Direct observation of the glue pairing the halo of the nucleus $^{11}\text{Li}$

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With the help of a unified nuclear structure–direct reaction theory we analyze the reaction $^1\text{H}(^{11}\text{Li},^{9}\text{Li})^3\text{H}$. The two halo neutrons are correlated through the bare and the induced (medium polarization) pairing interaction. By considering all dominant reaction processes leading to the population of the $1/2^-$ (2.69 MeV) first excited state of $^{9}\text{Li}$, namely multistep transfer (successive, simultaneous and non–orthogonality), breakup and inelastic channels, it is possible to show that the experiment provides, for the first time in nuclear physics, direct evidence of phonon mediated pairing.

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There exists conspicuous circumstantial evidence which testifies to the important role medium polarization effects play in the phenomenon of nuclear superfluidity (see e.g. [1] and refs. therein). In spite of this, a quantitative assessment of it is still lacking. Specially promising in this quest are highly polarizable exotic nuclei, in particular, the light halo nucleus $^{11}\text{Li}$, for which, the balance between bare and induced pairing interactions is strongly shifted in favour of the induced interaction ([2], see also [3], [4], [5], [6], [7]).

In this nucleus, the last two neutrons are very weakly bound ($S_{2\nu} \approx 380\text{keV}$ [8], [9], [10]). If one neutron is taken away from $^{11}\text{Li}$, a second neutron will come out immediately leaving behind the core of the system, the ordinary nucleus $^9\text{Li}$. This result testifies to the fact that pairing is central in the stability of $^{11}\text{Li}$ (see e.g. [11], [12]).

In ref. [2] it has been shown that the two outer (halo) neutrons of $^{11}\text{Li}$ in its ground state attract each other, not only due to the strong nuclear force acting among them, but also and primarily due to the virtual processes associated with the exchange of collective vibrations. In particular, the quadrupole vibration of the $^9\text{Li}$ core, and the dipole vibration associated with the neutron halo field (pigmy resonance of $^{11}\text{Li}$ [13]). Such a pairing mechanism is clearly reflected in the calculated ground state wavefunction of $^{11}\text{Li}$ [8].

$^{11}\text{Li}(gs); 3/2^- = |0\rangle_\nu \otimes |1p_{3/2}(\pi)\rangle$,  

where $\pi$ and $\nu$ indicate proton and neutron degrees of freedom respectively, while $|0\rangle_\nu$ indicates the halo neutron Cooper pair wavefunction, that is,

$$|0\rangle_\nu = |0\rangle + \alpha(|p_{1/2}, s_{1/2})_1^- \otimes 1^-; 0\rangle + \beta(s_{1/2}, d_{5/2})_2^- \otimes 2^+; 0\rangle,$$

with

$$\alpha \approx 0.7, \quad \text{and} \quad \beta \approx 0.1,$$

and

$$|0\rangle = 0.45|s_{1/2}(0)\rangle + 0.55|p_{1/2}(0)\rangle + 0.04|d_{5/2}(0)\rangle,$$

the states $|1^-\rangle$ and $|2^+\rangle$ being the (RPA) states describing the dipole pigmy resonance of $^{11}\text{Li}$ and the quadrupole vibration of the core $^9\text{Li}$ (see [2], see also Tables 11.3 and 11.5 of ref [1]). The intrinsic non–observability of virtual processes (like the exchange of collective vibrations between Cooper pair partners leading to the second and third components of the state $|0\rangle_\nu$) is a fact. However, in those cases in which the experimental tool exists which specifically probes the phenomenon under study, one can force the virtual processes of interest to become real. In this way one could, for example, hope to observe the collective vibrations of $^{11}\text{Li}$ and of $^9\text{Li}$ correlating the two–halo neutrons, with the help of a two–particle transfer process, specific probe of pairing in nuclei ([14], [15]). In what follows we shall show, with the help of a quantitative reaction plus nuclear structure analysis, that the experiment $^1\text{H}(^{11}\text{Li},^{9}\text{Li})^3\text{H}$ recently carried out at TRIUMF ([16]), provides direct evidence of phonon exchange between nuclear Cooper pair partners.
FIG. 1: Representative Nuclear Field Theory–Feynman diagrams associated with correlation process ((a),(b),(c)) and with one– and two–particle pick–up reactions ((i),(j) and (d),(e) respectively) of the halo neutrons of $^{11}\text{Li}$ (Cooper pair, indicated in terms of a double arrowed line). Also shown are the possible diagrams associated with other channels (breakup and inelastic) populating the $1\frac{1}{2}^–$ (2.69 MeV) state: i) one of the neutrons is picked up (the other one going into the continuum, i.e. breaking up from the $^9\text{Li}$ core) together with a neutron from the $p\frac{3}{2}^+$ orbital of the $^9\text{Li}$ core leading, for those events in which the neutron moving in the continuum falls into the $p\frac{3}{2}^+$ hole state, leading to the excitation of the $1\frac{1}{2}^–$ final state ($2^+$ density mode (wavy line)) coupled to the $p\frac{3}{2}^+$ (π). g) the proton field acting once breaks the Cooper pair forcing one of the halo neutrons to populate a $p\frac{3}{2}^+$ continuum state (the other one follows suit), while acting for the second time picks up one of the neutrons moving in the continuum and another one from those moving in the $p\frac{3}{2}^+$ orbital of $^9\text{Li}$ eventually leaving the core in the quadrupole mode of excitation. In (h) the two–step transfer plus inelastic final channel process exciting the $(2^+ \otimes p\frac{3}{2}^+\text{π})$ is shown.

To convey the details of such an analysis, which is based on the nuclear structure description of $^{11}\text{Li}$ reported in [2], Nuclear Field Theory (NFT)–Feynman diagrams (see e.g. refs. [17], [18], [19] and their generalization to deal with reaction processes [20]) are used (Fig.1). In reference [2], the two halo neutrons correlate through the bare interaction (Fig.1(a)) and through the exchange of collective vibrations, leading to self–energy (see [21] and refs. therein) and vertex corrections (boxed processes in Figs.1(c) and 1(b) respectively; see also Eqs. (1)–(4)). Solving the associated eigenvalue problem a bound Cooper pair is obtained ($S_{2n}$=330 keV).

From the diagrams displayed in Figs.1(b) and 1(c), it is easy to understand how the virtual propagation of collective vibrations (in the present case $1^–$ and $2^+$ vibrations) can be forced to become a real process: by transferring one or two units of angular momentum in a two–neutron pick up process. In particular, the correlation mechanism displayed in Figs.1(b) and 1(c) predict a direct excitation of the quadrupole mul-
take into account the interference between the contributions obtained order perturbation theory, instead of a coupled channel
associated with the di
µ
where
the
transition with the 1
(see e.g. [28], [29], [30] as well as [20]), breakup and
can also be excited through a breakup process in which one
50 MeV of excitation energy, we have calculated the corre-
technically demanding calculation which can be considered a

Making use of all the elements discussed above, multistep
transfer to the ground state of
resulting in the inelastic ex-
citation of the 1/2– state.

In Table I we display the probabilities
those associated with successive, simultaneous and
non–orthogonality transfer channels (see also Fig. 3).

\[
\sigma_c = \frac{\pi}{k^2} \sum_l (2l + 1) |S_l^{(c)}|^2, \tag{5}
\]

k being the wave number of the relative motion between the
reacting nuclei.

In keeping with the small values of \( p_l \), in what follows we
take into account the interference between the contributions
associated with the different reaction paths making use of sec-
ond order perturbation theory, instead of a coupled channel
treatment [24] [25] [26] [27]. In particular in the case of the
1/2– (2.69 MeV) first excited state of \(^9\)Li,

\[
\frac{d\sigma}{d\Omega}(\theta) = \frac{\mu^2}{16\pi^2\hbar^2} \left| \sum_l (2l + 1) P_l(\theta) \sum_{c=2}^5 T_l^{(c)} \right|^2, \tag{6}
\]

where \( \mu \) is the reduced mass and \( T_l^{(c)} \) are the transition
data the elements (in the DWBA [22]) associated with the different
channels and for each partial wave.

Making use of all the elements discussed above, multistep
transfer (see e.g. [28], [29], [30] as well as [20]), breakup and
inelastic channels were calculated, and the results displayed
in Figs. 2 and 3 and in Table III. Theory provides an overall
account of the experimental findings. In particular, in connec-
tion with the 1/2– state, this result essentially emerges from
cancellations and coherence effects taking place between the
three terms contributing to the multistep two–particle trans-
fer cross section (see Fig. 3), tuned by the nuclear structure
amplitudes associated with the process shown in Fig. 1(e) as
well as Eqs. 1–4. In fact, and as shown in Figs. 2 and 3 the
contribution of inelastic and breakup processes (Figs. 1(f),(g) and (h) respectively) to the population of the 1/2–
(2.69 MeV) first excited state of \(^9\)Li are negligible as com-
pared with the process depicted in Fig. 1(e). In the case of the
breakup channel this is a consequence of the low bombarding
energy of the \(^{11}\)Li beam (inverse kinematics), combined with
the small overlap between continuum (resonant) neutron \(p_{1/2}\)
wavefunctions and bound state wavefunctions. In the case of
the inelastic process (Fig. 1(h)), it is again a consequence of
the relative low bombarding energy. In fact, the adiabaticity

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\( l \) & 1 & 2 & 3 & 4 & 5 \\
\hline
1 & \( 4.35 \times 10^{-3} \) & \( 1.79 \times 10^{-3} \) & \( 4.81 \times 10^{-6} \) & \( 2.90 \times 10^{-11} \) & \( 3.79 \times 10^{-8} \) \\
2 & \( 3.50 \times 10^{-3} \) & \( 9.31 \times 10^{-4} \) & \( 1.47 \times 10^{-5} \) & \( 1.87 \times 10^{-9} \) & \( 1.09 \times 10^{-6} \) \\
3 & \( 7.50 \times 10^{-4} \) & \( 8.00 \times 10^{-5} \) & \( 2.45 \times 10^{-5} \) & \( 1.25 \times 10^{-8} \) & \( 1.21 \times 10^{-6} \) \\
4 & \( 6.12 \times 10^{-4} \) & \( 9.81 \times 10^{-5} \) & \( 1.51 \times 10^{-6} \) & \( 6.50 \times 10^{-10} \) & \( 2.20 \times 10^{-7} \) \\
5 & \( 1.10 \times 10^{-4} \) & \( 1.18 \times 10^{-5} \) & \( 2.21 \times 10^{-7} \) & \( 4.80 \times 10^{-11} \) & \( 1.46 \times 10^{-8} \) \\
6 & \( 3.65 \times 10^{-5} \) & \( 2.16 \times 10^{-6} \) & \( 7.42 \times 10^{-9} \) & \( 6.69 \times 10^{-13} \) & \( 9.63 \times 10^{-10} \) \\
7 & \( 1.35 \times 10^{-5} \) & \( 6.05 \times 10^{-6} \) & \( 2.88 \times 10^{-9} \) & \( 8.04 \times 10^{-15} \) & \( 1.08 \times 10^{-11} \) \\
8 & \( 4.93 \times 10^{-6} \) & \( 7.78 \times 10^{-7} \) & \( 6.01 \times 10^{-11} \) & \( 4.05 \times 10^{-16} \) & \( 5.26 \times 10^{-13} \) \\
9 & \( 2.43 \times 10^{-6} \) & \( 2.62 \times 10^{-7} \) & \( 7.4 \times 10^{-11} \) & \( 1.26 \times 10^{-16} \) & \( 9.70 \times 10^{-17} \) \\
\hline
\end{tabular}
\caption{Probabilities \( p_l \) associated with the processes described in
the text for each partial wave \( l \). The different channels are labeled
by a channel number \( c \) equal to: \( l \), multistep transfer to
the \(^9\)Li ground state (Fig. 1(d)); \( l\), multistep transfer (Fig. 1(e)),
breakup (Fig. 1(f)), \( l\), breakup (Fig. 1(g)), and \( l\) inelastic processes (Fig. 1(h))
involving in the population of the 1/2– (2.69 MeV) first excited state
of \(^9\)Li. Of notice that the probabilities displayed in columns 1
and 2 result from the (coherent) sum of three amplitudes namely
those associated with successive, simultaneous and
non–orthogonality transfer channels (see also Fig. 3).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Experimental (16) and theoretical differential cross sections
(including multistep transfer as well as breakup and inelastic channels).}
\end{figure}
TABLE II: Integrated two-neutron differential transfer cross sections associated with the ground state (gs (3/2−)) and with the first excited state (2.69 MeV; 1/2−) of 9Li in comparison with the data. In the case of the 1/2− state two calculations have been carried out. One making use of the microscopic wavefunction of ref. [10] (see Eqs. (4) and (5)). A second one in which it is (arbitrarily) assumed that β = 0 (see Eq. (2)). That is, that the only processes populating the first excited state of 9Li are associated with breakup and inelastic channels (see also Fig. 3).

| l | ΔL | Theory | Experiment |
|---|---|---|---|
| gs (3/2−) | 0 | 6.1 | 5.7 ± 0.9 |
| 2.69 MeV (1/2−) | 2 | (β = 0.1) 0.7 | 5 × 10−2 |

FIG. 3: Successive, simultaneous and non-orthogonality contributions to the 1H+11Li,9Li)→9Li differential cross section associated with the 1/2− state of 9Li, displayed in Fig. 2. Also shown is the (coherent) sum of the breakup (c = 3 and 4) and inelastic (c = 5) channel contributions.

parameters ξc,ξN (see eqs. (IV.12) and (IV.14) of ref. [20]) associated with Coulomb excitation and inelastic excitation in the t+9Li channel are larger than 1, implying an adiabatic cutoff. In other words, the quadrupole mode is essentially only polarized during the reaction but not excited. The situation is quite different in the case of the virtual process displayed in Fig. (c). Being this an off–the–energy shell process, energy is not conserved, and adiabaticity plays no role.

Of notice that the final states observed in the two neutron pick up process can, in principle, also be populated in a one–particle pick up process (see Figs. (1i) and (1j)). This prediction could likely be checked with the same experimental setup used in [16].

Summing up, through a unified structure–reaction NFT analysis of the experiment of Tanihata et al [16] we are able to conclude that virtual quadrupole vibrations of 9Li, tailored glue of the halo of 11Li, in its process of propagating from one partner of the Cooper pair to the other has been caught in the act by the external pair transfer field produced by the ISAC–2 facility at TRIUMF, forced to become a real final state and to bring this information to the active target detector MAYA. This is a first in the study of pair correlations in nuclei, providing direct information on the central role polarization effects play in nuclear Cooper pair stabilization.

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