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Y. Ayyad *et al.*

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Investigating Neutron-Proton Pairing in sd-Shell Nuclei via (p,^{3}He) and (^{3}He,p) Transfer Reactions

Y. Ayyad,[1,2,*] J. Lee,[3,4,†] A. Tamii,[1] J. A. Lay,[5,‡] A. O. Macchiavelli,[6] N. Aoi,[1] B. A. Brown,[7] H. Fujita,[1] Y. Fujita,[1] E. Ganioglu,[8] K. Hatanaka,[1] T. Hashimoto,[1] T. Ito,[1] T. Kawabata,[9] Z. Li,[10] H. Liu,[10] H. Matsubara,[11] K. Miki,[1] H. J. Ong,[1] G. Potel,[2] I. Sugai,[12] G. Susoy,[8] A. Vitturi,[5] H. D. Watanabe,[9] N. Yokota,[9] and J. Zenihiro[1]

[1]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, 567-0047, Japan*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[3]*Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong, China*
[4]*RIKEN Nishina Center, Wako, Saitama, 351-0198, Japan*
[5]*Dipartimento di Fisica e Astronomia Galileo Galilei, Universita di Padova and INFN, Sezione di Padova, via Marzolo 8, Padova 35131, Italy*
[6]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[7]*Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[8]*Department of Physics, Istanbul University, Istanbul 34134, Turkey*
[9]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[10]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[11]*National Institute of Radiological Sciences (NIRS), Inage, Chiba, 263-8555, Japan*
[12]*KEK, Oho 1-1, Tsukuba-shi, Ibaraki, 305-0801, Japan*

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Neutron-proton pairing correlations have been investigated in detail via np-transfer reactions on $N = Z$ sd-shell nuclei. In particular, we studied the cross section ratio to the lowest 0^+ and 1^+ states as an observable to quantify the interplay between T=0 (isoscalar) and T=1 (isovector) pairing strengths. The experimental results are compared to second-order Distorted Wave Born Approximation (DWBA) calculations with proton-neutron amplitudes obtained in the Shell Model formalism by using USDB interaction. Our results suggest the underestimation of the non-neglible isoscalar pairing strength in the Shell Model descriptions at the expense of the isovector channel.

The nucleon pairing phenomenon in atomic nuclei plays a crucial role in understanding many nuclear properties at low-energy such as even-odd staggering in binding energies, moments of inertia, fission fragments charge distributions, and dynamics of spontaneous fission [1]. Similarly to the Bardeen−Cooper−Schrieffer (BCS) theory of superconductors, neutron-neutron (nn) and proton-proton (pp) form strongly correlated pairs responsible for the appearance of such effects. Due to the short range interaction between nucleons, neutrons and protons may couple to a correlated state with angular momentum $J = 0$ and isospin $T = 1$ (isovector or spin-singlet). In nuclei with large $N - Z$ imbalance, the pairing interaction is essentially ruled by separated nn and pp correlations. Another channel to couple a neutron and a proton is the isoscalar (spin-triplet) mode with $J = 1$ and $T = 0$, which is allowed under the Pauli principle.

In particular, for nuclei near the $N = Z$ line, the protons and the neutrons have a large wave function spatial overlap because the shell model orbits for both of them are similar near the Fermi surface. In this case, the spin-triplet channel interaction could become dominant, enabling the formation of np pairs. In addition, due to the charge independence of the nuclear force, pairing should manifest equivalently for the np pair with $T = 1$ and $S = 0$, and for the nn and pp [2]. Although the spin-triplet bare interaction is stronger than the spin-singlet, there is widespread agreement that a strong nuclear spin-orbit interaction induces a stronger suppression of the former [3–5].

In spite of clear evidences of the np isovector mode $T = 1$, the existence of correlated isoscalar np pairs in condensate form and the magnitude of such collective pairing are still a controversial and fascinating topic that has renewed the interest in nuclear pairing. In particular, most of the current effort conducted on this topic tries to elucidate the interplay between the isoscalar and isovector np modes and the possible transitions (and possible mixing configurations) between them.

From the theoretical point of view, the np pairing and the interplay between both modes has been extensively studied using different approaches and formalisms, mainly based on shell model and mean field calculations. The earliest research efforts on np pairing were devoted to extending the Hartree−Fock−Bogoliubov (HFB) theory to include isovector and isoscalar pairing

* ayyad@lbl.gov; Present address: Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
† jleehc@hku.hk
‡ Present address:Departamento de Física Atómica, Molecular y Nuclear, Facultad de Física, Universidad de Sevilla, Apartado 1065, 41080 Sevilla, Spain

modes (see Ref. [6] and references therein). In these early works, for $N = Z$ and $N > Z$ even−even nuclei with $A < 50$, the isoscalar and isovector pairing modes appears, respectively, in the ground state. More recently, the HFB theory was applied by Bertsch and Luo [5] to investigate the competition between the isoscalar and isovector pairing in nuclei with $A > 100$. They concluded that spin-triplet pairing would dominate in $N = Z$ nuclei with at least $A \sim 130 - 140$, a region close to the drip line. Using a many-body model described by Bogoliubov-de Gennes equations and the same Hamiltonian as Ref. [5], Gerzelis, Bertsch and Luo [7] found that the condensate is a mixture of spin-singlet and spin-triplet pairing, which appears when there is a large $N - Z$ imbalance, close to the proton drip-line. By examining the pairing vibrations around ^{56}Ni, Macchiavelli et al. [8], confirmed the collective behavior of the isovector pairing vibration. However, their results do not support any manifestable collectivity of the isoscalar mode. Later, Yoshida [9] demonstrated that low-lying 1^+ states in odd-odd $N = Z$ nuclei can be a precursory soft mode of the $T = 0$ pairing condensation. In his Skyrme−EDF (energy density functionals) framework, the strong collective nature of the $T = 0$ np pairing vibrational may enhance the np-transfer strength to the 1^+ state. This enhancement of the np-transfer over the single particle strength was previously pointed out by Fröbich [10] and more recently by Van Isacker and collaborators [11] within the Interacting Boson Model (IBM). As with the case of (t,p) and (p,t) reactions, the experimental measurement of an np pair transfer would constitute one of the most adequate probes to understand pairing correlations. The addition of particles in the system will introduce a transition to a pair condensate ground state for nuclei far from closed shells. In that superfluid region, cross sections are rather constant and enhanced by a factor Ω^2, Ω being the single-particle degeneracy. It seems therefore natural to perform np pair transfer reactions on odd-odd self conjugate nuclei, especially for heavier systems with larger single-particle degenerancies Ω.

In this work, we performed (p,^{3}He) and (^{3}He,p) transfer reactions in $N = Z$ sd-shell nuclei to quantify the nature and interplay between $T = 0$ $(J = 1)$ and $T = 1$ $(J = 0)$ pairing correlations. Since $\Delta T = 0$ and $\Delta T = 1$ are allowed in these reactions, the exclusive cross sections to the lowest 0^+ and 1^+ states in the odd-odd $N = Z$ nuclei can be measured. Although several of these reactions were previously investigated [12–14], the measurements were performed in different experimental conditions by several different groups over a number of years. For almost all of these previous measurements, no cross section data were obtained at the forward angles, where the effect of the addition of the $L = 2$ component is minimum in the case of the 0^+ to 1^+ transition. In our experiment, we measured the differential cross sections covering an angular range from close to 0° up to 30° degrees to disentangle the $L = 0$ and $L = 2$ contributions. We obtained the ratio between the cross sections $\sigma(0^+)/\sigma(1^+)$ which provides a model-independent measurement of the $T = 1/T = 0$ interplay and of the pairing collectivity [2, 15]. Moreover, absolute cross sections are essential to determine the dynamical implications of $T = 0$ and $T = 1$. Coupled with theoretical structure and reaction studies, a quantitative comparison between these measurements and theoretical cross sections is presented. Our work provides an essential framework for evaluating the microscopic descriptions of np pairing correlations in the many-body wave functions and serves as the foundation for systematic studies of np pairing along $N = Z$ nuclei via cross section measurements. These newly improved systematic measurements under the same experimental conditions will provide an independent test of effective interactions employed in nuclear shell models.

The experiment was conducted using the Grand Raiden (GR) high-resolution spectrometer (see Fig. 1) at the Research Center for Nuclear Physics of Osaka University (Japan) [16]. The aim of the experiment was to measure absolute differential cross sections with high precision. We performed systematic measurements in normal kinematics, namely ^{24}Mg(^{3}He,p)^{26}Al, ^{24}Mg(p,^{3}He)^{22}Na, ^{28}Si(p,^{3}He)^{26}Al, ^{40}Ca(p,^{3}He)^{38}K and ^{32}S(^{3}He,p)^{34}Cl. The thickness of the targets, of around 300 μg/cm^2, was chosen to minimize the straggling and achieve an excitation energy resolution below 70 keV (FWHM) for all the measurements listed above. The Azimuthally Varying Field cyclotron (AVF) delivered ^{3}He and p beams at 25 and 65 MeV, respectively, with an intensity of around 50 pnA. These energies are appropriate due to the momentum matching for these reactions where the transition to 0^+ and 1^+ are possible with $L = 0$ and $L = 2$ angular momentum.

The outgoing proton/^{3}He particles were momentum analyzed by the GR spectrometer (see Fig. 2). The position of such particles in the focal plane was determined by using two multi-wire drift chambers of the vertical drift type. The identification of the particles was done by measuring the time-of-flight and the energy loss of the particles in the focal plane using a plastic scintillator. The particles were detected from 0° up to 30° degrees (with 2° intervals) using a magnetic setting that allowed us to measure up to 3 MeV of excitation energy. For angles below 6°, the spectrometer was operated in over-focused mode [17]. The target thickness was also monitored during the experiment by detecting elastically scattered proton/^{3}He particles at 60° in the focal plane of the Large Acceptance Spectrograph (LAS). The angular distributions were compared to calculations performed with well known optical potentials, as discussed later in the text, to infer the thickness of the target.

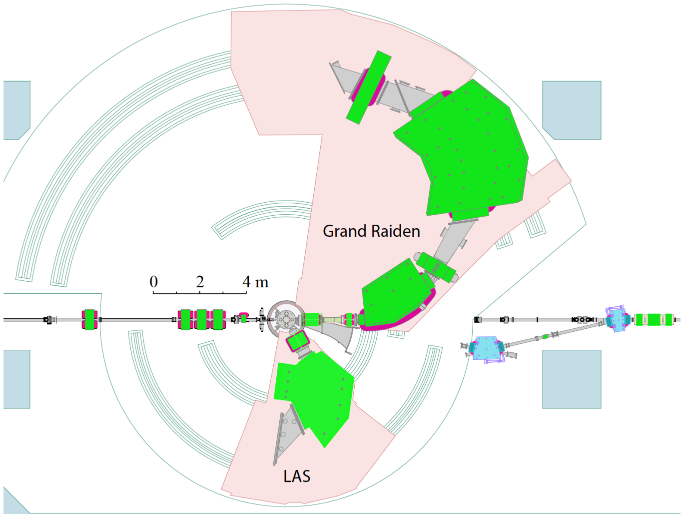

FIG. 1. Sketch of Grand Raiden (GR) spectrometer and the Large Acceptance Spectrograph (LAS). Measurements at around 0° were performed by operating the spectrometer in over-focused mode [17] and by stopping the beam at a Faraday cup placed inside the first dipole magnet of the Grand Raiden spectrometer. The Faraday cup was also used to integrate the current of the beam.

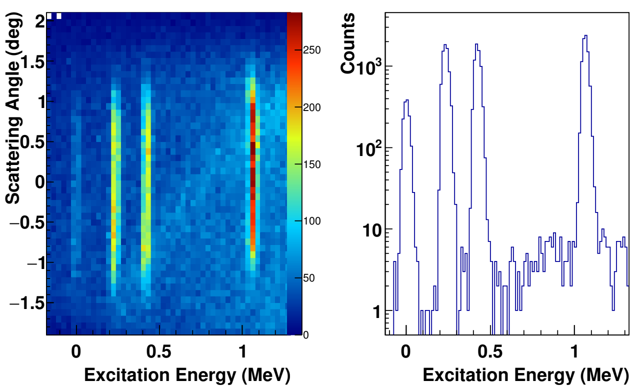

FIG. 2. Left panel: Excitation energy spectrum as a function of the scattering angle for the ^{24}Mg(^{3}He,p)^{26}Al reaction. The spectrum is gated on protons. The ^{26}Al states can be unambiguosly identified: 0.0 MeV (5^+), 0.228 MeV (0^+), 0.416 MeV (3^+) and 1.06 MeV (1^+). Right panel: Same as left panel but projected into the excitation energy axis.

In order to understand the underlying reaction mechanism, we have performed second-order Distorted Wave Born Approximation (DWBA) calculations with the code FRESCO [18, 19] which should account properly for the reaction mechanism at the energies used in this work. In second-order DWBA, two different contributions interfere in order to create the total transfer cross section: simultaneous and sequential transfer. On top of that, there is another contribution arising from non-orthogonality terms which we avoid here by choosing the *prior-post* form for the sequential term [18]. The correct assessment of the three terms and its interference is expected to quantitatively reproduce the full transfer cross section without using any "unhappiness" factor as has been shown in recent cases [20–22]. To the best of our knowledge, this is the first time that second-order DWBA calculations have been applied to np-transfer. This new framework provides valuable insight into determining whether a structure model successfully predicts the np pairing and, more importantly, the relative importance between the T=0 and T=1 possibilities.

The wide variety of optical potentials introduces an additional dimension of uncertainty. However, the ratio of the cross section populating the 0^+ and the one populating the 1^+ should not strongly depend on the selected optical potential as long as one uses the same one in both calculations. We have kept the same family of optical potentials for the different counterparts of all the reactions. For all of the reactions, the best overall agreement is found when using Menet for protons, Lohr-Haeberli for deuteron potentials, and Bechetti-Greenlees for the ^{3}He potentials [23]. Other options have been explored leading to important variations in the cross section at zero degrees. However, these differences are considerably reduced if we only consider those combinations of optical potentials that produce an angular distribution consistent with the experimental data. These differences are also smaller in the ratios as expected, although they can be still important. Therefore, we have checked that these variations do not affect the present conclusions. In particular, the ^{32}S(^{3}He,p)^{34}Cl case is the only one here whose ratio is affected by the choice of the optical potential. Details of the impact from different choices of optical model parameters will be presented in a follow-on longer manuscript.

The overlaps of the $sd-$shell nuclei studied were constructed from two-nucleon spectroscopic amplitudes calculated with wave functions obtained from the USDB (Universal sd-shell interaction B) [24] Hamiltonian using the Shell Model code NuShellX [25]. USDB is a phenomenological interaction specifically fitted to reproduce the spectrum of nuclei in the $sd-$shell. For the sequential part of the transfer reaction we make an intermediate state factorization of the two-nucleon amplitude into two terms. This division is arbitrary but the result is insensitive to this change provided that the total form factor is consistent with the two-nucleon amplitude. The energy of the intermediate state is defined as half the energy difference between initial and final states. We show in Fig. 3(a) the results for the ^{24}Mg(^{3}He,p)^{26}Al reaction and in Fig. 3(b) those for the ^{40}Ca(p,^{3}He)^{38}K one. For the former, the theoretical predictions overestimate the T = 1 case but indicates a good agreement for the T = 0 case. Different results were reported in Ref. [26] indicating a systematic underestimation of the T = 0 np pair removal cross section in the $p-$shell. This calculation is similar to the more standard (t,p) case for $T = 1$. For the $T = 0$ case, $L = 0$ and $L = 2$ components are mixed. Both contributions can be determined with these calculations, with the $L = 0$ component dominant at small angles. In this way, it is possible to estimate the relative strength of correlations in $T = 0$ and $T = 1$ through the ratio of the cross sections. The present calculation can also be used to estimate the uncertainty of this ratio for those cases where measuring at 0^o has not been possible.

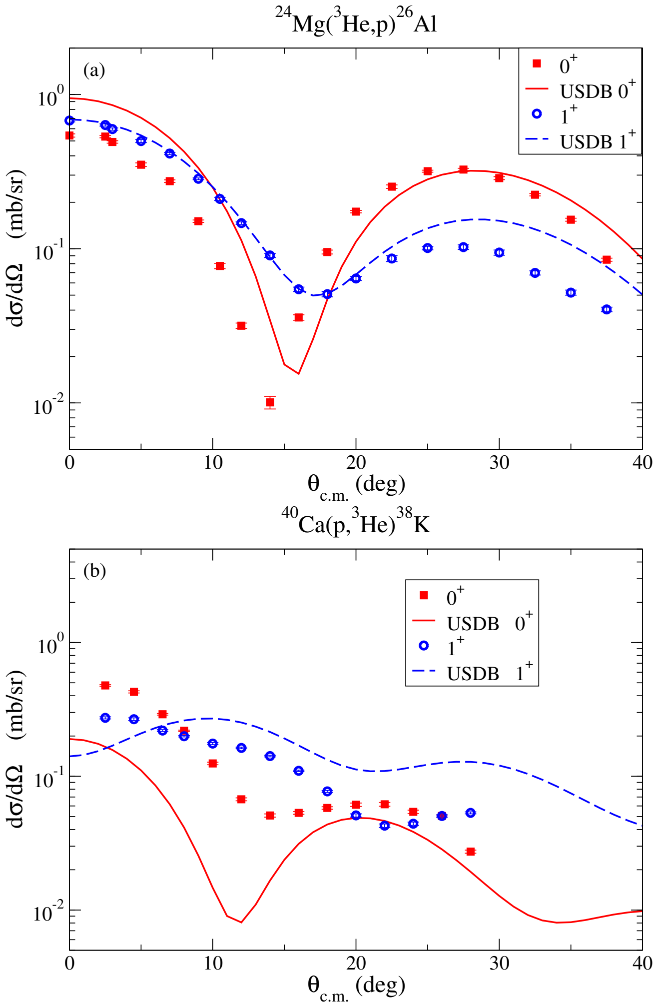

FIG. 3. Cross sections for (a) ^{24}Mg(^{3}He,p)^{26}Al and for (b) ^{40}Ca(p,^{3}He)^{38}K for the $np-$transfer to the first 0^+ and the first 1^+ states. We compare with the second-order DWBA calculations (see text). Uncertainties are smaller than the points representing the data for some angles.

For the ^{40}Ca(p,^{3}He)^{38}K reaction, the agreement in magnitude is less satisfactory than the previous case. We have to keep in mind that ^{40}Ca is at the end of the sd-shell and is therefore a double magic nucleus. For this reaction, we do not include here f orbitals which might contribute to the total cross section improving the present results. The theoretical ratio between the cross sections to the 0^+ and the 1^+ states at around zero degrees is underestimated (1.35 instead of 1.75), and the angular distribution is not perfectly reproduced. However, we believe that these results open up promising perspectives considering that the components from the fp-shell are not included.

In general, good agreement is found overall between the measurement and the theoretical calculations for the shape and magnitude of the different reactions studied. However, this agreement does not translate into a satisfactory reproduction of the trend of the experimental ratios. Fig. 4 shows the ratio between the transfer cross sections to the 0^+ and the 1^+ states in the final nuclei measured at the smallest angle possible in each case. In the abscissa we have chosen the half-sum of the initial and final mass number of the nuclei of interest. This selection is based in the fact that a hypothetical $A(^3\text{He},p)A+2$ from a 0^+ ground state to a 0^+ ground state will yield the same cross section as the inverse reaction $A + 2(p,^3\text{He})A$. With the present selection of the abscissa, both cross sections will coincide in the plot for an x value of $A + 1$. Theoretical calculations for the same ratios are also shown in Fig. 4 with open symbols. These theoretical ratios have always been calculated for 0^o.

The experimental ratios do not show a clear trend with the number of valence particle. However, if we compare these ratios with the independent particle limit (open green circles in Fig. 4), we see how the deviation from this reference line increases. The estimation of this independent particle may differ from previous calculations [15]. This is due to the fact that we performed full 2^{nd} order DWBA calculations taking into account a zero admixture for the wave functions which includes the proper values of the Q-values. We found these independent particle ratios to depend on the different Q-values and also on the component for the pure wave function. In this regard, we have chosen the dominant component in the Shell model calculation, i. e. $(\mathrm{d}_{5/2})^2$ for the first three reactions, and $(\mathrm{d}_{3/2})^2$ for the latter two. This independent particle limit always underestimates the transfer cross section, since it does not include any pairing. Even a small amount of the latter will increase the cross section. When comparing the ratios, if the experimental value is above (or below) the single particle limit, we can infer that the $T = 1$ (or $T = 0$) pairing is dominant versus the other one.

For some cases, the deviation shows a dominance of the cross section populating the 1^+ state, thus supporting the idea of a strong $T = 0$ $np-$pairing. Comparing with shell model calculation, the USDB interaction seems to overestimate this deviation. For the ^{40}Ca(p,^{3}He)^{38}K case we see that the single-particle ratio is pretty close to the experimental point as expected for a doubly magic nucleus. However, the sole single-particle cross section does not fully reproduce the experimental one for neither of the two cases. There is room for a little enhancement which in any case is compatible with a possible treatment of this case as a vibration in ^{40}Ca.

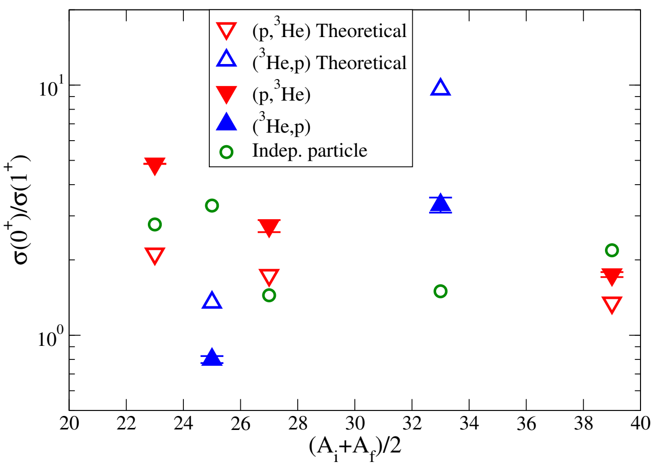

FIG. 4. (color online) Experimental ratios (full triangles) between the transfer cross sections to the 0^+ and the 1^+ states in the final nuclei measured at the smallest angle possible in each case. The abscissa is the half-sum of the initial and final mass number of the nuclei of interest. Triangles indicate (^{3}He,p) reactions whereas inverted triangles represent (p,^{3}He) reactions. We also include the corresponding theoretical ratios represented by open symbols. Open triangles correspond to the ratio calculated with the USDB spectroscopic factors and open green circles, to the ratio calculated by assuming independent particles without pairing (see text).

The collective nature of the $T = 0$ $np-$pairing can be understood theoretically by looking at how the different parts of the np wave function contribute to the final cross section. In a nn superfluid nucleus, all the components interfere constructively to the transfer from ground state to ground state, thus creating a characteristic large enhancement of the cross section. In Fig. 5, we show the calculations for the transfer of an np $L = 0$ pair to the first ^{26}Al 1^+ state where we have included the different parts of the overlap. Considering only the part of the neutron and the proton in the $d_{5/2}$ wave, we see that each additional term consistently increases the total cross section, especially at 0^o. It is necessary to add almost all the components in order to reproduce the experimental data. Fig. 5 also shows that there is a non-negligible enhancement resulting from parts of the overlap where the neutron and the proton are not in the same state. In other words, the $(d_{5/2})(d_{3/2})$ component increases the cross section even at 0^o and, therefore, it is needed in order to explain the ratio shown in Fig. 4. This component does not appear in the nn (or pp) BCS Cooper pair. However, the $(d_{5/2})(d_{3/2})$ component is perfectly allowed in the case of $T = 0$ and has to be taken into account when generalizing BCS for $np-$pairing.

In conclusion, we have established a novel analysis

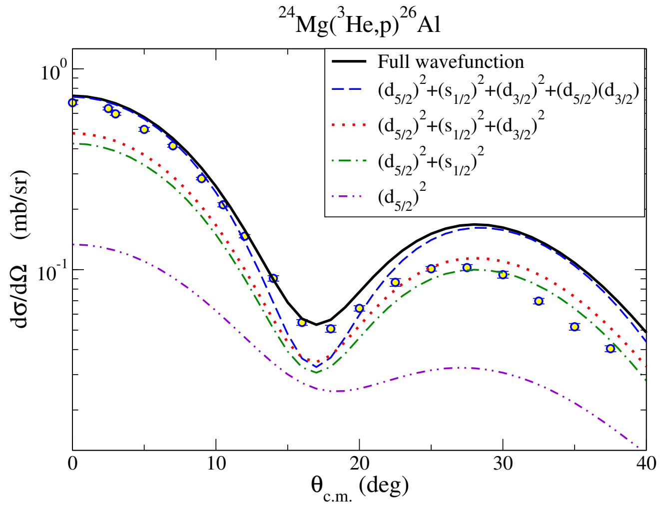

FIG. 5. (color online) Cross sections for ^{24}Mg(^{3}He,p)^{26}Al for the first 1^+ state. Uncertainties are smaller than the points representing the data. The different lines corresponds to the theoretical calculations for transferring $L = 0$ pairs but adding different parts of the overlap up to recover the full overlap $\langle^{24}\text{Mg}(0^+)|^{26}\text{Al}(1^+)\rangle$. The corresponding theoretical spectroscopic factor for each part of the wave function is omitted in the legend but considered in the calculation.

framework that improve understanding of the np-pairing phenomena in other systems, and helps to elucidate if the isoscalar pairing force interaction is present. In order to shed some light on the nature of the T=0 isoscalar np-pairing, we performed a series of systematic np-transfer measurements on sd-shell $N = Z$ nuclei. These high quality data were taken under identical conditions to avoid systemic uncertainties, spanning a wide angular distribution from close to 0° up to 30°. We obtained the absolute differential cross sections with high precision and thus the ratio between the cross sections $\sigma(0^+)/\sigma(1^+)$. In order to understand how the cross section ratio relates to the relative strength between the isoscalar and isovector pairing modes, we performed second order DWBA calculations taking into account shell model calculations with the USDB interaction. We found a satisfactory agreement for the shape of the distribution but not for the absolute comparison of the ratios. With the help of these second order DWBA calculations we can compare with the ratios for pure or zero pairing wave function. From this comparison, we find cases in which the $T = 0$ pairing appears to dominate over the traditional or more standard $T = 1$ channel. We have also shown how the different components contributes coherently to increase the cross section in one of these particular cases: ^{24}Mg(^{3}He,p)^{26}Al(1^+). In addition, the results indicate that the cross sections to the 1^+ are dominated by the transfer of an $L = 0$ pair as in the $T = 1$ pairing. However, certain components with a non negligible contribution to this $L = 0$ transfer are not included in the typical Cooper pair [5]. Building on this foundational work, new and follow-up experiments with radioactive beams are required to further understand the evolution of np-pairing correlations along the $N = Z$ line. Such challenging experiments will be available in future rare-isotope facilities capable of providing high-intensity proton-rich beams.

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