ISTITUTO NAZIONALE DI FISICA NUCLEARE
Gruppo Collegato di Messina

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EVIDENCE FOR PAIR CORRELATION EFFECTS IN HEAVY ION REACTIONS

L. Auditore*, R. C. Barná*, V. D'Amico*, D. De Pasquale*,
A. Italiano◇, A. Trifiró*, M. Trimarchi*
◇*Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Messina,*
**Dipartimento di Fisica, Universitá di Messina,*
I-98166 Vill. S. Agata, Messina, Italy

Abstract

The study of (35 MeV) $^{14}N + {}^{12}C$ elastic transfer reaction has been performed. The experimental data have been fitted by taking into account np pair correlations by means of EFR-DWBA (Exact-Finite-Range Distorted Wave Born Approximation) analysis. The angular distribution, fairly reproduced, confirms the validity of the generalized BCS (Bardeen-Cooper-Schrieffer) theory to explain this behaviour. As a consequence, evidence for a possible nuclear Josephson effect has been found.

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1 Introduction.

Since the end of the sixties, many physicists were interested in the study of a nuclear effect which has an analogous one in the superconductivity: the *Josephson effect*[1−3]. The Josephson effect is two paired nucleon transfer at an energy below Coulombian barrier energy. This process can be seen as tunneling of the nucleon pair through the barrier. The main element of this effect is the enhancement of transfer probability compared to the theoretical one. One sees a perfect analogy with the Cooper pairs tunneling through a junction made up by two coupled superconductors. In this case, in fact, we can note that the tunneling supercurrents are greater than the supercorrents that we expect to observe in two electron tunneling[4,5].
Up to now, physicists studied the nuclear Josephson effect analyzing two like-particles transfer reactions. Aim of this work is the study of the nuclear Josephson effect when the transferred nucleon pair does not consist of identical nucleons but by a proton and a neutron.
The results found for the reactions we can found in literature, are expected to count for even in this case, owing to the charge indipendence of strong interaction.
Experimental data analysis was performed by the EFR-DWBA method, using SATURN-MARS code[6], by means of the generalized BCS theory.

2 The generalized BCS theory.

The generalized BCS theory basis on nucleon-nucleon correlations and, in particular, it considers the possibility to have n-p correlations and their intensity. The starting idea of this theory is to write the many body system Hamiltonian

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

where *ijkl* are indexes defining the single-particle states, C_i^+ and C_i are creation and annihilation particle operators and T is kynetic energy operator, as follows:

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

where E_0 is quasi-paticle vacuum energy, H_{qp} describes the elementary quasi-particle excitations and H_{qp-int} should consider the quasiparticle interactions we think to be weak ones.

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

$$\begin{pmatrix} (\mathcal{H}-\rfloor) & \Delta \\ -\Delta^* & -(\mathcal{H}-\rfloor)^* \end{pmatrix} \begin{pmatrix} \mathbf{U}_i \\ \mathbf{V}_i \end{pmatrix} = E_i \begin{pmatrix} \mathbf{U}_i \\ \mathbf{V}_i \end{pmatrix} \tag{3}$$

that can be written in a compact form

$$\kappa \mathbf{X}_i = E_i \mathbf{X}_i \tag{4}$$

where

$$\kappa = \begin{pmatrix} (\mathcal{H}-\rfloor) & \Delta \\ -\Delta^* & -(\mathcal{H}-\rfloor)^* \end{pmatrix} \tag{5}$$

In this equations $\mathcal{H}$ is the Hartree-Fock Hamiltonian, E_i are quasi-particle energies, $\mathbf{X}_i$ are the transformation vectors between particle operators and quasi-particle operators, which are used in Bogoliubov transformation[7,13)]. Moreover, Δ is pair potential and c is defined so that includes the terms relative to the broken simmetries (parity violation, rotational inveriance and permanent deformation of ground quasi-particle state).

The BCS equations are solved with an iterative method and in their expressions is included even the *pairing tensor t*. This is very important to take account of *p-n* pairing. In fact, for this kind of pairing there are two possibilities; that is we can have two pair fields: one with isospin *T=0*, *isoscalar field*, and one with isospin *T=1*, *isovector field* [8,11,12,14)].

Goodman demonstrated that the coesistence of the two pair field is possible[14)]. This situation is more complicated than two like-particles pairing; in fact, in this case we can have only one pair field, the isovector pairing *T=1*.

Now, let consider the many body sistem hamiltonian in terms of coupling costants

$$H = \sum_{jmt} \epsilon_{jt} a^+_{jmt} a_{jmt} - \frac{1}{4} \sum_{jmj'm'} \sum_{tt'} G_{tt'} a^+_{jmt} a^+_{\overline{jmt'}} a_{\overline{j'm't'}} a_{j'm't} \tag{6}$$

where ϵ_{jt} is single-particle energy, *jmt* identify the single-particle state, t is the isospin projection, a^+_{jmt} (a_{jmt}) is creation (annihilation) particle operator, $a_{\overline{jmt}} = (-1)^{j-m} a_{j-mt}$ and $G_{tt'}$ are the three coupling costants which characterize pairing interaction.

When we have $\epsilon_{jp} = \epsilon_{jn}$ and the coupling costants are identical, $G_{nn} = G_{pp} = G_{np} = G$, the Hamiltonian describes an isovector field where all the three kinds of pair are taken in account in the same way, at least as far as the interaction is concerned. As a consequence, in N=Z nuclei pairing energies Δ_{nn}, Δ_{pp} and Δ_{np} are expected to be the same. Instead, when we consider the isoscalar pairing T=0, the three coupling

costants aren't the same; in paticular, we have G_{nn} =G_{pp} = 0 and $G_{pn} \neq 0$ because we cannot have an isoscalar field when the pair is made up of two like-particles.
Another fundamental consequence of the existence of two pair fields for *n-p* pairing is their competition[15)].
By recent study performed on this argument, it has been deduced that in *N=Z* nuclei the *T=0* pairing dominartes the *T=1* pairing. Neverthless, when the excess of neutrons enhances, the *T=1* pairing become stronger, then competition of the two couplings is more significant. It has been demonstrated that when there is two neutron excess, the two pairing modes are of similar intensity. But when this excess is greater than two unities, *T=1* pairing is stronger and can prevail on *T=0* pairing. This argument is right for $A < 40$ nuclei. For other nuclei, the situation is not so simple.
The generalized BCS theory appears as a fair theory to justify physical phenomena connected to the existence of strong pair correlations. On the other hand, since the Josephson effect can be explained supposing a strong pair interaction between the two nucleons transferred in a transfer reaction through the Coulombian barrier, we try to interpret experimental data to highlight a possible nuclear Josephson effect when the transferred pair is a *pn* pair.

3 Pair nucleon transfer reactions.

The nucleon pair transfer reactions are a powerful tool to study pairing correlations in nuclei. In literature, the angular distibution for $^{32}S(90MeV)$ + ^{30}Si reaction shows a disagreement between experimental and theoretical angular distribution[3)].
Since the studied reaction is an elastic transfer, the total cross section is due to the following terms: one referred to elastic scattering and the other are related to the transfer process. In the low angle region the Rutherford scattering dominates; in the backward angle region a set of oscillations appears. The EFR-DWBA approach, allows to reproduce the low angle distribution satisfactorily but not the experimental data for the region in which transfer process prevails. Moreover, the experimental distribution shows a phase displacement between experimental and theoretical oscillations.
This disagreement can be considered as a proof of the existence of strong pair correlations between the protons transferred: these correlations are so strong that a nucleon pair current is generated, in which paired nucleons occupy coherent states. In this case, the pairing intensity, neglected by EFR-DWBA method, favours the nucleon pair transfer as binded state and this causes the enhancemet of cross section. There

is a Cooper pair transfer through the Coulombian barrier. Since EFR-DWBA neglects the pairing correlations, this method cannot be used to reproduce experimetal data.

4 The $^{12}C(^{14}N,^{14}N)^{12}C$ elastic transfer reaction.

To study the possible evidence for nuclear Josephson effect in the case of *np* pair transfer, we used the $^{12}C(^{14}N,^{14}N)^{12}C$ elastic transfer reaction, performed at 35 MeV[9)]. Let us consider a general case of an elastic scattering between heavy ions where the interacting ions differ for *n* nucleons. Let suppose *n=2*, as well as in our case. If the two nucleons by which the interacting nuclei are different, are transferred, the outgoing channel isn't distinguishable from elastic scattering. The two processes, in fact, can be seen as in *Fig.*1 and *Fig.*2

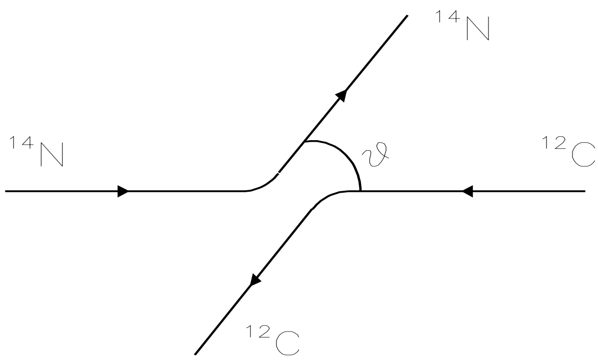

Figure 1: *Feynman-like diagram of pure elastic scattering.*

The cross section for elastic transfer comes from these two contributions.

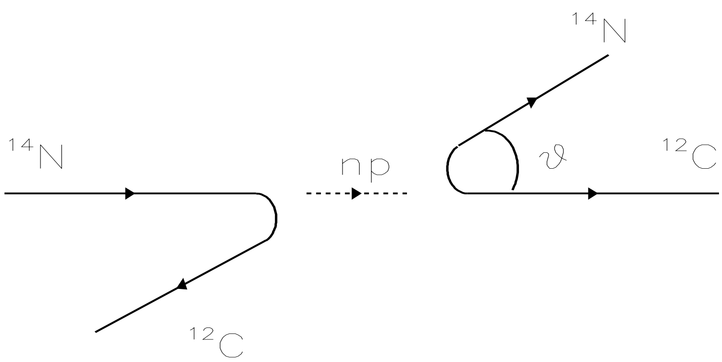

Figure 2: *Feynman-like diagram of pure transfer process.*

From the First Principles of Quantum Mechanics, one has to coherently sum the contributions of two processes, the elastic and transfer amplitudes, so that the total cross section is reproduced[10)].

The transfer reactions depend on two spectroscopic factors: one referred to the transfer of cluster from incident ion and the other referred to the capture of the cluster by target. On the other hand, in the elastic transfer reactions, the cores are identical then even the two spectroscopic factors should be identical.

5 Experimental results.

In the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction studied at 35 MeV two processes contribute to the total cross section: elastic scattering, which determines its form to low angles, and the transfer process, which is displayed in backward angles region with the presence of oscillations.

*Fig.*3 shows the experimental cross section vs. $\theta_{c.m.}$, for the considered reaction.

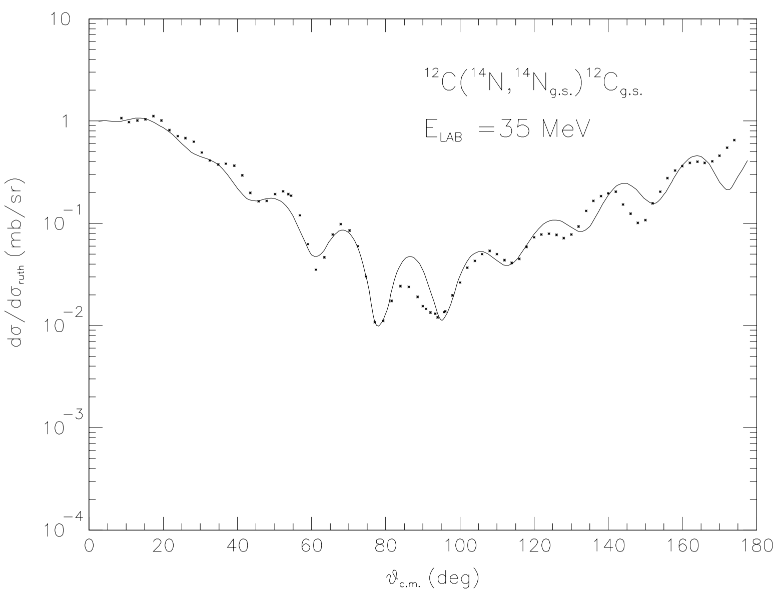

Figure 3: *Fit of experimental to Rutherford cross section ratio for the* $^{12}C(^{14}N,^{14}N)^{12}C$ *reaction at E(*^{14}N*)=35 MeV.*

By properly applying the DWBA in its EFR approximation, one can easily get a quite satisfactory fit (solid line) to the experimental data.

From a physical point of view, the fair reproduction of the angular distribution for the studied elastic transfer reaction allows us to claim that a coherent superposition of elastic and one-step d-transfer processes does exist, so giving an indirect proof for the nuclear Josephson effect, by supposing strong pair correlations between the transferred nucleons[3)].

One infers that *the pairing interaction is so strong that gives rise to np pair current flowing by donor to acceptor nucleus; the nucleon pair transition is favoured to enhance the experimental cross section with respect to the theoretical expected one.*

This pairing has another consequence: the coherence of nuclear states interested by transfer process.

The generalized BCS theory, which considers the pairing interaction not as a simple residual interaction but as the main interaction so that experimental data can be reproduced, appears in this way confirmed.

EFR-DWBA analysis of deuteron transfer (as cluster) allows to reproduce experimental data in a fair way.

One can state that evidence of nuclear Josephson effect has been shown even in the case of *np* transfer, since the strong pair correlations found in this case produce an enhancement of *np* pair transfer probability if compared to the single-nucleon transfer one. The pair correlations investigated, lead to say that single-particle states paired to form coupled *np* state are coherent states. For this phase coherence, we can say that the transferred pair makes a tunneling strongly favoured through the Coulombian barrier and since the two particles are strongly interacting, tunneling current is so to enhance *np* pair transfer probability, giving rise to Josephson effect.

The optical potential parameters used in these analysis are reported in *Table* 1:

	V_0	W	a_0	a_w	r_0	r_w	r_c
Ingoing channel	90	2.2	0.68	0.65	1.02	1.55	1.55
Outgoing channel	90	2.2	0.68	0.65	1.02	1.35	1.55

Table 1: *Optical potential parameters for the* $^{12}C(^{14}N,^{14}N)^{12}C$ *reaction.*

6 Conclusions.

The study of $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at 35 MeV confirms that strong pair correlations exist for the transferred pair so that we have a good fit of experimental transfer data supposing that transfer process take place in one step, when simultaneous transfer of the two nucleons occurs. This can be assumed as an indication of the existence of nuclear Josephson effect in the studied process.
In superconductor Josephson effect the generated supercurrents pass through the insulating barrier then the inverse process should give rise to the same barrier transition probability for Cooper pairs as for direct process.
In the nuclear case for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction, we get that transfer probability for direct reaction should be *analogous* to transition probability for the inverse one[1].
On the other hand, this should mean that time invariance is conserved, that is a property of strong interaction which dominates the reaction. Moreover, since in our reaction an elastic transfer occurs, the direct reaction is identical to the inverse one, giving us a further affinity between superconductors and nuclear matter.

This close analogy between solid-state and nuclear physics shows once more how far fields of Physics can be described by a *scale-invariant* formalism, so stimulating further investigations both theoretically and experimentally on this subject. Analysis of the same reaction, at different energy, is in progress.

[1] i.e. direct reaction cross section, $\sigma_{(a\rightarrow b)}$, and inverse reaction cross section, $\sigma_{(b\rightarrow a)}$, are connected by the relation

$$\frac{\sigma_{(a\rightarrow b)}}{(2I_A+1)(2i_a+1)p_\alpha^2} = \frac{\sigma_{(b\rightarrow a)}}{(2I_B+1)(2i_b+1)p_\beta^2} \tag{7}$$

where p_α and p_β are relative moments of a respect to A and of b respect B).

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