication of the Te targets. This work was supported by the U.K. Science and Technology Facilities Council; the U.S. Department of Energy, Office of Nuclear Physics, under Contract Nos. DE-AC02-06CH11357 (Argonne) and DE-AC02-05CH11231 (Berkeley); Grant Nos. DE-FG02-91ER40609 and DE-FG02-04ER41320 (Yale); and NSF Grant No. PHY-08022648 (JINA).

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