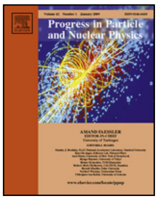
Progress in Particle and Nuclear Physics 78 (2014) 24–90

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp



Review

Overview of neutron–proton pairing

S. Frauendorf[a], A.O. Macchiavelli[b,*]

[a] Department of Physics, University Notre Dame, Notre Dame, IN 46556, United States
[b] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States

ARTICLE INFO

Keywords:
Isovector vs. isoscalar pairing
HFB theory
Shell model
Binding energies
Rotational bands
Beta decay

ABSTRACT

The role of neutron–proton pairing correlations on the structure of nuclei along the $N = Z$ line is reviewed. Particular emphasis is placed on the competition between isovector ($T = 1$) and isoscalar ($T = 0$) pair fields. The expected properties of these systems, in terms of pairing collective motion, are assessed by different theoretical frameworks including schematic models, realistic Shell Model and mean field approaches. The results are contrasted with experimental data with the goal of establishing clear signals for the existence of neutron–proton (*np*) condensates. We will show that there is clear evidence for an isovector *np* condensate as expected from isospin invariance. However, and contrary to early expectations, a condensate of deuteron-like pairs appears quite elusive and pairing collectivity in the $T = 0$ channel may only show in the form of a phonon. Arguments are presented for the use of direct reactions, adding or removing an *np* pair, as the most promising tool to provide a definite answer to this intriguing question.

Contents

---

[*] Corresponding author.
E-mail address: aomacchiavelli@lbl.gov (A.O. Macchiavelli).

http://dx.doi.org/10.1016/j.ppnp.2014.07.001
0146-6410/

1. Introduction

More than 50 years ago Bohr, Mottelson and Pines [1], suggested a pairing mechanism in the atomic nucleus analogous to that observed in superconductors. Since then, a wealth of experimental data has been accumulated, supporting the important role played by *nn* and *pp* "Cooper pairs" in modifying many nuclear properties such as deformation, moments of inertia, alignments, etc. [2–4]. Due to advances in experimental techniques and sensitive detector systems, together with the new possibilities available with radioactive beams, we are seeing a renaissance of nuclear structure studies, in particular, along the $N = Z$ line. Of interest here is the role played by the isoscalar ($T = 0$) and isovector ($T = 1$) pairing correlations.

For almost all known nuclei, i.e. those with $N > Z$, the pair correlated state consists of neutron (*nn*) and/or proton (*pp*) pairs coupled to angular momentum zero and isospin $T = 1$. For nuclei with $N \approx Z$, the protons and neutrons near the Fermi surface occupy identical orbitals, which allows for a different type of pairs consisting of a neutron and a proton (*np*). The *np* pairs can couple to angular momentum zero and isospin $T = 1$ (isovector), or, since they are no longer restricted by the Pauli exclusion principle, they can couple to $T = 0$ (isoscalar) and $J = 1$. Fig. 1 illustrates the two types of pairs for the LS coupling scheme, which applies only for light nuclei. For medium-mass nuclei the spin–orbit potential induces the *jj* coupling. Fig. 2 shows the experimental effective interaction between two nucleons derived by Molinari et al. [5] and Schiffer and True [6]. As expected for a short range interaction, the favored angular momenta are $J = 0$ for $T = 1$ pairs and $J = 1$ or $J = J_{max}$ for $T = 0$ pairs. Charge independence of the nuclear force implies that for $N = Z$ nuclei, $J = 0,\ T = 1$ *np* pairing should exist on an equal footing with $J = 0,\ T = 1$ *nn* and *pp* pairing. There is convincing evidence for this expectation that will be reviewed. However, it is an open question whether strongly correlated $J = 1,\ T = 0$ *np* pairs also exist. Another interesting question relates to the consequences of the strong attraction between the proton and neutron in a $J = J_{max},\ T = 0$ pair. Both questions are the focus of this review.

We believe it is important, right at the start, to clarify what we mean by "pairing" in the context of this work. While it is obvious that a strong pairing force is present in the $T = 0$ channel, the question is whether or not a correlated state can be formed. This correlated state is that in analogy to the pair phase of superconductors and superfluids. Far from the thermodynamic limit, the definition of such state is to be discussed in detail. In fact, as simple models and general arguments indicate, the control parameter that induces the transition between a normal system and a pair correlated depends not only on the strength of the force G but also on the available degeneracy Ω and the single particle spacings D, usually in the form $G\Omega/D$. In a mean field approach there is a pair field and a correlation energy that comes with it. In the context of exact solutions (either simple soluble models, or the Shell Model,) a careful definition is needed. Many authors have used the same terms as "correlation energy", "number of pairs", "order parameter", "paired phase" but meant something different. This has lead to a certain degree of confusion, in particular with respect to the question: "Is there isoscalar *np* pairing?" We adopt the following point of view: The "paired" wave function must substantially deviate from the "unpaired" one by correlating nucleons into pairs. The amount of such correlations can be quantified by the expectation value of the order parameter, which is the pair transfer matrix element, or the correlation energy, which is the difference between the expectation values of the pair interaction between the correlated state and some uncorrelated reference state. Such a definition relates the nuclear pairing phenomena with superconductivity and superfluidity, which represent the limit of very large particle number. However, one has always to keep in mind that the nucleus is a relatively small -mesoscopic- system. The neutron–proton pair phenomena which will be discussed appear in nuclei with $A < 100$, for which the number of