Neutron-Proton Pairing in N=Z Nuclei Studied through 2N Transfer Reactions

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INTRODUCTION

Pairing in exotic nuclei is a subject of active research in nuclear physics. Of particular interest is the competition between isovector (T=1) and isoscalar (T=0) Cooper pairs, expected to occur in N=Z nuclei.

Near ^{40}Ca and ^{56}Ni, earlier systematic analyses of two-neutron (L=0) transfer reactions [1,2] found the data consistent with a picture involving configuration mixing induced by simple pairing degrees of freedom of the valence neutrons. While providing evidence for isovector pairing in the form of pairing vibrations [2,3], the question of whether the isoscalar component generates collective modes is still an open one.

Direct reactions involving the transfer of an *np* pair from even-even N=Z nuclei could be excellent probes to study *np* correlations.

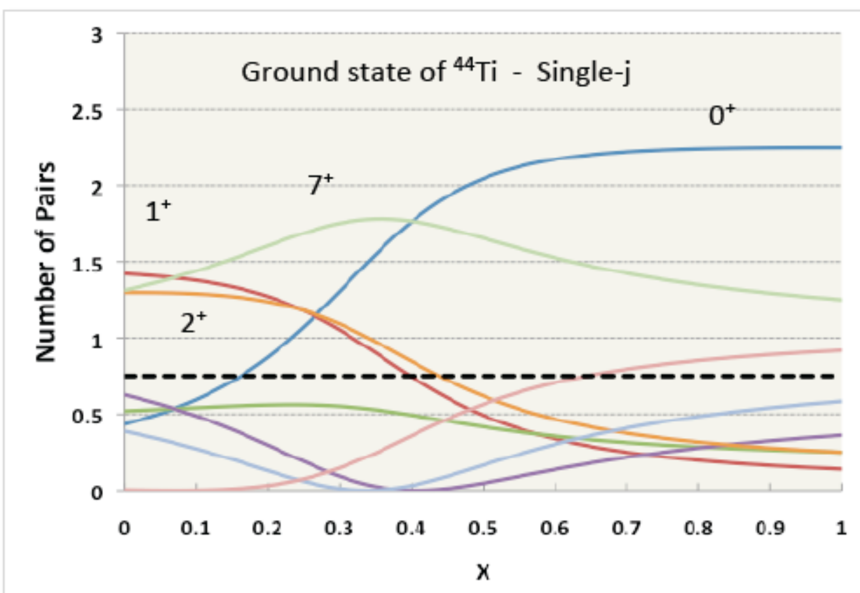

FIGURE 1. Number of pairs of a given spin in the ground state of ^{44}Ti as a function of the relative strength of T=0 vs. T=1 pairing, measured by the parameter x. Pure isoscalar corresponds to x=0 and pure Isovector x=1.

While absolute cross-section values are always desirable, we note that the ratio $\sigma(0^+)/\sigma(1^+)$ itself provides a clear measure of the pairing collectivity in the respective channels. This is illustrated schematically in **Figure 1**. showing the number of pairs of a given angular momentum J in the ground state of ^{44}Ti as a function of the parameter x, that measures the relative strengths of the T=0 vs. T=1 pairing forces. The calculations were performed following the formalism described in Ref. [4]. Note the strong (and opposite) dependence of the number of 0^+ and 1^+ pairs with x. Naturally, cross sections will scale with the number of pairs.

Of possible reactions such as (d,α), (α,d), (p, ^{3}He), (^{3}He,p), etc. we have chosen to study the latter one due to energy and kinematic considerations, but more importantly because both ΔT=0,1 are allowed. In this way both low lying 0^+,1^+ states in odd-odd self conjugate nuclei will be populated.

THE (^{3}HE,P) REACTION IN REVERSE KINEMATICS

With ^{40}Ca being the last stable N=Z nucleus, we started a program at the ATLAS facility in Argonne National Laboratory to study the (^{3}He,p) in reverse kinematics as required for radioactive beams. The experiments conducted so far included a proof of principle of the experimental technique, using the stable beams of ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca and the first successful application with a radioactive beam of ^{44}Ti. The setup, similar to that previously used in refs. [5,6], consisted of two annular Si strip detector (S1 type, 16 rings x 16 sectors) covering the angular range from 163^o to 148^o, a ^{3}He gas target cell (50 – 100 μg/cm^2) and the FMA.

The angular range covered by the Si detectors in the CM system is 8^0-18^0, where the L=0 transfer cross sections are favored. Because of its Q-value, the (^{3}He,p) reaction is extremely clean in the backward angles but the singles spectrum is dominated by charged particles emitted by compound reactions in the Ti windows of the gas cell.
In addition, the ^{44}Ti beam delivered by ATLAS contained also ^{44}Ca in a ratio ~2/1. Therefore, channel selection by a mass analyzer is required.

In our test run [7], the cross sections derived from the measurements in ^{40}Ca are in good agreement with previous work, performed in normal kinematics [8].

For the ^{44}Ti run, approximately 100μCi of ^{44}Ti were purchased from LANL and mixed with natural Ti, in oxide form, to make a cone for the sputtering ion-source of the ATLAS Tandem. Over a 3 day run, we had an average beam intensity of ~5×10^5 part/s

Preliminary results of the ^{44}Ti reaction are presented in **Figure 2.** The left panel shows the identification of ^{46}V using the FMA setup and the right panel the proton spectra observed on two groups of rings in the S1 detectors, obtained after kinematic correction of the proton energies.

With the intensity above, a target thickness of ~100μg/cm^2 and taking into account the FMA efficiency , we estimate a cross sections for the (^{3}He,p) reaction to the gs of approximately ds/dΩ~ 1mb/str at forward angles in the CM, in line with results in ^{40}Ca.

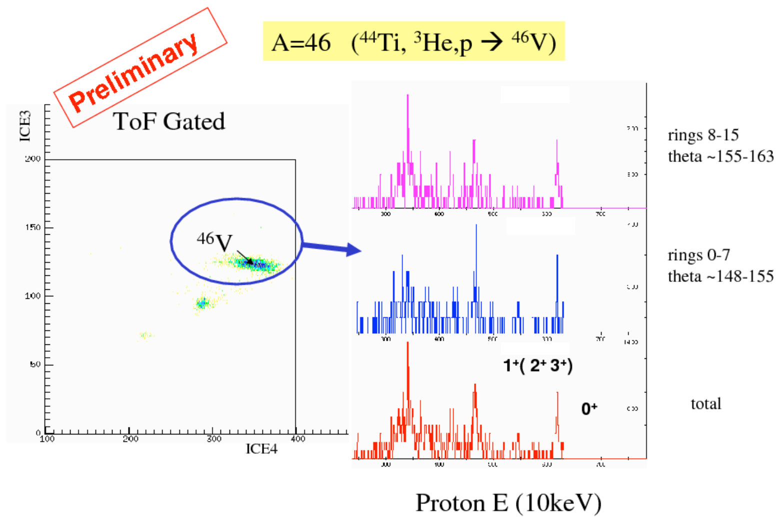

FIGURE 2. Proton spectra for the ^{44}Ti reaction. These are obtained by selecting ^{46}V recoils as seen by the FMA

As discussed earlier, we will concentrate on the ratio $\sigma(0^+)/\sigma(1^+)$. The systematic of this ratio for nuclei up to ^{40}Ca is shown in **Figure 3**. The trend of the experimental data is shown by the red line and as references, a "single-particle estimate" by the blue line and the superfluid limit for isovector pairing by the green line. The "single-particle estimate" includes (i) a spin statistics factor (2J+1), (ii) the probability of a t=0 or a t=1 *np* pair in ^{3}He, and (iii) a LS-jj recoupling coefficient that gives the amplitude of an L=0 pair in a pure j^2 configuration. The single particle estimate varies from 1/9 for an $s_{1/2}$ orbit to 1/3 in the limit of large j. It appears to be some enhancement of the T=1 over the T=0, and one could argue *loosely* that this arises from the T=1 extra-correlations.

The blue point is a preliminary result for the ^{44}Ti. The measured ratio lies close to the value expected within the vibrational scheme, for *n* –phonons [2,3]

$$\sigma(n \rightarrow n+1) = (n+1)\sigma(0 \rightarrow 1)$$

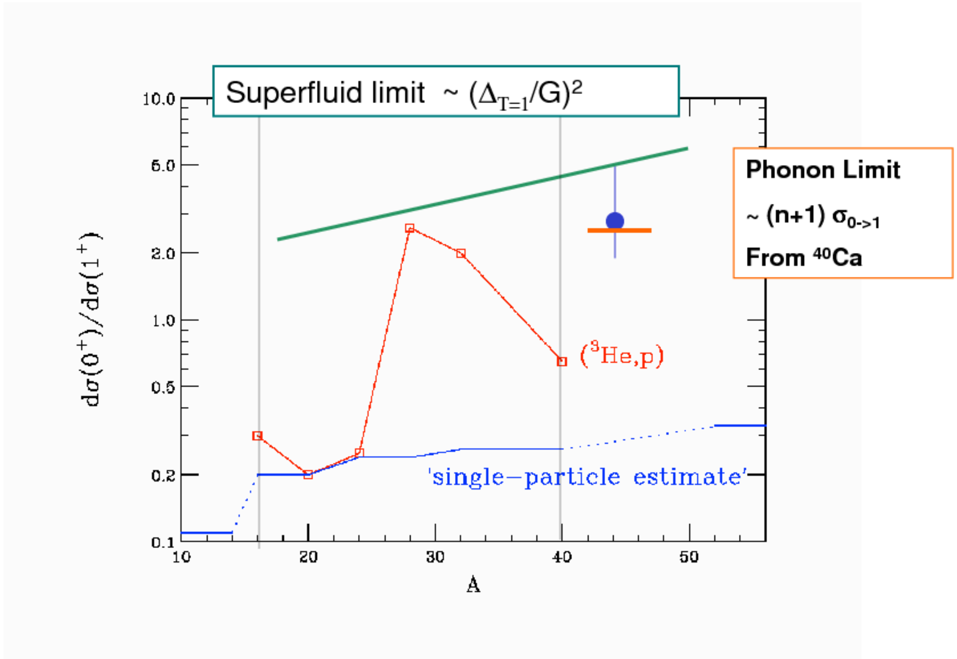

FIGURE 3. Sytematics of $\sigma(0^+)/\sigma(1^+)$ for nuclei up to ^{40}Ca. The preliminary result for the ^{44}Ti experiment is also shown. Single-particle and superfluid (T=1) limits are indicated as references.

With ^{44}Ti interpreted as a two phonon (T=1) state on the doubly magic ^{40}Ca, and from the observed ratios in ^{42}Sc we expect an enhancement $\sigma(0^+)/\sigma(1^+)_{46V} \sim 3$ $\sigma(0^+)/\sigma(1^+)_{42Sc} \sim 2$.

SUMMARY

Direct reactions are unique tools in our experimental study of exotic nuclei. Following earlier studies of the (t,p) and (p,t) reactions, two nucleon transfers provide specific probes to study the amplitude of pairing collective modes.

In particular for *np* pairing, we believe the (^{3}He,p) reaction stands out as an ideal tool to study *np* correlations. The use of radioactive beams require inverse kinematics and we have carried out a proof of principle with stable beams and a successful first experiment with a ^{44}Ti beam at ATLAS.

Reactions like (d,α), (α,d) and (p, ^{3}He) will provide important complementary information and in fact, the (d,α) reaction is planned at GANIL.

The study of *np* pairing in N=Z nuclei using these reactions will constitute a unique program at FRIB/ReA12 and EURISOL. Based on current estimates of N=Z beam intensities at these facilities and improvements in the experimental setups over the pilot experiment described in this talk, one can envision approaching nuclei near ^{88}Ru, in the region where the most collective effects are expected.

Of particular importance for the success of such a program is a parallel development in reaction and structure theory to firmly elucidate this question.

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