PHYSICAL REVIEW C **82**, 027308 (2010)

Pair correlations in the neutrinoless double-β decay candidate ^{130}Te

T. Bloxham,[1,*] B. P. Kay,[2] J. P. Schiffer,[2] J. A. Clark,[2] C. M. Deibel,[2,3] S. J. Freeman,[4] S. J. Freedman,[1] A. M. Howard,[4]
S. A. McAllister,[4] P. D. Parker,[5] D. K. Sharp,[4] and J. S. Thomas[4]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48825, USA*
[4]*Schuster Laboratory, University of Manchester, Manchester, M13 9PL, United Kingdom*
[5]*A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA*
(Received 7 June 2010; published 16 August 2010)

Pair correlations in the ground state of ^{130}Te have been investigated using pair-transfer experiments to explore the validity of approximations in calculating the matrix element for neutrinoless double-β decay. This nucleus is a candidate for the observation of such decay, and a good understanding of its structure is crucial for eventual calculations of the neutrino mass, should such a decay indeed be observed. For proton-pair adding, strong transitions to excited 0^+ states had been observed in the Te isotopes by Alford *et al.* [Nucl. Phys. A **323**, 339 (1979)], indicating a breaking of the BCS approximation for protons in the ground state. We measured the neutron-pair removing (p,t) reaction on ^{130}Te and found no indication of a corresponding splitting of the BCS nature of the ground state for neutrons.

DOI: 10.1103/PhysRevC.82.027308 PACS number(s): 25.40.Hs, 23.40.−s, 27.60.+j

I. INTRODUCTION

One of the key challenges to modern physics is the determination of the neutrino masses. It is now clear that neutrinos must have mass from observations of neutrino oscillations [1–3]. The mass differences are known, but only limits exist for the absolute mass scale. These limits are imposed by analysis of the details of the microwave background by the Wilkinson Microwave Anisotropy Probe combined with the Two-Degree-Field Galaxy Redshift Survey [4], and place upper limits on the combined masses of the three neutrinos of 0.7–1.7 eV [5].

The question then arises of how to establish the absolute mass scale for neutrinos. There are direct approaches, such as the measurement of the shape near the endpoint of the tritium β-decay spectrum, which should be sensitive to the electron neutrino mass if it were greater than 0.2 eV [6]. An alternate approach would be if the massive neutrinos were indeed of Majorana character and the lepton-number violating neutrinoless double-β decay process $(0\nu\beta\beta)$, $(Z, A) \rightarrow (Z+2, A) + 2e^-$, were to compete with the lepton-number nonviolating decay mode $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\overline{\nu}$. The decay rate of the former is proportional to the effective neutrino mass squared:

$$\left(t_{1/2}^{0\nu}\right)^{-1} = a_{0\nu} F_{0\nu} |M_{0\nu}|^2 \frac{\eta^2}{\log(2)}, \qquad (1)$$

where the half-life $\tau_{1/2}^{0\nu}$ is related to the nuclear matrix element for the decay, $M_{0\nu}$, the effective mass of the electron neutrino, η, and a phase-space factor, $a_0 F_{0\nu}$ [7].

The calculations of the nuclear matrix elements for this process are difficult. They involve not only the wave functions of the initial and final states but require a summation over all possible intermediate virtual states. The momentum transfer in the neutrinoless mode is large and thus many intermediate states and multipolarities are involved. This is unlike the two-neutrino double-β decay where the virtual momentum transfer is small and only a few intermediate states contribute significantly. To handle all this complexity most of the calculations that have been carried out are conducted through the quasiparticle random phase approximation (QRPA), in which several simplifying assumptions are made (see Ref. [8] for a summary and references therein). One of these is that the initial and final states (ground states of even-even nuclei) can be described in terms of a BCS sea of neutron pairs and another of proton pairs. Shell-model calculations do not make this assumption [9].

The best experimental probe of pair correlations is pair-transfer reactions such as (p,t) and $(^3\text{He},n)$, in which a localized pair of neutrons or protons is removed from or added to their respective BCS seas. If the BCS approximation is a valid description of the ground states, essentially all the $\ell = 0$ pair-transfer strength in these reactions will proceed to the ground states and almost none to excited 0^+ states. Appreciable strength to excited states is a measure of a breakdown of the BCS approximation. This can happen when there is a gap in valence orbits that is larger than the pairing interaction inducing the correlations. In such a case only the BCS condensate from the lower valence orbits will be represented by the ground state and a second correlated 0^+ state appears at higher excitation energy and may be considered as a BCS condensate of the upper valence orbits. Sometimes this is referred to as a pairing vibration [10].

Here we consider the pairing aspects of the ground states of tellurium nuclei that are expected to be good potential candidates for the experimental observation of neutrinoless double-β decay. For example, the decay of the ^{130}Te nucleus is the subject of the CUORE experiment [11]. The ^{128}Te measurement was included for comparison. The measurements

---

[*] tbloxham@lbl.gov

discussed here are relevant to the validity of the BCS approximation for the ground states of ^{128,130}Te in the calculation of the nuclear matrix element for double-β decay. Because the decay involves removing a pair of neutrons from the parent nucleus and adding a pair of protons, we have explored the neutron pair-removal process from measurements of the (p,t) reaction on targets of ^{128,130}Te and we discuss the results with reference to a previous proton-pair transfer experiment [12]. The (p,t) reaction on ^{128,130}Te has been performed twice before [13,14]; however, the former covered insufficient angle range to reliably identify $\ell = 0$ transitions, and the latter focused only on transitions to negative-parity states. Similar measurements for another neutrinoless double-β decay candidate, ^{76}Ge, had been carried out by Freeman *et al.* [15] and no strong transitions to 0^+ excited states were observed in the relevant Ge and Se isotopes; the complementary proton-pair-adding measurement has not yet been performed.

II. METHODOLOGY

The beam energy was selected such that both protons and tritons would be well above the Coulomb barrier; 23-MeV protons from the Yale tandem Van de Graaf accelerator were used for the (p,t) measurements. Light ions from the reaction were momentum analyzed using the Yale split-pole spectrograph and detected and identified in a gas-filled focal plane detector. To determine the target thickness, elastic scattering of 15-MeV α particles was measured at 20° using the spectrograph, well within the Rutherford regime, with the same targets in the same position, using the same setting on the beam-current integrator and the same solid angle on the spectrograph, to obtain accurate relative and absolute cross sections. Throughout the experiment, a Si surface barrier detector at 30° to the beam direction was used to monitor elastic scattering and, in turn, target thickness.

The experiment was performed at several forward angles to identify transitions with zero angular-momentum transfer to states above the ground states. The targets were evaporated onto thin carbon backings and were 416-μg/cm^2 thick for ^{128}Te and 645-μg/cm^2 thick for ^{130}Te.

The $\ell = 0$ (p,t) transitions are the strongest in the spectrum of final states at very forward angles and the distorted wave Born approximation (DWBA) works best at those angles. It was therefore desirable to carry out measurements at as forward angles as possible, which in this case was 5°. Spectra were also measured at 11°, 17°, and 22°. It is straightforward to select and characterize transition peaks as corresponding to 0^+ states based on their angular distributions, and our results also confirm assignments from the literature. DWBA calculations, carried out using the PTOLEMY code [16], are shown in Fig. 1, with optical-model parameters for protons from Perey [17], and triton potentials from Perry [18]. The exact shapes of these curves, such as the ratios of the sharp forward maximum for $\ell = 0$ to the first minimum, depend sensitively on the details of the potentials and are not relevant in the present context. Nevertheless, the ratio of the cross sections between, for instance 5° and 17° is always at least an order of magnitude larger for $\ell = 0$ than it is for $\ell = 2, 3,$ or 4 and provides a robust signature of 0^+ states.

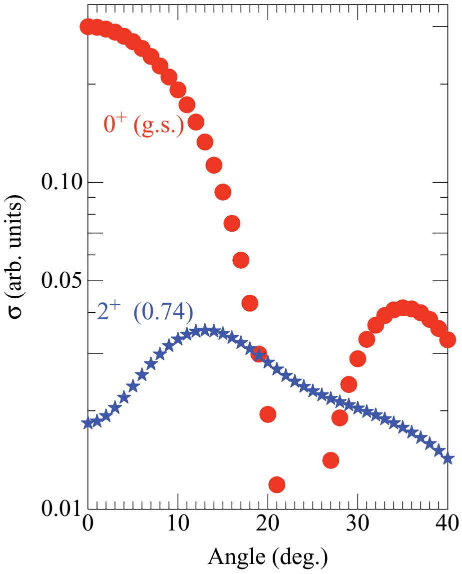

FIG. 1. (Color online) Calculated angular distributions for the ground-state 0^+ transition and for the 2^+ excited-state transition in ^{130}Te$(p,t)^{128}$Te reaction.

III. RESULTS

It can be seen from Fig. 2 that for neutron-pair removing reactions the cross section for excited 0^+ states is very small, which is consistent with the BCS approximation for the ground states that is implicit in the QRPA calculations used in the

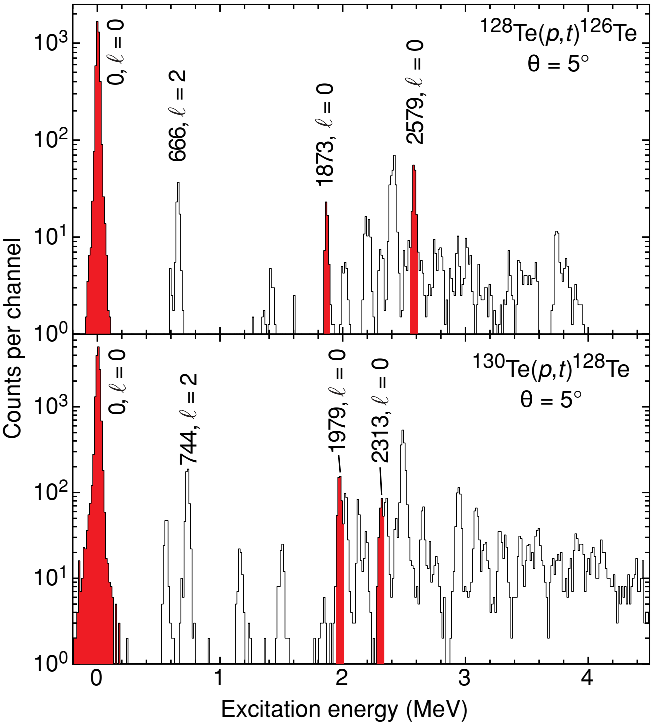

FIG. 2. (Color online) Outgoing triton spectra from neutron-pair transfer reactions on ^{128}Te (top) and ^{130}Te (bottom) at 5°. The excitation energies, and ℓ transfer, are labeled for states of interest and $\ell = 0$ states are shaded (red online).

TABLE I. Cross sections for 0^+ states populated in neutron-pair removing and proton-pair adding reactions on ^{128}Te and ^{130}Te. Those quoted for neutron-pair removal are for $\theta_{\text{lab}} = 5^\circ$ and have systematic uncertainty of ∼7%, while those quoted for proton-pair addition are at $\theta_{\text{lab}} = 0^\circ$ and are taken from Ref. [12]. Energies are taken from Ref. [19] unless otherwise stated.

Reaction	E (MeV)	σ (mb/sr)	Ratio[a]	Normalized strength[b]
^{128}Te(p,t)	0	4.21	90	1.21
	1.873	0.06	20	0.02
	2.579	0.15	21	0.04
^{130}Te(p,t)	0	3.49	89	1.00
	1.979	0.05	50	0.01
	2.313(4)[c]	0.05	>20	0.01
^{128}Te(^{3}He,n)	0	0.24	–	0.96
	2.13	0.095	–	0.32
^{130}Te(^{3}He,n)	0	0.26	–	1.00
	1.85	0.098	–	0.34
	2.49	0.062	–	0.21

[a] Ratio of 5° to 17° cross sections, for the (p,t) reaction only.

[b] Cross sections corrected for the DWBA dependence and normalized to the ground-state transition from ^{130}Te.

[c] State newly identified in this work and assigned as 0^+. The ratio is a lower limit as this peak is obscured by the adjacent one at 17°.

calculation of double-β decay matrix elements. The only observed cross sections from reactions on ^{128}Te to 0^+ excited states are transitions to the 1.873-MeV excited state of ^{126}Te and another to one at 2.579 MeV; they are less than 4% of the ground-state strength. Both of these states have been reported previously, though the only available data are the energies and cross sections at 30° [13,19]. There are also similarly weak transitions in the reaction on ^{130}Te to states at 1.979 and 2.313(4) MeV; the latter is tentatively identified as having spin-parity 0^+ in this work. The cross sections at 5° are listed in Table I, along with the ratios to the cross sections at 17°. The latter angle is near the minimum of the $\ell = 0$ angular distribution and the ratio therefore is a useful signature of $\ell = 0$ transitions. The systematic uncertainties in cross sections are estimated as ∼7% with statistical errors becoming significant (>10%) only below ∼0.06 mb/sr.

The ratio of cross sections for these peaks between 5° and 17° is much larger than 1.0 which is the signature for $\ell = 0$ transitions and therefore of 0^+ states. Because all the excited 0^+ states are weakly excited, they do not represent a significant breaking of the BCS symmetry.

For protons the situation is very different. The proton-pair adding reaction Te(^{3}He,n) had been studied [12] and a strong (∼30%) transition is seen to excited 0^+ states at approximately 2.6-MeV excitation in all the Te isotopes. This appears to be a classic case of a pair vibration [10] and is likely a consequence of the subshell gap at proton number $Z = 64$, separating the 14 protons in the $g_{7/2}$ and $d_{5/2}$ orbits from the 18 in $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$.

Such a proton pair vibration is *not* consistent with the assumptions of QRPA. The implication of this splitting could therefore be substantial for the matrix element for neutrinoless double-β decay. We note that there are 28 neutrons in ^{130}Te in the major oscillator shell between $N = 50$ and 82, leaving a vacancy of 4. At the same time there are two protons above $Z = 50$, leaving 30 vacancies. If the proton orbits above $Z = 64$ do not participate in the corrrelated final ground state then, assuming all orbits are equally important, this would reduce the number of vacancies by a factor of $(82 - 52)/(64 - 52) = 2.5$. Shell-model calculations have been used to describe the $A = 130$ double-β decay candidates [20], but it has not been demonstrated whether these calculations successfully describe the observed pair transfer strength to excited 0+ states.

IV. CONCLUSIONS

There is ample experimental evidence for the existence of a subshell at $Z = 64$ for protons, but no comparable gap exists for the neutron orbits. The connection between this subshell and pairing vibrations for protons has apparently not been previously emphasized and the effect of such a splitting of a simple BCS state on the double-β decay matrix elements is unexplored.

There is a need for more experimental work in this mass region and we are planning to perform quantitative measurements of the populations of the valence orbits in ^{130}Te and ^{130}Xe by one-nucleon transfer [21], similar to those that were done for ^{76}Ge [22].

From the overall pair-transfer data available on these tellurium isotopes, it appears that there may be a serious problem with the approximations inherent in QRPA in the mass 130 region (i.e., transitions are observed to occur that QRPA forbids from its basic assumptions). This could significantly affect the matrix elements predicted for the decay of tellurium, and needs clarification for the extraction of information on the effective neutrino mass, when and if results become available from the experiments searching for neutrinoless double-β decay.

A summary of these data are available online in the Experimental Unevaluated Nuclear Data List (XUNDL) database [23].

ACKNOWLEDGMENTS

This work was supported by the US Department of Energy, Office of Nuclear Physics, under Contract Nos. DE-AC02-05CH11231, DE-AC02-06CH11357, and DE-FG02-91ER-40609, and by the UK Science and Technology Facilities Council.

[1] S. Fukuda *et al.*, Phys. Rev. Lett. **86**, 5651 (2001).
[2] M. H. Ahn *et al.*, Phys. Rev. Lett. **90**, 041801 (2003).
[3] S. N. Ahmed *et al.*, Phys. Rev. Lett. **92**, 181301 (2004).
[4] Ø. Elgarøy *et al.*, Phys. Rev. Lett. **89**, 061301 (2002).

[5] V. Barger, D. Marfatia, and A. Tregre, Phys. Lett. B **595**, 55 (2004); S. Hannestad, J. Cosmol. Astropart. Phys. 05 (2003) 004.
[6] V. M. Lobashev and P. E. Spivak, Nucl. Instrum. Methods A **240**, 305 (1985).
[7] K. Zuber, Phys. Rep. **305**, 295 (1998).
[8] F. T. Avignone III, S. R. Elliott, and J. Engel, Rev. Mod. Phys. **80**, 481 (2008).
[9] J. N. Bahcall, H. Murayama, and C. Peña-Garay, Phys. Rev. D **70**, 033012 (2004).
[10] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. II, p. 386.
[11] M. Pedretti *et al.*, Int. J. Mod. Phys. A **23**, 3395 (2008).
[12] W. P. Alford *et al.*, Nucl. Phys. A **323**, 339 (1979).
[13] R. Seltz and N. M. Hintz, University of Minnesota, Annual Report 1971, p. 97 (1971).
[14] M. Matoba *et al.*, Nucl. Phys. A **261**, 223 (1976).
[15] S. J. Freeman *et al.*, Phys. Rev. C **75**, 051301(R) (2007).
[16] M. H. Macfarlane and S. C. Pieper, ANL-76-11 Rev. 1, ANL Report (1978).
[17] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[18] R. Perry, A. Nadasen, D. L. Hendrie, P. G. Roos, and N. S. Chant, Phys. Rev. C **24**, 1471 (1981).
[19] M. Kanbe and K. Kitao, Nucl. Data Sheets **94**, 227 (2001); J. Katakura and K. Kitao, *ibid.* **97**, 765 (2002).
[20] E. Caurier, J. Menéndez, F. Nowacki, and A. Poves, Phys. Rev. Lett. **100**, 052503 (2008).
[21] T. Bloxham, Bull. Am. Phys. Soc. **55**, 48 (2010).
[22] J. P. Schiffer *et al.*, Phys. Rev. Lett. **100**, 112501 (2008); B. P. Kay *et al.*, Phys. Rev. C **79**, 021301(R) (2009).
[23] [www.nndc.bnl.gov/xundl].