Evidence for Pair Correlation Effects in Heavy Ion Reactions

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Abstract. The study of the $^{12}\text{C}(^{14}\text{N},^{14}\text{N})^{12}\text{C}$ reaction was performed at 28 and 35 MeV beam energies. The results were analyzed in the frame of the EFR-DWBA (Exact-Finite-Range Distorted Wave Born Approximation) assuming the simultaneous and sequential transfer of a np pair. The angular distributions, fairly reproduced in the first case, confirm the validity of the generalized BCS (Bardeen–Cooper–Schrieffer) theory to explain this behaviour. Moreover, this process could be regarded as a possible Nuclear Josephson Effect.

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1. Introduction

In almost all models dealing with the nuclear structure, the pairing term is generally regarded as a residual interaction. However, in many cases, this interaction can be so strong as to promote a process rather than another one, or to produce particular effects. In particular, in multi-nucleon transfer reactions pairing correlations can play a crucial role.

The aim of this work was to emphasize the importance of the pairing correlations during the $^{12}\text{C}(^{14}\text{N},^{14}\text{N})^{12}\text{C}$ transfer at 28 and 35 MeV. Moreover, since the possible pairing interaction between the transferred particles makes the pair a bound state (before, during and after the transfer), the pairing correlations could be regarded as a possible evidence of Nuclear Josephson Effect [1–3]. This effect, due to the transfer of two paired nucleons at energies below the same barrier energy, can be
regarded as the tunneling of the nucleon pair through the barrier. The main feature of this effect is the enhancement of transfer probability compared to the theoretical one. We can recognize an analogy with the Cooper pairs tunneling through a junction made up of two coupled superconductors. Also in this case the tunneling supercurrents are larger than the supercurrents expected when we observe the two simultaneous electron tunnelings [4, 5].

A brief introduction to the generalized BCS theory is presented in Section 2, an application to the $^{14}\text{N} + ^{12}\text{C}$ nuclear system is shown in Section 3, while the theoretical analysis of the $np$ transfer is presented in Section 4. The results and conclusions are summarized and discussed in the last section.

2. The Generalized BCS Theory

A generalization of the BCS theory has recently [13] been proposed, starting from the nucleon-nucleon correlations and, in particular, by considering the possibility of having $np$ correlations. We can write the Hamiltonian for the many body system as follows

$$H = \sum_{ij} \langle i|T|j \rangle C_i^+ C_j + \frac{1}{4} \sum_{ijkl} \langle ij|v_{\alpha}|kl \rangle C_i^+ C_j^+ C_k C_l, \quad (1)$$

where $ijkl$ are indices defining the single-particle states, $C_i^+$ and $C_i$ are creation and annihilation particle operators and $T$ is kinetic energy operator. As the generalized BCS theory prescribes, we can rewrite $H$ as follows

$$H = E_0 + H_{qp} + H_{qp-int}, \quad (2)$$

where $E_0$ is quasi-particle vacuum energy, $H_{qp}$ describes the elementary quasi-particle excitations and $H_{qp-int}$ takes into account the quasiparticle interactions that we think are weak.

Neglecting the $H_{qp-int}$ term, the resulting Hamiltonian is not invariant with respect to a set of symmetries. To avoid this problem, the Hamiltonian (2) is replaced by the reduced Hamiltonian

$$H' = H - \lambda_p N_p - \lambda_n N_n - \omega J_x$$

$$- \sum_{LM \geq 0} \chi_{LM} (1 + \delta_{M0})^{-1} [Q_{LM} + (-1)^M Q_{-m}], \quad (3)$$

where the added terms take into account the broken symmetries (parity violation, rotational invariance and permanent deformation of quasi-particle ground state) and are defined so that the physical observables assume the expectation value [13].

Using this expression of the Hamiltonian of the system, we can deduce these BCS equations:

$$\begin{pmatrix}
(\mathcal{H} - c) & \Delta \\
-\Delta^* & -(\mathcal{H} - c)^*
\end{pmatrix}
\begin{pmatrix}
U_i \\
V_i
\end{pmatrix} = E_i \begin{pmatrix}
U_i \\
V_i
\end{pmatrix} \quad (4)$$