Chapter 8

Nuclear Structure with two-nucleon transfer

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(COOPER, ONE)

I what follows we apply the formalism worked out in the previous Chapter with the help of software developed to calculate absolute two-particle transfer reactions [redacted] induced by both light and heavy ions. ~~For~~ [redacted] ~~simplicity we restrict these application to spherical nuclei.~~

Two examples are treated with special detail. Namely, two-particle transfer in halo unstable nuclei and in superfluid medium heavy nuclei lying along the stability valley.

8.1 The $H(^{11}Li, ^{9}Li)^{3}H$ reaction: evidence for phonon mediated pairing

In what follows the analysis of the two-neutron pickup reaction $^{1}H(^{11}Li, ^{9}Li)^{3}H$ (Tanihata et al 2008) is discussed, setting special emphasis ~~on~~ treating the structure of the process and reaction aspects on equal footing. Special attention is paid to the direct excitation of the $1/2^-$ state of ^{9}Li lying at 2.69 MeV. For this purpose, the importance of inelastic (cf. Ch. 5) and knockout (cf. Ch. 6) channels is considered, let alone successive transfer process. While this processes is the dominant one, the other mentioned two-step channels are found to contribute little to the absolute differential (cf. app. 8 B)

[anti pairing effects]

cross section. These results provide evidence (8.1)a for a new mechanism of pairing correlations in nuclei: pigmy resonance mediated pairing interaction (Barranco et al (2001), see also App. 8.A), which strongly renormalizes the bare, NN - $^1S_0$ interaction (Potel et al 2010). This is but a particular embodiment of phonon mediated pairing interaction found throughout in nuclei (cf. e.g. Barranco et al (1999), Gori et al (2002), cf. also Brink and Broglia (2005), Ch. 10 and Ch. 11). The main difference between light halo exotic nuclei and medium heavy superfluid nuclei lying along the valley of stability, is the role fluctuations play in dressing particles (quasiparticles) and in renormalizing their properties (mass, charge, etc) and their interactions.

Saperstein
Litvinova

While e.g. in Sn-nuclei one can, as a rule, explain observables, in particular two-nucleon transfer absolute cross sections in terms of spectroscopic amplitudes obtained solving the BCS equations in terms of an effective, ω-independent coupling constant (see however Sect. 8.2 (Sn-isotopes, Fig. 1.7 p.14 Thesis Andrea)), this is not possible in the case of ^{11}Li (Barranco et al (2001)).

Barranco, F. (2001) - - - Eur. Phys. J. A 11, 385

Litvinova
Saperstein, etc, etc } refs. World scientific + article PRC Sn

Tanihata, I, ... (2008) - - - PRL 100, 192502

Potel, G. ... (2010) Evidence for phonon... PRL 105; 172502

Brink D.M and Broglia, R.A. (2005) Nuclear Superfluidity, Cambridge University Press, Cambridge.

Barranco, F. .... (1999) PRL 83: 2147-50.

Gori, G., ... (2002) Dynamical correlation effects in deformed nuclei and in nuclei far from the stability valley, PhD Thesis, University of Milan (unpublished)

In particular, the ~~case~~ fact that the first empty single-particle ~~[illegible]~~ state in which one can place a neutron in ^{9}Li is the $s_{1/2}$ virtual state of ^{10}Li, implies a pairing-anti halo effect for the lowest energy unperturbed pair state of ^{11}Li, namely $|s_{1/2}^2(0)\rangle$. Because the bare $^1S_0$ interaction, namely the short range pairing interaction, builds its strength out of many contributions of different, but ever increasing multipolarities, it is not surprising that it cannot bind an $s_{1/2}^2(0)$ Cooper pair, nor mix it with e.g. the $p_{1/2}^2(0)$ resonant configuration with any probability (Barranco et al 2001). In the following Section we ellaborate on this point (see ~~also~~ App 3.A).

8.2

6.1.3 (II)

(Tanihata (2008))

8.1 The $^1H(^{11}Li, ^9Li)^3H$ reaction; evidence for phonon mediated pairing

In what follows we dwell on the nuclear structure information, in particular the origin and nature of pairing in halo exotic nuclei, making use of inverse kinematic $^1H(^{11}Li,^9Li)$ (p,t) ^9Li reaction

6.3

8.1.1 Structure

~~Within this scenario~~ Within the scenario presented in connection with the phenomenon of parity inversion and associated dressing of the $s_{1/2}$ a $p_{1/2}$ virtual and resonant states of ^{10}Li discussed in Sect. 6.2.1, in particular Fig. 6.1.3 (cf. also Fig 8A.1), App. 8A in particular ^{11}Li(gs) corresponds to an unbound $s^2_{1/2}(0)$ configuration (see Fig. 3(II)). The bare residual interaction lowers this configuration by less than 100 keV. On the other hand, the exchange of the quadrupole mode of the ^{9}Li core plus the pigmy resonance of ^{11}Li lead to a neutron Cooper pair bound by about 370 keV, the experimental value being $\approx$ 380 keV. Of notice that the pigmy resonance is the result of a delicate (Baron Münchausen–like) bootstrap process, in which an originally extended neutron halo created by the two unbound neutrons passing by ^{9}Li are, quantum mechanically, forced to slosh back and forth with respect to the proton core field (App. 8C pushing model). In other words, the pigmy resonance is in a very real sense a consequence of (translational) symmetry restoration and of a virtual process (vibrations of an extended neutron field) becoming real as low–lying excitation, after having acted as glue to bind the two outer neutrons to the ^{9}Li core thus generating the weakly, but nonetheless bound ground state of ^{11}Li ~~(see Fig. 3, lower part, and Fig. 3(II), see also ref.[19] and refs. therein)~~, the resulting Cooper pair wavefunction being ⓐ – ⓐ

We are then in presence of a paradigmatic nuclear embodiment of a Cooper's model[20] which is at the basis of BCS theory: a single weakly bound neutron pair on top of the Fermi surface of the ^{9}Li core. But the analogy goes beyond these aspects, and covers also the very nature of the interaction acting between Cooper pair partners. Because of the high polarizability of the system under study, most of the Cooper pair correlation energy stems, according to NFT ~~(see refs. in Fig. 3)~~, to the exchange of collective vibrations, the rôle of the bare interaction being, in this case, minor. In other words, we are in the presence of a nuclear realization of Cooper's model in which a Bardeen–Pines–like lattice phonon induced interaction,[21] Frölich typical of standard metallic superconductors, is taken up by collective vibrations of the nuclear medium. Because one is in possess of the specific tool to probe pairing correlations in nuclei, namely, two–particle transfer reactions ~~(see contribution Potel and Broglia)~~, one can force these virtual processes to become real (see Fig. 6). ⓑ – ⓑ 8.1.1 and 8.1.2

~~Making use of the extension of NFT to reactions[22] (continuum states, already present in embrio in the calculation of the single–particle resonant states of ^{10}Li (see Fig. 3(I))), one can calculate the absolute ^{11}Li(p,t) ^{9}Li$(p_{3/2}(\pi)\otimes 2^+(^9Li); 1/2^-)$ cross section to the first excited state of ^{9}Li, that is, to the lowest member of the ^{8}He quadrupole vibration, coupled to a $p_{3/2}$ proton. As shown in Fig. 5, to do this, one has to take properly into account the successive and non–orthogonality contributions to the transfer amplitude. As a rule, and exception made Q–value ef-~~

6.5

(cf. also Fig 8H.1)

~~It is worth mentioning that the~~

8.3

fects in which single–particle channels become close (see e.g.[23,24] for recent references), the successive contribution to the two–particle transfer cross section is the dominant one, non–orthogonality cancelling much of the already weak, simultaneous contribution. Of notice that similar issues were debated in connection with the proposal of Josephson concerning the possibility of observing a supercurrent across a dioxide layer separating two superconductors, and Bardeen's objection that the pairing gap is zero inside the layer. The answer to such an objection is to be found in the fact that it is α_0 (see Fig. 5 as well a cation to Fig. 14) which controls tunneling and not Δ, a fact that emerges naturally from Gorkov's formulation of superconductivity (see contribution of Potel and Broglia to the present Volume).

Within the framework of nuclear reactions, one in dealing, as a rule, with normal–superfluid tunneling, and thus with the situation discussed by Cohen, Falicov and Phillips in connection with the Josephson–Bardeen discussion ([25–27], see also[28,29]).

Be as it may, the NFT description of the single Cooper pair system ^{11}Li summarized in Fig. 3 together with the NFT reaction description of ^{11}Li(p,t) ^{9}Li (Figs 4 and 5), provide[30] an accurate account of the experimental findings[31]. ~~In particular~~ direct evidence for phonon mediated pairing in nuclei (~~Fig. 5~~). At variance with the case of the infinite system (e.g. normal superconducting metals) in which there is a bound state for any strength of the interaction, in finite FMBS there is a lower limit for the strength below which the system correlates but does not condense. This is what happens around closed shell nuclei, in which the decoupling between occupied and empty states blocking pair condensation, arizes from the gap in the single–particle spectrum observed at magic numbers, and forced upon the system by the "external" mean field produced by all the nucleons on the motion of each single neutron and proton.

C-C ~~Thus~~ Away from closed shell (open shell nuclei), such a (large) single–particle gap disappears, and one is left with rather modest differences in energy between occupied and empty states. Under such circumstances, Cooper pairs condense, the system becomes superfluid, and BCS theory provides an excellent description of nuclear properties. In particular the fact that the mixing between occupied and empty states gives rise to a priviledged orientation in gauge space, and thus to particle number violation. The observation of pairing rotational bands being the fingerprint of nuclear spontaneous symmetry breaking in gauge space. ~~(see Fig. 6)~~ The probing of ~~the~~ such a band (ground state of Sn-isotopes), is the subject of this section.

then give opt. pars. diff. cross section Table

8.2 Pairing rotational band with two-nucleon transfer: Sn-isotopes

p.3 rev. paper sect II A up to the end of p. 5

8.4

Making use of the spectroscopic amplitudes (40)-(41) and of the optical potentials collected in Table 8.2.1 the corresponding absolute differential cross sections have been calculated

associated modified formfactors were worked out (cf. App. 8.C) and the

Adding one further nucleon to ^{10}Li leads to a bound system. In fact, $^{11}_{3}Li_8$ displays a two-particle separation energy $S_{2n} \approx 400$ keV. A NFT description of this system which provides

a quantitative, overall account of the experimental findings,(see[53] and references therein) testifies to the fact that the glue binding the neutron Cooper pair to the ^{9}Li closed shell system are the core quadrupole vibration, and the dipole pigmy resonance resulting from the sloshing back and forth of the neutron halo with respect to the core protons, the bare NN–interaction playing a small role in determining the neutron Cooper pair structure, as testified by the wavefunction[51]

(a)

$$|0\rangle_\nu = |0\rangle + \alpha|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle + \beta|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle, \tag{40}$$

with

$$\alpha = 0.7, \quad \text{and} \quad \beta = 0.1, \tag{41}$$

and

$$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle, \tag{42}$$

the states $|1^-\rangle$ and $|2^+\rangle$ being the (RPA) states describing the dipole pigmy resonance of ^{11}Li and the quadrupole vibration of the core. While these states are virtual excitations which, exchanged between the two neutrons bind them to the Fermi surface provided by the ^{9}Li core, they can be forced to become real with the help of the specific probe of Cooper pairs in nuclei, namely two–particle transfer reactions.

(a)

(b)

Table 8.1.1

Within this context, it is revealing that, the two final states excited in the inverse kinematics, two–neutron pick up reaction ^{1}H(^{11}Li,^{9}Li)^{3}H are, the $|3/2^-\text{gs}(^9\text{Li})\rangle$ and the first excited $|1/2^-, 2.69\text{MeV}\rangle$.[50] (Fig 8.1.2) The associated absolute differential cross sections thus probe, within the NFT scenario, the $|0\rangle$ and the $|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$ component of the Cooper pair wavefunction respectively, the $p_{3/2}$ proton acting as a spectator. It is of notice that the $|1/2^-, 2.69\text{MeV}\rangle$ state of ^{9}Li can be viewed as the $1/2^-$ member of the multiplet resulting from the coupling of the ^{8}He core quadrupole vibration and the $p_{3/2}$ proton. Theory is compared with the experimental findings in Fig. 8.1.3 It reproduces the absolute two–particle differential cross section within experimental errors.

inelastic scatt.

(cf. Ch. 5)

~~While no theory, let alone NFT is able to predict a single small amplitude of a wavefunction like β with great accuracy (due essentially to the limited experimental information concerning the corresponding collective state), it can with uniqueness signal whether a rare channel is open or not.~~ Because detailed, second order calculations of inelastic, break up (cf. Ch. 9) and final state interaction channels, which in principle can provide alternative routes to the $|1/2^-, 2.69\text{MeV}\rangle$ state ~~than that~~ predicted by the NFT (β component), lead to absolute cross sections which are smaller by few orders of magnitude than that ~~shown in~~ Fig. 8.B.2 (excited state),[51] one can posit that quadrupole core polarization effects in $|\text{gs}(^{11}\text{Li})\rangle$, are essential to account for the observation of the $|1/2^-, 2.69\text{MeV}\rangle$ state, thus providing

knockout

(cf. also app. 8.B)

(b)

~~6.1. *Hindsight*~~

~~Essentially three decades ago, the observation of the ^{14}C decay of ^{223}Ra, leaving behind the almost doubly magic nucleus ^{209}Pb was reported in the literature.[54] This observation started a flurry of activity to individuate and explain exotic decay, as the phenomenon was~~

8.1.2 Reaction

Succ. + simultaneous

associated with the direct (simultaneous, successive plus non-orthogonality) two-nucleon transfer process, as shown in

Table 8.1.1

8.5

	f	Theory a)	Experiment b)	
		$\sigma(gs \to f)$ (mb) b)		
~~$^7Li(t,p)^9Li$~~	~~gs~~	~~14.8~~	~~14.7 ± 4.4 c,i)~~	~~[$0.4° < \theta < 103.7°$]~~
$^1H(^{11}Li,^9Li)^3H$	gs	6.1	5.7 ± 0.9	[$20° < \theta < 154.5°$]
	$1/2^-$	0.7	1.0 ± 0.36	[$30° < \theta < 100°$]
~~$^{10}Be(t,p)^{12}Be$~~	~~gs~~	~~2.3 c)~~	~~1.9 ± 0.57 c,j)~~	~~[$4.4° < \theta < 57.4°$]~~
$^{48}Ca(t,p)^{50}Ca$	gs	0.55 c)	0.56 ± 0.17 c,m)	[$4.5° < \theta < 174°$]
$^{112}Sn(p,t)^{110}Sn$, $E_{CM} = 26$ MeV	gs	1301 d)	$1309 \pm 200(\pm 14)$ d,g)	[$6° < \theta < 62.2°$]
$^{114}Sn(p,t)^{112}Sn$, $E_{CM} = 22$ MeV	gs	1508 d)	$1519 \pm 456(\pm 16.2)$ d,g)	[$7.64° < \theta < 62.24°$]
$^{116}Sn(p,t)^{114}Sn$, $E_{CM} = 26$ MeV	gs	2078 d)	$2492 \pm 374(\pm 32)$ d,g)	[$4° < \theta < 70°$]
$^{118}Sn(p,t)^{116}Sn$, $E_{CM} = 24.4$ MeV	gs	1304 d)	$1345 \pm 202(\pm 24)$ d,g)	[$7.63° < \theta < 59.6°$]
$^{120}Sn(p,t)^{118}Sn$, $E_{CM} = 21$ MeV	gs	2190 d)	$2250 \pm 338(\pm 14)$ d,g)	[$7.6° < \theta < 69.7°$]
$^{122}Sn(p,t)^{120}Sn$, $E_{CM} = 26$ MeV	gs	2466 d)	$2505 \pm 376(\pm 18)$ d,g)	[$6° < \theta < 62.2°$]
$^{124}Sn(p,t)^{122}Sn$, $E_{CM} = 25$ MeV	gs	838 d)	$958 \pm 144(\pm 15)$ d,g)	[$4° < \theta < 57°$]
$^{112}Sn(p,t)^{110}Sn$, $E_p = 40$ MeV	gs	3349 e)	3715 ± 1114 e,h)	
$^{114}Sn(p,t)^{112}Sn$, $E_p = 40$ MeV	gs	3790 e)	3776 ± 1132 e,h)	
$^{116}Sn(p,t)^{114}Sn$, $E_p = 40$ MeV	gs	3085 e)	3135 ± 940 e,h)	
$^{118}Sn(p,t)^{116}Sn$, $E_p = 40$ MeV	gs	2563 e)	2294 ± 668 e,h)	
$^{120}Sn(p,t)^{118}Sn$, $E_p = 40$ MeV	gs	3224 e)	3024 ± 907 e,h)	
$^{122}Sn(p,t)^{120}Sn$, $E_p = 40$ MeV	gs	2339 e)	2907 ± 872 e,h)	
$^{124}Sn(p,t)^{122}Sn$, $E_p = 40$ MeV	gs	1954 e)	2558 ± 767 e,h)	
$^{206}Pb(t,p)^{208}Pb$	gs	0.52 c)	0.68 ± 0.21 c,k)	[$4.5° < \theta < 176.5°$]
$^{208}Pb(^{16}O,^{18}O)^{206}Pb$	gs	0.80 c)	0.76 ± 0.18 c,f)	[$84.6° < \theta < 157.3°$]

TABLE ~~III~~.

Absolute value of two–nucleon transfer cross sections ~~The number in parenthesis (last column) corresponds to the statistical errors.~~ associated with the reaction $^1H(^{11}Li,^9Li)^3H$

a) ~~See ref. [11, 71]~~ Potel et al (2010)

b) ~~See ref. [50]~~. Tanihata et al (2008)

~~c) mb~~

d) μb

e) $\mu b/sr$ ($\sum_{i=1}^{N}(d\sigma/d\Omega)$; differential cross section summed over the few (3-7) experimental points).

f) See ref. [51].

g) See refs. [105, 110–114].

h) See ref. [115] .

i) See ref. [116].

j) See ref. [109].

k) See ref. [117].

m) See ref. [118].

n) See ref. [49].

pairing anti-halo Table PRL knockout + inel.

(C) The reason why in the case of ^{11}Li, evidence for phonon mediated pairing is, arguably, inescapable (see also Table 8B.1), is connected with the fact ~~that~~ reaching the limits of stability associated with drip line nuclei, and thus to situations in which medium polarization and spatial quantization effects become overwhelming. In fact ~~one~~ is, in such cases, confronted with elementary modes of nuclear excitation in which dynamic, fluctuation effects are as important as static, mean field effects. Nuclear Field Theory within the Bloch-Horowitz (Dyson) set up which allows one to sum to infinite order little convergent processes are specially suited to study these systems (cf. e.g. Barranco et al, 2001 and Gori et al, 2004). From these studies it emerges a possible new elementary mode of excitation, namely pair addition halo vibrations, of which the $|gs(^{11}Li)\rangle$ state is a concrete embodiment. They are closely connected with a new mechanism to stabilize Cooper pairs, arising from a (dynamical) breaking of gauge invariance (cf. App. 8, A). Their most distinctive feature, namely ~~that~~ of carrying on top a (dipole) pigmy resonance at a relative excitation energy of few MeV, a necessary although not sufficient condition for this new mode to exist, can be instrumental for its characterization.

8.5 a

Gori, G., Barranco, F., Vigezzi, E. and Broglia, R.A. (2004) Parity inversion and breakdown of shell closure in Be-isotopes, Phys. Rev. C, 69 041302.

It could thus be directly observed in an $L=0$, (8.4b) two-particle transfer reaction to excited states, or in terms of E1 decay of the pigmy resonance built on top of it. Within this context, it is an open question whether one could expect to find such a halo pair addition mode, for example, as an excited 0^+ state of ^{12}Be.

Pairing modes of elementary excitation based on s1/2 states at threshold having been found to lead, within the bare, short range, pairing interaction scheme to halo anti-pairing effects (cf. Bennaceur et al (2000), cf. also Hamamoto and Mottelson 2003, 2004). The fact that the separation energy of the halo neutrons (halo Cooper pair) of $^{11}Li(gs)$ is ≈ 400 keV, testifies to the fact that the anti-halo pairing effect is overwhelmed by (dynamical) medium polarization effects.

To conclude this section it is of notice that again, the interweaving of the different elementary modes of nuclear excitation, pairing and pigmy resonances in the present case, in this case, conditioned reaction studies, let alone the possibility to study (pigmy) giant resonances on excited states (cf. e.g. Bortignon et al, (1998), Brink (1955)). ©

Bennaceur, K., - - - (2000) Pairing anti-halo effect, Phys. Lett. B496, 154

Hamamoto, I, and Mottelson, B. R. (2003) Pair correlations in neutron drip line nuclei, Phys. Rev. C68, 034312

Hamamoto, I, and Mottelson, B. R. (2004) Weakly bound s1/2 neutrons in the many-body pair correlation of neutron drip line nuclei, Phys. Rev. C69, 064302.

Brink, D. (1955) Ph.D. Thesis, Oxford University (unpublished)

Bortignon, P.F., Bracco, A. and Broglia, R.A. (1998) Giant Resonances, Harwood Academic Publishers, Amsterdam

(8.6)

~~Virtual processes become real~~

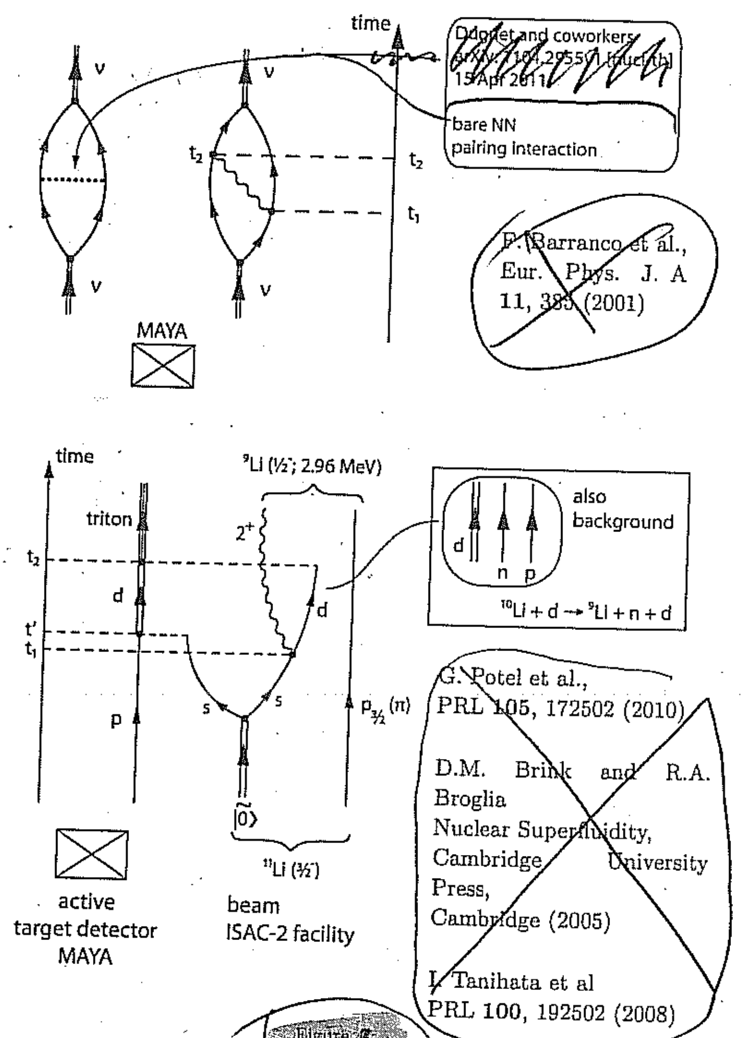

Figura ~~8.1~~ 8.1.1

Ch. 7

Schematic representation of the bare nucleon-nucleon and phonon induced pairing correlation (upper part) NFT diagrams, and of the excitation of the $|{}^9Li(1/2^-; 2.69\,MeV)\rangle$ state, in the TRIUMF experiment reported in Tanihata et al (2008). See also Fig. 8.2.

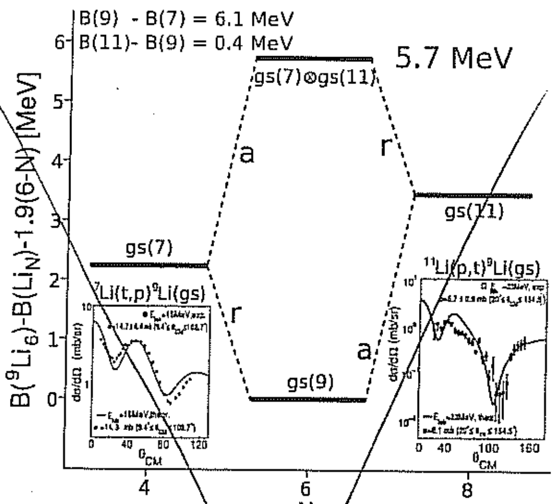

Figure 6. Pairing vibrations around ^{9}Li and absolute cross sections associated with removal [38] (see also [39]) and addition [37] modes. The theoretical absolute differential cross sections for ^{11}Li(p,t) ^{9}Li(gs) (addition: a) is reported in [29]. The theoretical absolute differential cross section associated with the reaction ^{7}Li(t,p) ^{9}Li(gs) (removal: r) was carried out making use of the wavefunction associated with the RPA solution of the pairing Hamiltonian (see [4], [21] and App. A as well as Table I), adjusting the coupling constant G to reproduce the correlation energy of the two neutron holes in the core of ^{9}Li (i.e. in the ground state of ^{7}Li). The optical potential parameters used were taken from ref. [38, 40]. Of notice that throughout in this paper, in particular in connection with this figure, we report absolute differential cross sections (see also Table II).

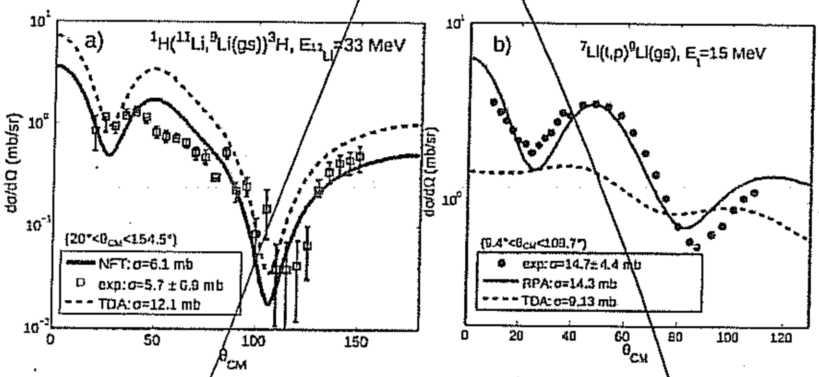

Figure 7. Absolute differential cross section of the pair addition and pair removal modes of ^{9}Li in comparison with the experimental findings. (a) The NFT results of the calculations of the absolute values of $d\sigma/d\Omega$ associated with the reaction ^{11}Li(p,t) ^{9}Li(gs) (pair addition mode) reported in Fig. 6 are compared with those labeled Tamm-Dancoff approximation (TDA), in which the interweaving of single-particle and particle-hole like vibrational modes are neglected while the $|s^2>, |p^2>, |d^2>$ components of the two-neutron wavefunction are normalized to one (see text). (b) The absolute value of the differential cross section $d\sigma/d\Omega$ associated with the reaction ^{7}Li(t,p) ^{9}Li(gs) (pair removal mode) and calculated making use of the RPA two-nucleon transfer spectroscopic amplitudes (X^r, Y^r-values, Table I) also reported in Fig. 6, is compared with that obtained neglecting ground state correlations and labeled TDA (see text).

(8.7)

color

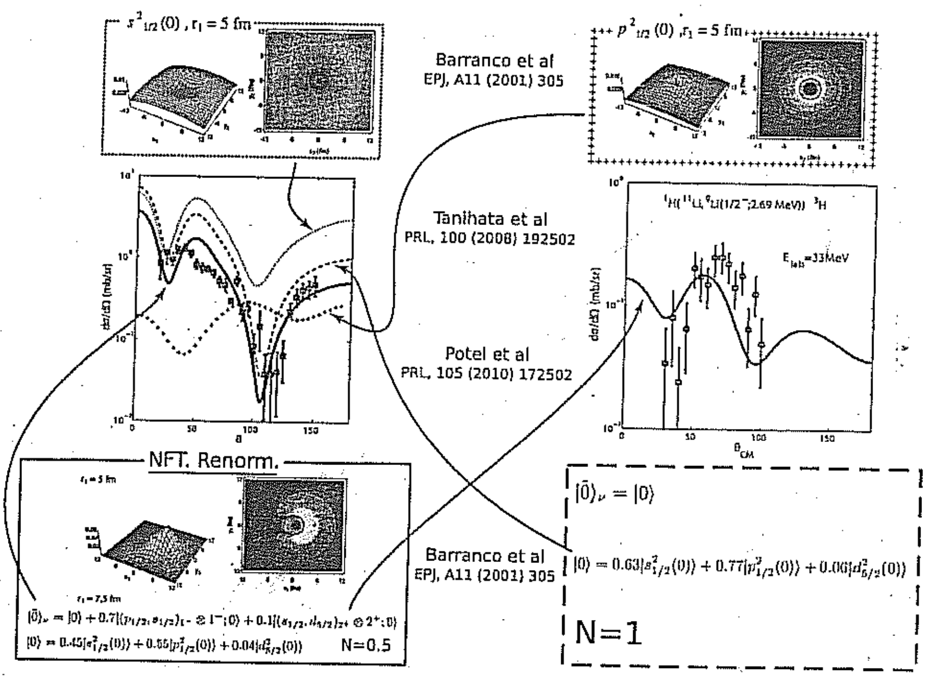

Fig. 8.1.13 Absolute, two-nucleon transfer differential cross section associated with the ground state and the first excited state of ^{9}Li, excited[50] in the reaction $^{1}H(^{11}Li,^{9}Li)^{3}H$[50] in comparison with the predicted differential cross sections[51] calculated making use of spectroscopic amplitudes and Cooper pair wavefunctions calculated in NFT

(reported with permission from Potel and Broglia, in Fifty Years of Nuclear BCS, World Scientific, Singapore (2003) p. 479, Copyright 20013, WSPC)

gregory, give the details of all the contributions continuum

8,8

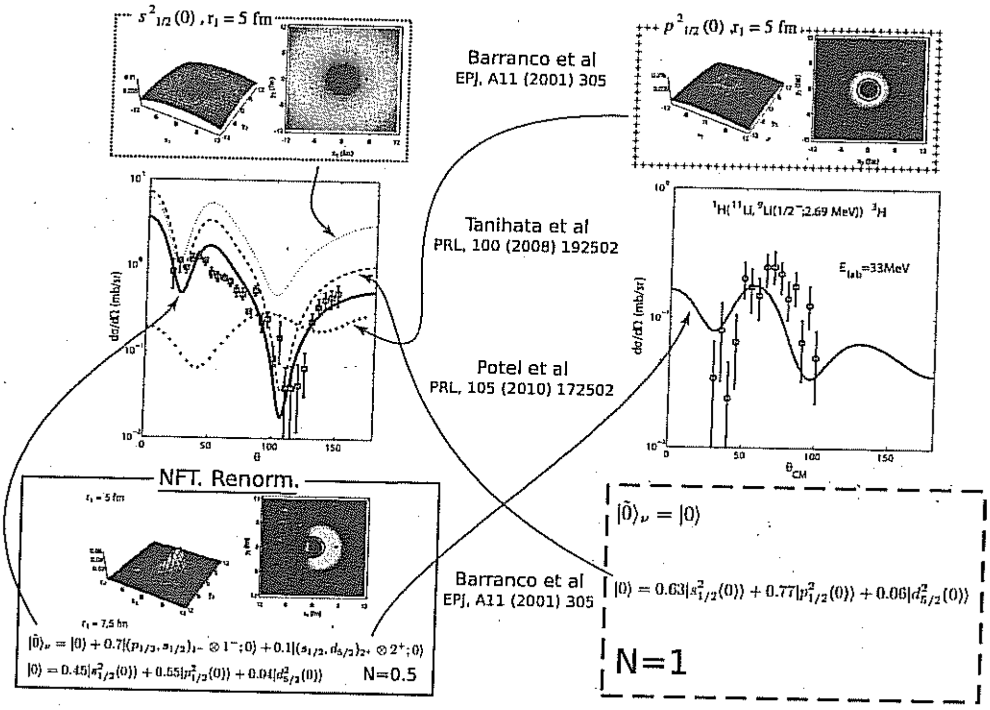
$s^2_{1/2}(0)$, r_1 = 5 fm
$p^2_{1/2}(0)$, r_1 = 5 fm
Barranco et al
EPJ, A11 (2001) 305
Tanihata et al
PRL, 100 (2008) 192502
Potel et al
PRL, 105 (2010) 172502
$^1H(^{11}Li, ^9Li(1/2^-;2.69\ MeV))\ ^3H$
E_{lab}=33MeV
$d\sigma/d\Omega$ (mb/sr)
θ_{CM}
NFT. Renorm.
r_1 = 5 fm
r_1 = 7.5 fm
$|\tilde{0}\rangle_\nu = |0\rangle + 0.7|(p_{1/2}, s_{1/2})_{1^-} \otimes 1^-; 0\rangle + 0.1|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle$
$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$
N=0.5
Barranco et al
EPJ, A11 (2001) 305
$|\tilde{0}\rangle_\nu = |0\rangle$
$|0\rangle = 0.63|s^2_{1/2}(0)\rangle + 0.77|p^2_{1/2}(0)\rangle + 0.06|d^2_{5/2}(0)\rangle$
N=1

Fig. 8.2