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Pair correlations in nuclei involved in neutrinoless double β decay: ^{76}Ge and ^{76}Se

S. J. Freeman,[1] J. P. Schiffer,[2,*] A. C. C. Villari,[3] J. A. Clark,[4] C. Deibel,[4] S. Gros,[2] A. Heinz,[4] D. Hirata,[3,5] C. L. Jiang,[2] B. P. Kay,[1] A. Parikh,[4] P. D. Parker,[4] J. Qian,[4] K. E. Rehm,[2] X. D. Tang,[2] V. Werner,[4] and C. Wrede[4]

[1]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*

[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*

[3]*GANIL (IN2P3/CNRS-DSM/CEA), B. P. 55027 F-14076 Caen Cedex 5, France*

[4]*A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA*

[5]*The Open University, Dept. of Physics and Astronomy, Milton Keynes, MK7 6AA, United Kingdom*

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Precision measurements were carried out to test the similarities between the ground states of ^{76}Ge and ^{76}Se. The extent to which these two nuclei can be characterized as consisting of correlated pairs of neutrons in a BCS-like ground state was studied. The pair removal (p, t) reaction was measured at the far forward angle of 3°. The relative cross sections are consistent (at the 5% level) with the description of these nuclei in terms of a correlated pairing state outside the $N = 28$ closed shells with no pairing vibrations. Data were also obtained for ^{74}Ge and ^{78}Se.

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Interest in the possibility of observing neutrinoless double β decay ($0\nu2\beta$) is considerable. If this decay were to be definitively observed, it would show that the neutrinos are their own antiparticles. In addition, the rate of the decay would be a measure of the neutrino rest mass, if the nuclear matrix element were known. Unfortunately, theoretical calculations of this do not agree well with each other [1]. It seems appropriate to determine additional properties of the ground states of the possible $0\nu2\beta$ systems by experiment, and thus help constrain and test theoretical calculations of this exotic decay mode. One of the likely candidate nuclei is ^{76}Ge decaying to the ground state of ^{76}Se. We have started with a study of the properties of the ground states of these nuclei, and especially the similarities and differences between them, using transfer reactions. One part of this study is an accurate measurement of one-nucleon transfer in order to probe the occupation numbers of valence orbits for both neutrons and protons, with particular attention to changes in these occupations. The other part is to study pair correlations in these nuclei by nucleon pair transfer. Here we report on a comparison of neutron pair transfer from the (p, t) reaction. We hope to obtain similar data on proton pair correlations from (^{3}He, n) reactions in a future experiment.

Pair transfer between 0^+ states in the (p, t) or (t, p) reaction proceeds via $L = 0$ transfer, and the angular distribution, for energies above the Coulomb barrier, is sharply forward peaked. This feature was recognized early [2] and was crucial in exploring the importance of such correlations and their excitations, the so-called pairing vibrations [3]. The latter are an indication of deviations from the simplest pairing picture and can occur in regions of changing shapes, or when there is a gap in single-particle states, such as near a shell closure.

We have carried out measurements of the neutron pair removal (p, t) reaction on targets of ^{74,76}Ge and ^{76,78}Se. The reaction on ^{78}Se was measured because the ^{78}Se$(p, t)^{76}$Se leads to ^{76}Se, while ^{76}Se$(p, t)^{74}$Se starts from the ground state of ^{76}Se. Thus both reactions are relevant to the pairing structure of this ground state. The ^{74}Ge target was included as a check.

There are two relevant aspects to these measurements. The first is the matter of pairing vibrations. The even Ge and Se isotopes are well studied, and evidence for excited 0^+ states has been established [4–6]. In some of the lighter isotopes of Ge and Se, two-neutron transfer reactions have shown significant strength populating excited 0^+ states. These pairing vibrations indicate that there are significant BCS-like pair correlations connecting the target ground state in an even initial nucleus to excited 0^+ states in the final. If there were significant differences in this regard between reactions leading to or from ^{76}Ge and ^{76}Se, this would be an indication that the pair correlations in the initial and final states in double β decay differ. Any reliable calculations of the process would presumably have to reproduce such differences in order to obtain a reasonable matrix element for the $0\nu2\beta$ decay. Secondly, if accurate cross sections were available for pair transfer, further checks could be made of the similarity between the initial and final wave functions used in such calculations.

Given that the $L = 0\,(p, t)$ transitions are the strongest in the spectrum of final states at very forward angles, which is also the region where the approximations inherent in the distorted wave Born approximation (DWBA) are best satisfied, it is desirable to carry out these measurements as close to 0° as feasible. The (p, t) reaction had been studied previously on Ge [4] and Se [6] isotopes; relevant (t, p) measurements have also been made [7–9]. Both the experimental methodology and the data analysis methods in the two (p, t) studies were different (the target thickness was estimated from high-energy elastic scattering where optical model predictions are ambiguous, the angular distributions start at 7.5°, and only angle-integrated cross sections are quoted, etc.), making a reliable systematic comparison of Ge and Se data difficult. Our purpose here was to measure the cross sections at as far forward angles

*Electronic address: schiffer@anl.gov

as feasible and to obtain a consistent set of accurate cross sections with particular care taken to reduce relative systematic uncertainties.

The choice of energy was governed by the desirability of having both protons and tritons well above the Coulomb barrier. For the present measurement, we therefore chose 23-MeV protons from the Yale ESTU tandem Van de Graaf accelerator. This energy is similar to that used in earlier experiments, for both (p,t) and (t,p) reactions. Because one of the objectives of the present measurement was to obtain accurate cross sections, we chose to measure the thickness of the evaporated germanium and selenium targets *in situ* by simply lowering the proton beam energy to 6 MeV, where the elastic scattering cross sections are very close to Rutherford values. The angle should not be so far forward that small uncertainties in angle would become significant, and 30° was chosen because calculations with several optical potentials showed that the deviation from Rutherford scattering was less than 2%. The ^{76,74}Ge and ^{78,76}Se target thicknesses were found to range between 160 and 400 μg/cm^2. Since Se can sublimate at a relatively low temperature, this low-energy target thickness measurement was made at the beginning and then at the end of the experiment; no significant differences ($<3\%$) were observed. The highest beam currents used were about 35 nA, though considerably lower (2–3 nA) for the 3° measurements.

The Yale Enge split-pole spectrograph was used for the measurements with a focal-plane detector that cleanly separates tritons from other reaction products. As monitors, two Si surface barrier detectors at ±32° were used. They were calibrated at 23 MeV in terms of beam intensity using a current integrator connected to a Faraday cup. The beam integrator was set to the same scale that was used for the low-energy measurements, and the solid-angle setting for the aperture of the spectrograph was also the same, thus establishing a relationship between an absolute cross section scale in terms of the monitor yields, instead of the beam intergrator, for each target.

The 3° setting for the spectrograph required that the Faraday cup be retracted so that the beam-current measurement had to rely on the previously calibrated monitor counters. Removal of the Faraday cup meant that the beam entered the spectrometer. The magnetic rigidity of the tritons from the reaction is such that, with the magnetic field set for observing tritons, protons from the target cannot directly reach the focal plane and are intercepted inside the spectrometer. Protons scattered at this point can enter the focal plane and, while they can be distinguished from tritons by their ionization density, they do impose a counting rate limit. As a result, the farthest forward angle where measurements could be made was 3°. Distorted-wave calculations indicate that the cross section at this angle is lower than that at 0° by about 8%. Spectra were also measured at the laboratory angle of 22°, which is close to the minimum for $L = 0$ angular distributions, though the location and depth of the minimum are very sensitive to the Q value and the distorting parameters, as seen in Fig. 1. Nevertheless, the ratio of the 3° to the 22° cross sections is huge compared to that for the other L values and is therefore an excellent identifier of $L = 0$ transitions, though the precise

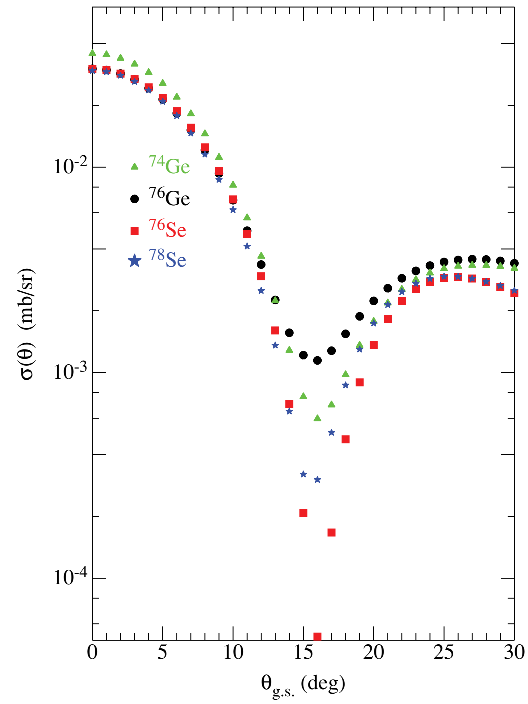

FIG. 1. (Color online) DWBA calculations of ground-state angular distributions at 23 MeV for different targets, using the proton optical potentials of Ref. [11] and the triton potential from Ref. [12]. Note the sensitivity of the shapes of the angular distributions to the Q values, while the peak cross sections remain relatively stable. The relative variation in the peak cross sections for different choices of potentials (e.g. Perey Ref. [13] instead of Becchetti and Greenleses Ref. [11]) is very similar.

value of this ratio will depend on the exact location and depth of the sharp minimum in the angular distribution.

Representative spectra from the 3° measurements are shown in Fig. 2, where the ground-state transitions are clearly seen to dominate. The results of the cross section measurements are shown in Table I, with ratios to the ground-state cross sections given only for states with yields, at 3°, larger than 1% of the ground-state yield. The transitions where the ratio of cross sections between 3° and 22° is consistent with $L = 0$ are shown in bold. More complete data, though at farther back angles and with less attention to accurate relative cross sections, had been reported, but the emphasis in these previous measurements was on angular distributions starting at 7.5°, and only angle-integrated cross sections are quoted [4,5]. The uncertainty in the present experimental cross sections is believed to be ±10%, while that in the relative values is estimated at ±5%. These uncertainties are dominated by estimates of systematic errors (constancy of the beam spot on target, accuracy of angle determinations in the monitors, possible small drifts in monitor calibration, possible inefficiency in the focal plane detector, uniformity of target thickness, etc.), while the statistical contribution is of the order of 1%.

The (p,t) differential cross sections at 3° for populating the 0^+ ground states for the four targets are very similar: 6.4, 6.7, 6.0, and 7.1 mb/sr for ^{74,76}Ge and ^{76,78}Se, respectively.

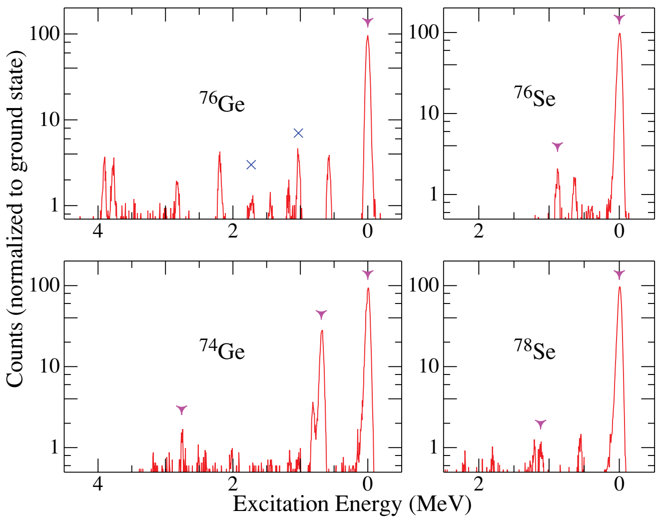

FIG. 2. (Color online) Spectra of tritons at 3° measured with Yale split-pole spectrograph, normalized to 100 for the ground-state peak, and labeled in each case by the target nuclide. Peaks corresponding to $L = 0$ transitions are identified by a pointer. Peaks due to isotopic impurities are marked by an x. Despite evidence in ^{74}Ge$(p, t)^{72}$Ge of substantial strength in a low-lying excited 0^+ state, there are no large admixtures seen for ^{76}Ge and ^{76}Se targets.

Excited 0^+ states stand out in the ratio between the 3° and 22° yields, which is an order of magnitude larger than for any other excited state. With the exception of the ^{74}Ge target, none of these excited 0^+ states is populated with a cross section at 3° that is more than 2% of that leading to the ground states. In the ^{74}Ge$(p, t)^{72}$Ge reaction, the cross section to the first excited 0^+ state is 1.9 mb/sr. This feature is well known [4] as an example of a pairing vibration. The case of ^{74}Ge is illustrative of effects that can be problematic; however, the context of the current work is related only to the ^{76}Ge/^{76}Se double β decay system.

TABLE I. Summary of (p, t) cross sections at 3° and ratio (in %) of these to the 22° values. Transitions consistent with $L = 0$ are shown in boldface.

Excitation energy (keV)	$(\sigma/\sigma_{gs})_{3^\circ}$	Ratio(3°/22°)
^{74}Ge$(p, t)^{72}$Ge	σ_{gs}(lab) = 6.4 mb/sr	
0	**100**	**86**
691	**29**	**280**
834	2.8	0.9
1464	0.5	1.5
2024	0.5	4
2762	**0.9**	**130**
^{76}Ge$(p, t)^{74}$Ge	σ_{gs}(lab) = 6.7 mb/sr	
0	**100**	**50**
596	3.2	1.0
1204	1.1	1.6
1463	2.2	0.8
2198	2.9	3
2833	1.7	6
^{76}Se$(p, t)^{74}$Se	σ_{gs}(lab) = 6.0 mb/sr	
0	**100**	**115**
635	1.0	0.4
854	**1.4**	**80**
^{78}Se$(p, t)^{76}$Se	σ_{gs}(lab) = 7.1 mb/sr	
0	**100**	**150**
559	1.2	0.4
1121	0.8	4
1220	0.7	1.0

TABLE II. 3° laboratory cross sections and ratios to DWBA. Cross sections are for the ground-state to ground-state transitions.

Target	σ_{exp}(lab) (mb/sr)	σ_{DWBA} (mb/sr)	$\sigma_{exp}/\sigma_{DWBA}$
^{74}Ge	6.4	0.0438	147
^{76}Ge	6.7	0.0499	135
^{76}Se	6.0	0.0437	137
^{78}Se	7.1	0.0431	164

DWBA calculations were carried out with the program PTOLEMY [10] to correct the dependence of the reaction on Q values. The consideration of the details of nuclear structure is beyond the scope of this study, even though ^{76}Ge and ^{78}Se have six neutron vacancies in the $N = 50$ shell, ^{74}Ge and ^{76}Se have eight. The form factor for the neutron pair was calculated assuming a mass-2, $\ell = 0$ dineutron bound in a Woods-Saxon potential with the appropriate binding energy and having three nodes in its wave function. The proton potentials were those of Ref. [13], and the triton potential that of Ref. [12]. The measured cross sections at 3° are given in Table II, together with the ratio of the experimental cross sections to the calculated values. The absolute magnitude of the DWBA cross section is very sensitive to the choice of distorting potential (with the proton potential of Ref. [11] the average ratio changes from 136 to 217), as is the location of the first minimum in the angular distribution. However, all

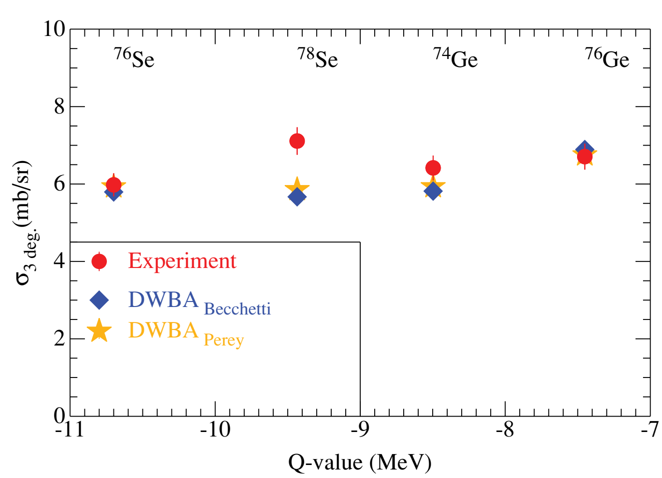

FIG. 3. (Color online) Ground-state 0^+ to 0^+ cross sections at 3° are plotted as a function of Q value, for convenience in display. Also shown are the DWBA cross sections multiplied by one average normalization factor for each proton potential. Estimated relative errors are shown on the experimental points.

calculations indicate that the relative values between these targets of the calculated cross sections at 3° remain the same (within 10%) with various reasonable potentials for protons and tritons.

The experimental cross sections by themselves are remarkably constant; without any correction for reaction dynamics, they vary by ±6%. Dividing the experimental numbers by the calculated reaction cross sections reduced the difference between ^{76}Ge and ^{76}Se even further. However, this improvement is probably not significant, in view of the estimated 5% relative error and the neglect of the different numbers of neutrons. The peak cross sections and DWBA trends are also shown in Fig. 3.

The pair-adding (t, p) reaction had been studied previously, for both the ^{74}Ge$(t, p)^{76}$Ge [7,8] and the ^{76}Se$(t, p)^{78}$Se [9] reactions. While the ground-state transitions are the same as the ones studied here, transitions to excited states could, in principle, show up and indicate pairing vibrations. While the angular distributions were not measured at as far forward angles as in the present work, some estimate can be obtained by comparing integral cross sections. No excited 0^+ states were seen in these (t, p) studies with a strength greater than 4% of the ground-state transition, confirming the dominance of pair correlations in the ground states of these nuclei, with no splitting into pairing vibrations.

In conclusion, the experimental cross sections measured in this experiment are remarkably constant for ground-state transitions with the various targets. The difference between ^{76}Ge and ^{76}Se, in the ratio of the experimental ground-state transition strengths divided by the appropriate DWBA calculations, is less than the 5% estimated accuracy of the measurements. Transitions to excited 0^+ states from ^{76}Ge and ^{76}Se targets are no more than a few percent of the ground-state transitions, indicating no sign of the pairing vibrations that appear in some of the lighter isotopes. Had such admixtures been present, this would have complicated a simple comparison of the ground states. The constancy of the ground-state strength in pair correlations seems to be as true for neutron pair adding transfers leading to these nuclei as it is for pair removal from them. The present results suggest that the ground states of ^{76}Ge and ^{76}Se exhibit quantitatively very similar neutron pair correlations. Changes in pairing are thus unlikely to be a significant complicating factor in the wave functions of these states for calculations of neutrinoless double β decay.

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