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STUDY OF THE REACTION MECHANISM OF THE $^{12}C +^{14} N$ PROCESS AT 28 AND 35 MeV

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Abstract

The study of the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction was performed at 28 and 35 MeV beam energy. 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.

The pairing interaction is generally regarded as a residual interaction almost in all nuclear structure models. However, in many cases this interaction can be so strong to promote a process rather another or to give rise to particular effects. In multi-nucleon transfer reactions pairing correlations can be important. The task of this work was to emphasize the importance of the pairing correlations during the $^{12}C(^{14}N,^{14}N)^{12}C$ transfer at 28 and 35 MeV. Morever, since the possible pairing interaction between the transferred particles make 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, 2, 3]. This effect, due to two paired nucleon transfer at an energy below the Coulombian barrier energy, can be seen as the tunneling of the nucleon pair through the barrier. The main element of this effect is the enhancement of transfer probability compared to the thoeretical one. We can see an analogy with the Cooper pairs tunneling through a junction made up of two coupled superconductors. In this case, in fact, we can note that the tunneling supercurrents are larger than the supercurrents expected when we observe the two simultaneous electron tunneling [4, 5].
A brief introduction to the generalized BCS theory is presented in Section 2; a theoretical analysis of the *np* transfer is presented in the fourth section of this work and results are summerized 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 *n*-*p* correlations. We can write the Hamiltonian for the many body system as follows

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

where *ijkl* are indeces 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

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

where E_0 is quasi-particle vacuum energy, H_{qp} describes the elementary quasi-particle excitations and H_{qp-int} keeps into account the quasiparticle interactions

that we think are weak.
Neglecting the H_{qp-int} term, the resulting Hamiltonian is not invariant respect a set of simmetries. To avoid this problem, the Hamiltonian (2) is replaced by the reduced Hamiltonian

$$\begin{aligned} H' = H - \lambda_p N_p \;&-\; \lambda_n N_n - \omega J_x \\ &-\; \sum_{L,M\geq 0} \chi_{LM}(1+\delta_{M0})^{-1}[Q_{LM} + (-1)^M Q_{-m}] \end{aligned} \tag{3}$$

where the added terms take into account the broken simmetries (parity violation, rotational invariance and permanent deformation of quasi-particle ground state) and are defined so that the physical osservables assume the expectation value [13].
Using this expression of the Hamiltonian of the system, we can deduce these BCS equations:

$$\begin{pmatrix} (\mathcal{H}-c) & \Delta \\ -\Delta^* & -(\mathcal{H}-c)^* \end{pmatrix} \begin{pmatrix} \mathbf{U}_i \\ \mathbf{V}_i \end{pmatrix} = E_i \begin{pmatrix} \mathbf{U}_i \\ \mathbf{V}_i \end{pmatrix} \tag{4}$$

that can be written in the compact form

$$\kappa \mathbf{X}_i = E_i \mathbf{X}_i \tag{5}$$

where

$$\kappa = \begin{pmatrix} (\mathcal{H}-c) & \Delta \\ -\Delta^* & -(\mathcal{H}-c)^* \end{pmatrix} \tag{6}$$

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 in order to include the terms relative to the broken symmetries.
The solution of BCS equation implies the *pairing tensor* $\mathbf{t}$, fundamental to take *np* pairing into account. For this kind of pairing one has two possibilities; *T=0 isospin isoscalar field* and *T=1 isospin isovector field* [8, 11, 12, 14].
The coexistence of the two pair field has been shown and explained [14]. We can consider the many body Hamiltonian system in terms of coupling constants

$$H = \sum_{jmt} \epsilon_{jt} a^+_{jmt} a_{jmt} - \frac{1}{4} \sum_{jmj'm'} \sum_{tt'} G_{tt'} a^+_{jmt} a^+_{\overline{jmt'}} a_{\overline{j'm't'}} a_{j'm't} \tag{7}$$

where ϵ_{jt} is a single-particle energy, *jmt* identifies the single-particle state, t is the isospin projection, a^+_{jmt} (a_{jmt}) is the creation (annihilation) particle operator,

$a_{\overline{jmt}} = (-1)^{j-m} a_{j-mt}$ and $G_{tt'}$ are the three coupling constants which characterize pairing interaction.
When we have $\epsilon_{jp} = \epsilon_{jn}$ and the coupling constants are identical, $G_{nn} = G_{pp} = G_{np} = G$, the Hamiltonian describes an isovector field where all three kinds of pairs are taken into account in the same way, at least as far as the interaction is concerned. Consequently, in N=Z nuclei pairing energies Δ_{nn}, Δ_{pp} and Δ_{np} are expected to be the same. On the contrary, when we consider the isoscalar pairing T=0, the three coupling constants change; in particular, we have $G_{nn} = G_{pp} = 0$ and $G_{pn} \neq 0$ since an isoscalar field cannot arise from two identical particle pairing.
Moreover, it has been shown that in N=Z nuclei the *T=0* pairing dominates the *T=1* pairing. Neverthless, when the neutron excess increases, the *T=1* pairing becomes stronger and stronger, then competition of the two couplings is more significant [15]. In the case when there is an excess of two neutrons, the two pairing modes have a similar intensity. But when this excess is greater than two units, *T=1* pairing is stronger and can prevail over *T=0* pairing. This argument is right for $A < 40$ nuclei, while it is not so easy for heavier nuclei matter.
The generalized BCS theory appears as a fair theory to justify physical phenomena connected to the existence of strong pair correlations. The nucleon pair transfer reactions are a powerful tool to study pairing correlations in nuclei (see e.g. Ref.[3]). On the other hand, since the Josephson effect can be explained by supposing a strong pair interaction between the two nucleons transferred in a transfer reaction through the Coulombian barrier, an evidence of these strong correlations beween the transferred particles can be seen as possible nuclear Josephson effect for a *np* transfer.

3 Data analysis.

The $^{12}C(^{14}N,^{14}N)^{12}C$ elastic transfer reaction has a the total cross section can be tought as due to two terms: one referred to the elastic scattering and the other one is related to the transfer process [10]. In the low-angle region the Rutherford scattering dominates; in the backward angle region a set of oscillations appears which indicates the presence of the transfer process. Elastic and transfer process for the considered reaction are described by two à la Feynman diagrams, reported in *Fig. 1* and *2*, respectively. Data have been collected in the ETH Laboratories, in Zuerich, using the tandem accelerator. Initially negatively charged ^{14}N ions were accelerated to 28 and 35 MeV kinetic energy, [9].

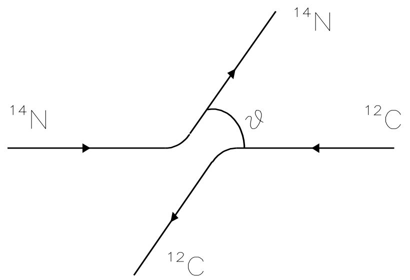

Figure 1: *Purely elastic scattering process for* $^{14}N+^{12}C$ *reaction.*

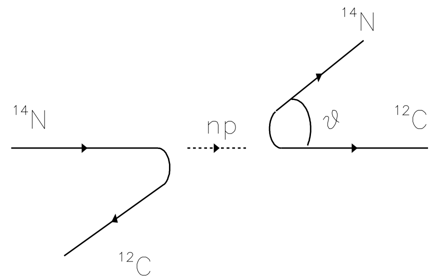

Figure 2: *Purely transfer process for* $^{14}N+^{12}C$ *reaction.*

The analysis performed was based on EFR-DWBA method both for the one-step and the sequential process. Exact finite range computer codes were used for computation of the reaction amplitudes. In particular, the SATURN-MARS code was used to evaluate the theoretical cross section for the one step correlated process; and the JUPITER5 code was used to evaluate the theoretical cross section for the sequential process. The first analysis was made by supposing that the np pair was transferred as bound state, that is as deuteron. In this ay we can take into account the pairing correlations. The second one was made by supposing a sequential transfer.

The distorted waves were generated using optical model potentials found by fitting the elastic scattering and their parameters are listed in Tables 1 and 2.

The reaction amplitudes were weighted by corresponding spectroscopic amplitudes and were added coherently to obtain resulting cross sections to be compared with the experimental data. Values of the spectroscopic amplitudes are listed in Table 3 for the two-step transfer process, and in Tables 4 and 5 for the one-step process.

The first set of spectroscopic amplitudes was taken from the literature, while the second one was deduced from the experiment, showing a weak dependence on the beam energy.

The results of the calculation of the one-step transfer of np pair in the reaction

Table 1: *Optical potential parameters for the* $^{12}C(^{14}N,^{14}N)^{12}C$ *reaction at 28 MeV.*

	V	W	a	a_w	r	r_w	r_c
ingoing channel	80	2.1	0.45	0.72	1.2	1.5	1.55
outgoing channel	80	2.1	0.45	0.72	1.2	1.5	1.55

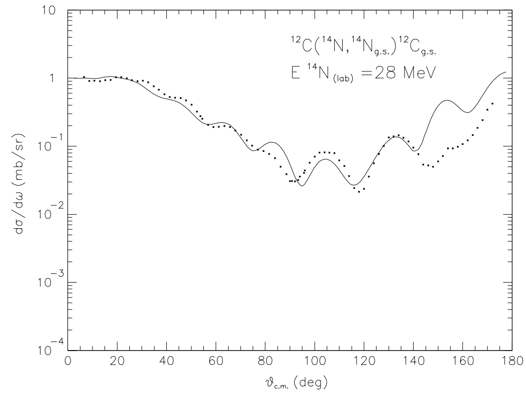

Figure 3: *One-step transfer analysis for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at E(^{14}N)=28 MeV.*

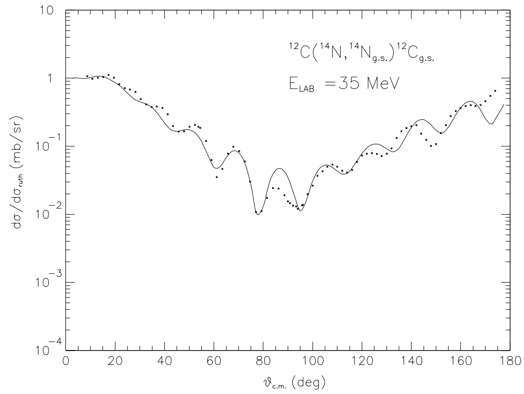

Figure 4: *One-step transfer analysis for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at E(^{14}N)=35 MeV.*

$^{12}C(^{14}N,^{14}N)^{12}C$ are reported in *Fig. 3* and *4* for the two laboratory energies. The cross sections resulting from one-step transfer of the *np* pair reproduce very well the experimental angular distributions. As mentioned above, two contributions contribute to the cross section shape. In the low-angle region we can recognize the elastic behaviour: the experimental cross section is roughly the Rutherford one, then it decreases as expected for the elastic process. In the backward region, there is a set of oscillations that can be justified only by supposing a transfer contribution. By supposing that the np transfer is a one-step transfer, that is the np pair was transferred as bound state (deuteron), we could reproduce the experimental angular distributions.

The results of calculations of the sequential transfer of a neutron and a proton in the studied reaction are presented in *Fig. 5* and *6* for the two laboratory energies. The cross sections resulting from sequential transfer analysis do not reproduce the experimental angular distributions in the backwards region. In particular, there is a deep disagreement between the experimental transfer data and the theoretical ones.

Table 2: *Optical potential parameters for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at 35 MeV.*

	V	W	a	a_w	r	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

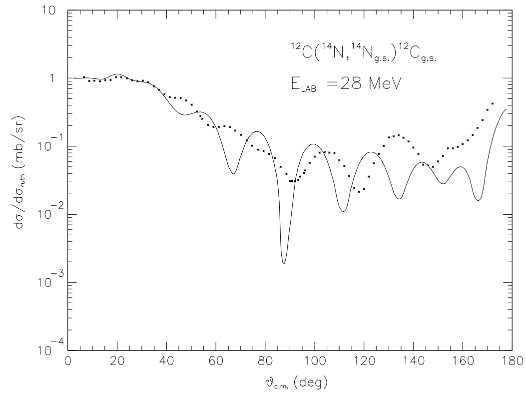

Figure 5: *Sequential transfer analysis for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at E(^{14}N)=28 MeV.*

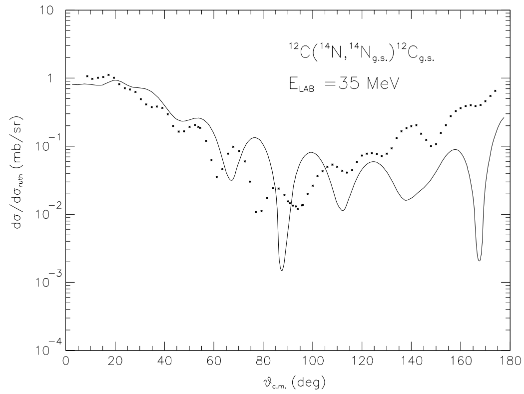

Figure 6: *Sequential transfer analysis for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at E(^{14}N)=35 MeV.*

4 Conclusions.

The $^{12}C(^{14}N,^{14}N)^{12}C$ reaction studied at 28 and 35 MeV confirms a strong pair correlations for the transferred pair's as a matter of fact, we get a good fit of experimental transfer data supposing that transfer process takes place in one step, when simultaneous correlated transfer of the two nucleons occurs.

The *np* pairs behave as Cooper pairs trough the potential barrier between the two interacting nuclei: there is a Cooper pairs current that flows from the *donor* to the *acceptor* nucleus. The np pairs are transferred as bound state. This image is similar to the nuclear Josephson effect one, even if the studied reaction was performed at

Table 3: *Spectroscopic amplitudes for one-nucleon transfer for the $^{12}C(^{14}N,^{14}N)^{12}C$ reaction at 28 and 35 MeV.*

Nucleus	Core	Cluster	n	l	2j	SA
^{14}N	^{13}N	n	0	1	1	-0.829
^{14}N	^{13}N	n	0	1	3	-0.063
^{13}C	^{12}C	n	0	1	1	+0.783
^{13}N	^{12}C	p	0	1	1	+0.783
^{14}N	^{13}C	p	0	1	1	-0.829
^{14}N	^{13}C	p	0	1	3	-0.063

Table 4: *Spectroscopic amplitudes for deuteron transfer for the* $^{12}C(^{14}N,^{14}N)^{12}C$ *reaction at 28 MeV.*

Nucleus	Core	Cluster	S1	S2
^{14}N	^{12}C	d	1.6	0.6
^{14}N	^{12}C	d	1.5	0.5
^{14}N	^{12}C	d	1.2	-1.5
^{14}N	^{12}C	d	-2.5	-0.7

Table 5: *Spectroscopic amplitudes for deuteron transfer for the* $^{12}C(^{14}N,^{14}N)^{12}C$ *reaction at 35 MeV.*

Nucleus	Core	Cluster	S1	S2
^{14}N	^{12}C	d	-1.15	1.3
^{14}N	^{12}C	d	1.2	1.4
^{14}N	^{12}C	d	1	-0.8
^{14}N	^{12}C	d	1.2	-0.7

energies above the Coulombian barrier. Then we can say that there is a possible evidence of a Nuclear Josephson effect even in the studied reaction. Even though the studied reaction was performed at energies above the coulombian barrier, we can image that the pair correlations are so strong to enhance the transfer probability of the np pairs through the barrier (coulombian plus centrifugal) so promoting the one-step transfer through the potential barrier. An analogous theoretical explanation was proposed by M. C. Mermaz and M. Girod [3] applied to different systems at energies above the corresponding Coulombian barrier founding a possible evidence of nuclear Josephson effect.

Finally, the evidence of strong pairing correlations in the case of np transfer reactions confirms the validity of the generalized BCS theory so considering the np pairing in the same way of the *nn* and *pp* pairing.

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