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Chapter 2

Pairing with transfer

2.1 Nuclear Structure in a nutshell

The low–energy properties of the finite, quantal, many–body nuclear system, in which nucleons interact through the strong force of strength $v_0(\approx -100$ MeV) and range $a(\approx 1$ fm) are controlled, in first approximation, by independent particle motion. This is a consequence of the fact that nucleons display a sizable value of the zero point (kinetic) energy of localization ($\hbar^2/Ma \approx 40$ MeV) as compared to the absolute value of the strength of the NN–potential[1] $|v_0| = 100$ MeV

The corresponding ground state $|HF\rangle = \Pi_i a_i^\dagger|0\rangle$ describes a step function in the probability of the occupied ($\epsilon_i \leq \epsilon_F$) and empty ($\epsilon_k > \epsilon_F$) states. Pushing the system it reacts with an inertia AM, sum of the nucleon masses. Setting it into rotation, assuming the density $\rho(r) = \sum_i |\langle \mathbf{r}|i\rangle|^2$ ($|i\rangle = a_i^\dagger|0\rangle$) to be spatially deformed, it responds with the rigid moment of inertia. This is because the single–particle orbitals are solidly anchored to the mean field.

Pairing acting an nucleons moving in time reversal states $\nu, \bar{\nu}$ ($\nu \equiv (nlj)$), in configurations of the type $((l)^2_{L=0}, (s)^2_{S=0})$, and lying close to the Fermi energy $\epsilon_F(\approx$ 36 MeV), alter this picture in a conspicuous way[2]. Within an energy range of the order of the absolute value of the pair correlation energy[3] $E_{corr}(\approx -3$MeV)

[1]The corresponding ratio $q = \left(\frac{\hbar^2}{Ma^2}\right)\frac{1}{|v_0|}$ is known as the quantality parameter and was first used in connection with the study of condensed matter (de Boer (1948, 1957); de Boer and Lundbeck (1948); ?). It was introduced in nuclear physics in Mottelson (1998) where its value $q = 0.4$ testifies to the validity of independent particle motion. It is f notice that questions like the one posed in connection with localization and long mean free path were already discussed by Lindemann (1910) in connection with the study of the stability or less of crystals. The generalization to aperiodic crystals, like e.g. proteins (Schrödinger, E. (1944)) was carried out in Stillinger and Stillinger (1990). Its application to the atomic nucleus is discussed in App. 2.C

[2]Broglia, R. A. and Zelevinsky, V. (2013).

[3]In BCS, $E_{corr} \approx \frac{N(0)}{2}\Delta^2$, where $N(0) = \frac{g}{2}$ is the density of states at the Fermi energy and for one spin orientation, $g_i = i/16$ MeV^{-1} ($i = N, Z$) being the result of an empirical estimate which takes surface effects into account (Bohr, A. and Mottelson (1975); Bortignon, P. F. et al. (1998)), while Δ is the pairing gap. For a typical superfluid, quadrupole deformed nucleus like ^{170}Yb, $N(0) = 5.3$ MeV^{-1}, $\Delta \approx 1.1$ MeV and $E_{corr} = -3.2$ MeV (Shimizu, Y. R. et al. (1989)).

Proceeding of a Conference held at Northeastern University, Boston, Eds. R. Arnowitt and Pran Nath, MIT Press, Cambridge, Mass. 311 (1976)

state which is abnormal in the nuclear case, but the normal state associated with closed shell systems[12]. It is of notice nonetheless, the role pairing vibrations play in the transition between superfluid and normal nuclear phases (cf. Fig. 2.1.2) as a function of the rotational frequency (angular momentum) as emerged from the experimental studies of high spin states carried out by, among others, Garrett and collaborators[13].

From Fig. 2.1.2 it is seen that while the dynamic pairing gap associated with pairing vibrations leads to a $\approx 20\%$ increase of the static pairing gap for low rotational frequencies, it becomes the overwhelming contribution above the critical frequency[14]. In any case, the central role played by pairing vibrations within the present circumstances is that to restore particle–number conservation, another example after that provided by the quantality parameter and by its generalization to pair motion, of the fact that potential functionals are, as a rule, best profited by special arrangements of fermions (spontaneous symmetry breaking), while fluctuations restore symmetry[15].

Within this context, there are a number of methods which allows one to go beyond mean–field approximation (HFB). Generally referred to as number projection methods[16](NP), they make use of a variety of techniques (Generator Coordinate Method, Pfaffians, etc.) as well as protocols (variation after projection, gradient method, etc.). The advantages of NP methods over the RPA is to lead to smooth functions for both the correlation energy and the pairing gap at the pairing phase transition between normal and superfluid phases. That is, between the pairing vibrational and pairing rotational schemes[17].

The above results underscore the fact that, at the basis of an operative coarse grained approximation to the nuclear many–body problem (within this context cf. App. 1.D, in particular the discussion following Eq. 1.D.5), one finds a judicious choice of the collective coordinates[18]. In other words, pairing vibrations are elementary modes of excitation containing the right physics to restore gauge invariance through their interweaving with quasiparticle states. Within the framework of the above picture, one can introduce at profit a collective coordinate α_0 (order parameter) which measures the number of Cooper pairs participating in the pairing condensate, and define a wavefunction for each pair $\left(U'_\nu + V'_\nu a'^{\dagger}_\nu a'^{\dagger}_{\bar{\nu}}\right)|0\rangle$ (indepen-

[12]See Potel, G. et al. (2013a) and refs. therein. Also Potel, G. et al. (2013b) in connection with the closed shell system ^{132}Sn.

[13]cf. Shimizu, Y. R. et al. (1989); cf. also Brink, D. and Broglia (2005), Ch. 6 and references therein.

[14]Shimizu, Y. R. et al. (1989), Shimizu, Y. R. and Broglia (1990), Shimizu, Y. R. (2013), Dönau, F. et al. (1999) Shimizu, Y. R. et al. (2000).

[15]??. Anderson and Stein (198), Anderson (1976).

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[16]cf. Ring, P. and Schuck (1980), Egido, J. L. (2013), Robledo, R. M. and Bertsch (2013); cf. also Frauendorf, S. (2013), Ring, P. (2013), Heenen, P. H. et al. (2013), and references therein.

[17]Figs. 2.1.1, 2.1.3, 2.1.4, see also Fig. 2.4.1 and Sects. 2.4.2 and 2.5; cf. Bès, D. R. and Broglia (1966), Bohr, A. and Mottelson (1975) and references therein.

[18]In this connection, we quote allegedly from S. Weinberg: "In solving a problem you may choose to use the degrees of freedom you like. But if you choose the wrong ones you will be sorry".

15 P.W. Anderson and D.L. Stein, Broken symmetry, emergent properties, dissipative structures, life: are they related? In Basic Notions of condensed matter, P.W. Anderson, p. 263 Benjamin, Menlo Park, CA (1984)

P.W. Anderson, Uses of solid state analogies in elementary particle theory, in Gauge theories and modern field theory, title

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