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THE $^{11}B + ^{12}C$ FEW–NUCLEON TRANSFER REACTION IN THE C.M. ENERGY RANGE FROM 5 TO 40 MeV: A COMPARATIVE STUDY OF DIFFERENT REACTION MECHANISM

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1 Introduction.

Few nucleon transfer reactions can be considered an effective tool to study the relationship between reaction dynamics and nuclear structure.

Besides the inclusion of core excitations, a peculiar complexity arises in the analysis of transfer mechanism.

One could consider the transferred nucleons as a single, frozen unit, which is transferred simultaneously. A more specific treatment of such a process suggests one keep into account also a sequential transfer mechanism, i.e. one nucleon followed by the others, and the different weights of these contribution have to be evaluated.

Despite the progress made in understanding many properties of transfer nuclear reactions, some features remain anomalous. The study of the ^{11}B+^{12}C system, performed in a wide energy range (from 5 to 40 MeV in C.M.), shows how unexpected questions arise from the analysis of such a reaction.

2 Experimental details.

Measurements have been performed at the van de Graaf Tandem of National Laboratories of Catania (Italy), by using ^{11}B or ^{12}C beams impinging on ^{12}C and $11B$ targets, respectively. The detection of the outgoing particles was ensured by two $\Delta E - E$ telescopes, each one formed by an axial geometry Ionization Chamber (I.C.) constructed *ad hoc* to be matched to a Position Sensitive Si Detector. I.C. windows, with a surface of $9x45\ mm^2$, were closed by polypropylene windows 0.5 μm thick. The gas (isobutane) filling the I.C.'s was held at the pressure of 50 $mbar$. The angular calibration of the detectors was performed by means of a twelve-slit grid placed in front of them. Use of position sensitive detectors like E detectors allowed us to cover an angular range of about 8 degrees in the laboratory for each telescope. Energy resolution of I.C.'s was good enough to allow a fair Z -identification of the reaction products (see Fig. 1), while *total* energy resolution was lower than 500 keV thus permitting us to resolve - besides elastic ones - also some inelastic peaks in the B and C ejectiles spectra (see Fig. 2). In particular, we were able to resolve the elastic peak in boron and carbon ejectile spectra from the 2.12 MeV inelastic one (first excited ^{11}B level). The other boron and carbon isotopes were well separated from the elastic peaks due to the negative Q-values. The elastic cross section was measured - for E_{cm}=26.8 MeV only - by using a kinematical method [1]. The two PSD's, working in coincidence, identified particles and Q-values with a resolution $\Delta m/m \leq 4\%$ and $\Delta Q \simeq 0.4\ MeV$.

Next, the detection system was updated by cooling the detectors in order to improve the signal/noise ratio thereby obtaining more detailed identification of the reaction products.

3 Anomalous behaviour of spectroscopic factors in p-elastic transfer.

Optical Model analysis of the elastic scattering has been performed successfully and a good agreement with experimental data has been obtained. The optical model analysis fits the elastic scattering data, by means of the PTOLEMY code [2], reproducing the behaviour of experimental cross-sections measured in the energy interval investigated by us and already treated in literature [3,4,5] in other energy intervals. When necessary, the JUPITER-5 code [6] was employed to keep into account the *interference* between elastic scattering and transfer amplitude.

This analysis allowed us to extract the proton spectroscopic factors.

Previous studies of p-elastic transfer gave indications on a strong energy dependence of the proton spectroscopic factor which reaches, at the $E_{C.M.}$=14.6 MeV, the value 5.5, which significantly exceeds the theoretical limit.

Anyway, one must observe that a gap is present in literature for experimental data between 14.6 and 41.6 MeV, whose corresponding spectroscopic factors are close to the theoretical predictions.

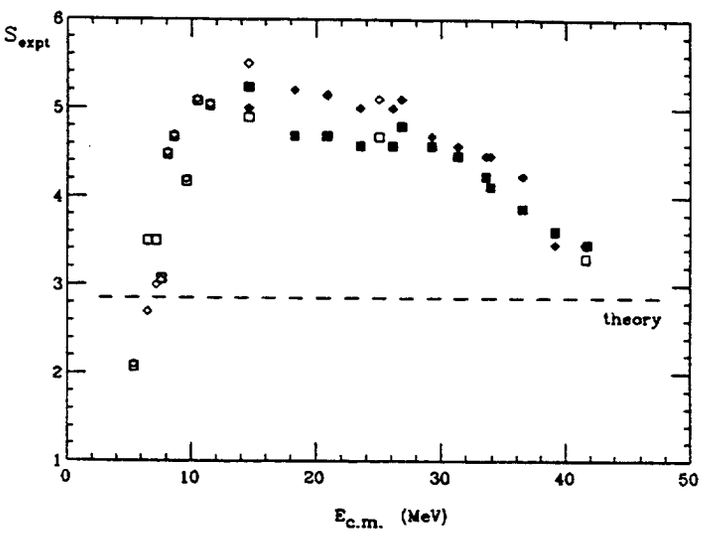

Fig. 1

To complete - and extend - this study, the above measurements carried out covered this energy gap allowing us to draw the important conclusion according to which the proton spectroscopic factors as deduced by DWBA calculations show a smooth change with energy.

In fact, as Fig. 1 shows, they increase from a value close to the theoretical one, i.e. S=2.85, at $E_{C.M.} \simeq 7$ MeV, to a value exceeding S=5, at about $E_{C.M.}$= 15 MeV. Then the spectroscopic factors slowly decrease to S=3.5 at the highest available energy $E_{C.M.}$= 41.7 MeV.

As a matter of fact, it is always possible to get different spectroscopic values from DWBA analysis, simply by changing the geometry of the proton binding potential, thus introducing an unrealistic (*unphysical*) way a potential radius which depends on the energy. This is manifestly an assumption not acceptable without a reasonable theoretical justification. The values of the geometrical parameters of the proton binding potential we assume in this analysis well reproduce the charge distribution value of ^{12}C obtained from high-energy electron scattering experiments [7,8].

These results manifestly show an abnormal behaviour of the spectroscopic factor [9], observed in the whole region of energy investigated, that cannot be explained by different distorsions of waves in the model calculations.

Actually, second order processes - from which one could expect to be able to explain the anomalous behaviour - have already been taken into account [10], but their contribution is so low as to be neglected.

Since effects found in this analysis cannot be explained in terms of reaction-mechanism model, one should look for some phenomena related to nuclear structure. So, the anomalous behaviour of the proton spectroscopic factor in ^{12}C deserves further theoretical considerations.

4 DWBA analysis of the p-inelastic transfer.

The explanation of the peculiar behaviour of the p spectroscopic factor in ^{11}B+^{12}C elastic transfer should be attributed to some nuclear structure phenomena, or to the reaction mechanism.

It is interesting to study if the same abnormal behaviour of this parameter can also be found when other channels are investigated. To this aim, extended measurements of angular distributions for inelastic scattering with unresolved excitations of the 2^+ (4.44 MeV) ^{12}C level and $1/2^-$ (2.12 MeV), $5/2^-$ (4.44 MeV) ^{11}B levels have been performed.

The excitations of ^{11}B and ^{12}C due to mean field deformations or to inelastic proton transfer have been analyzed in the framework of DWBA, assumed a

single-step mechanism of the processes.

A good description of all measured angular distributions has been obtained in the whole energy range investigated, as shown by Fig.2.

The values of the spectroscopic factors, for the excited $^{11}B^{*}_{2.12}$ and $^{12}C^{*}_{4.44}$, do not show a strong dependence on the energy, but appear about 60% larger than the respective shell-model predictions.

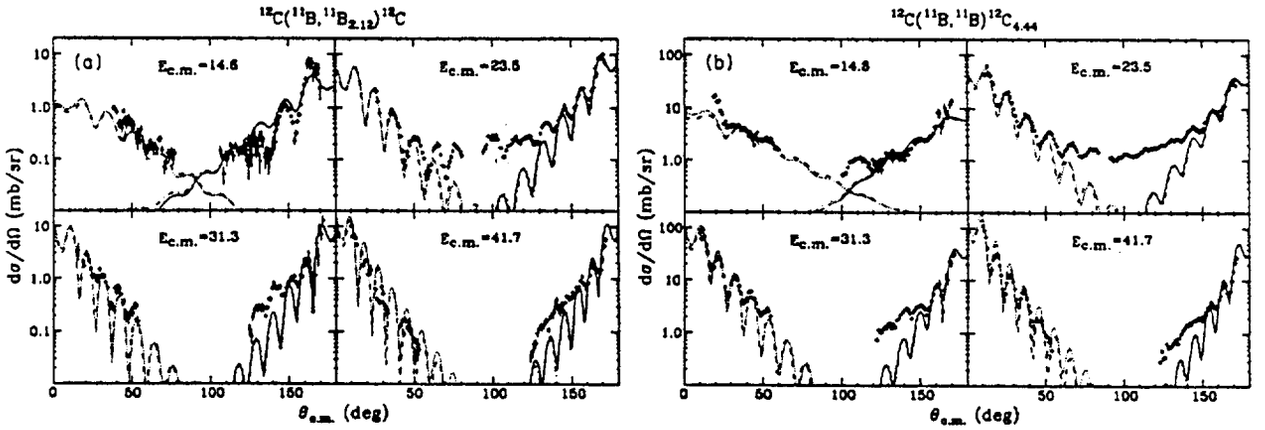

Fig. 2

5 The transfer of an α-particle as a tool to study the structure of ^{16}O nucleus.

Many states of ^{16}O nucleus show - according to many Authors - an α-structure, since they can be interpreted as members of two rotational bands $K = 0^{+}$ (built on the 6.05 MeV 0^{-} state) and $K = 0^{-}$ (starting from the 9.59 MeV 1^{-} state), described in terms of an α-cluster structure of ^{16}O, i.e. $^{16}O \equiv {}^{12}C{+}\alpha$.

If α-particle-like correlations do exist they could induce deformations in ^{16}O ground state, which is expected - in a shell model frame - to reveal a spherical symmetry because of its doubly magic character. According to many models [11,12,13,14] the coexistence of shell-model structure of ^{16}O ground state and

(^{12}C+ α) molecule-like structure was found; in particular, some tetrahedral deformation could not be excluded. To investigate the problem more thoroughly, Elliott [15] suggested the use of the $^{12}C(^{6}Li,d)^{16}O$ α-transfer reaction, in order to study the possible tetrahedral deformation of ^{16}O nucleus. In describing experimental data, these Authors propose an *ad hoc* modification of the standard shell model, introducing a distorsion of the mean field to deduce the spectroscopic factors. In particular, they found an α-particle clusterization varying from a factor 11 (for 4^+ 11.1 MeV state) to 215 (for the ground state). So, one could infer that α-particle transfer reactions give irrefutable evidence of a tetrahedral nature of ^{16}O nucleus. Firstly, one can observe that the choice of a reaction such as the $(^{6}Li, d)$ is truly not a proper one, due to the bad fulfilling of perturbation theory in a case when in the projectile partition the transferred particle is heavier than the core (α-particle and deuteron, respectively). Also from a strictly theoretical point of view, an α-particle transfer reaction induced by heavy ions appears to be more suitable. The ^{11}B induced reaction $^{12}C(^{11}B,^{7}Li)^{16}O$ has been studied by analyzing the population of different ^{16}O states, in the wide projectile energy interval ranging from 28 to 80 MeV in the laboratory system. The ^{16}O states under investigation are those belonging to hypothetical tetrahedral rotational band of the ground state, and to $K = 0^+$ and $K = 0^-$ based on 6.05 MeV 0^+ and 9.59 MeV 1^- levels, respectively.

The experimental data relative to these states were analyzed in the frame of DWBA to check whether the standard shell model fully reproduces the experimental data or it is necessary to invoke some distorsion potential to better describe them. This investigation is also an interesting check for the assumed reaction mechanism and gives, at the same time, information on nuclear structure of ^{16}O.

Fig. 3 shows some examples of the experimental energy spectra of ^{7}Li as detected particle when the beam energy was 40 and 80 MeV. As one can see, the peaks corresponding to transitions to the ground, 6.13 MeV (3^-), 6.92 MeV (2^+), 10.36 MeV (4^+), 11.10 MeV (4^+), 14.82 MeV (6^+), 16.28 MeV (6^+) and 20.86 MeV (7^-) states of ^{16}O are well identified.

Three of these levels, namely the O^+ g.s., the 3^- 6.13 MeV and the 4^+ 11.1 MeV are the possible members of a tetrahedral rotational band of the ground state. Due to kinematical conditions, high-spin levels have been strongly populated with respect to the low-spin ones, thus allowing an easier identification. In analyzing the experimental data, the DWBA was adopted.

The theoretical angular distributions, deduced by a proper choice of optical model potentials, were evaluated by means of a coherent sum of amplitudes related to the α-transfer process leading to two different orbitals of α particle inside ^{11}B nucleus ($L = 0$ and $L = 2$, respectively).

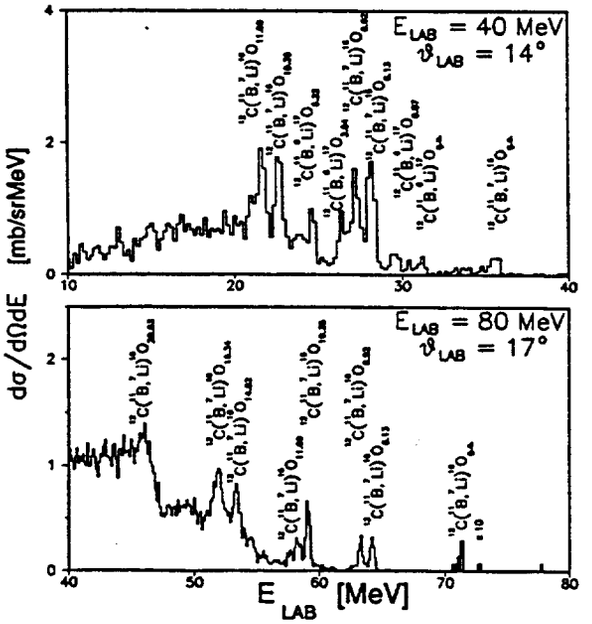
E_LAB = 40 MeV
ϑ_LAB = 14°
E_LAB = 80 MeV
ϑ_LAB = 17°
dσ/dΩdE [mb/srMeV]
E_LAB [MeV]

Fig. 3

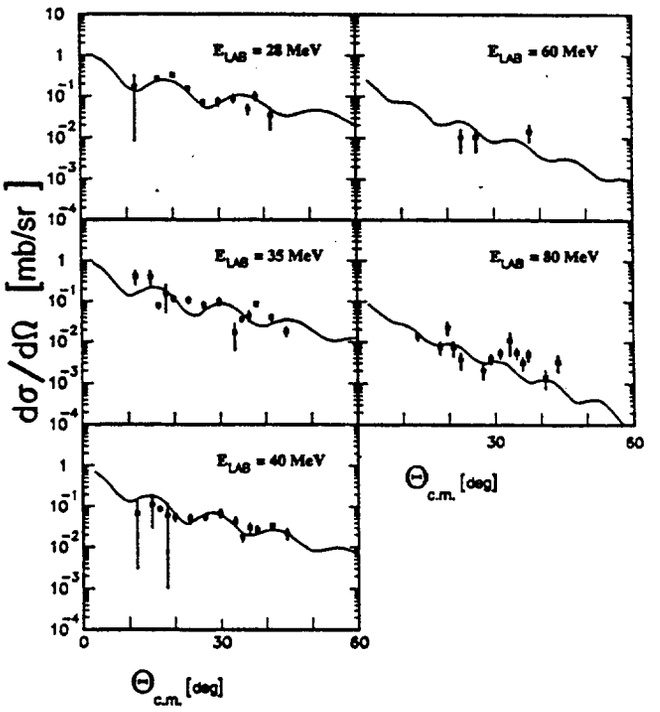
E_LAB = 28 MeV
E_LAB = 60 MeV
E_LAB = 35 MeV
E_LAB = 80 MeV
E_LAB = 40 MeV
dσ/dΩ [mb/sr]
Θ_c.m. [deg]

Fig. 4

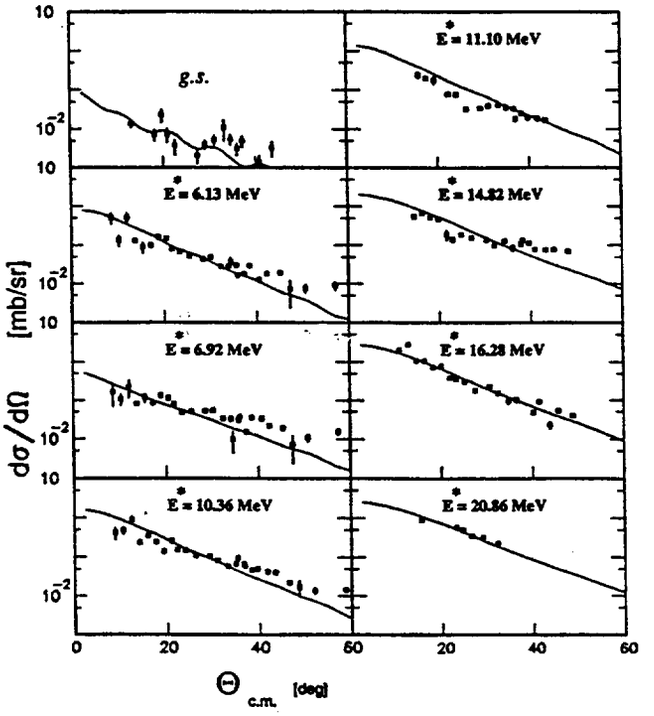

Fig. 5

So, the only adjustable parameters were the spectroscopic values for α-particle inside ^{16}O states.

Fig. 4 shows the experimental angular distributions together with the theoretical ones, for different beam energies and leading to ^{16}O ground state, while Fig. 5 refers to the several excited ^{16}O states reached at 80 MeV beam energy.

The values of the spectroscopic factors for ^{16}O seen as $^{12}C_{g.s.} + \alpha$ agree very well with the shell model calculations performed by other Authors [15,16] giving a satisfactory picture of the use of DWBA. The experimental angular distributions are reproduced with a such high quality that we believe we can claim that it is not necessary to introduce any *ad hoc* modification of shell model Hamiltonian to get a better agreement with experimental data [17].

The superfluity of such a hypothesis appears more evident if one observes

that we were able *also* to reproduce the $^{12}C(^6Li, d)^{16}O$ reaction angular distributions, without adding any tetrahedral term to the single-particle Hamiltonian, as shown by Fig. 5. The significant discrepancy of DWBA calculation performed by other Authors, who added a *phenomenological* deformation term, may depend on the imaginary deuteron potential in DWBA calculations, four times deeper than the original potential previously used by the same Authors.

6 The $^{11}B + ^{12}C \rightarrow ^6Li + ^{17}O$ five-nucleon transfer channel.

Recently, many people addressed their efforts to the investigation of the five-nucleon transfer both in light - and heavy - ion induced reactions. A quantitative analysis of such a process has usually been performed by assuming a single step transfer of inert ^5He and/or ^5Li clusters, to successfully show the presence of $^5He/^5Li$ clusterization in light nuclei. Anyway, it can also occur that the transfer process proceeds not or *not only* in one step, i.e. the total process cross section arises from a number of stages to be added coherently.

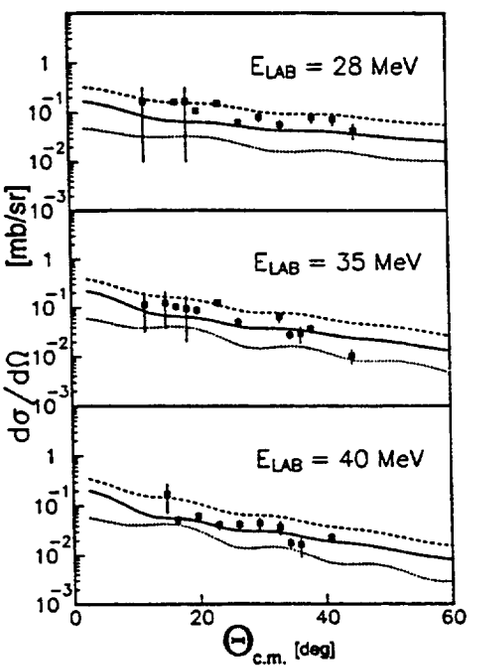

Fig. 6

One has to underline that simultaneous transfer is a more general mechanism with respect to single-five-nucleon transfer, since the costituent of the cluster, i.e. the α-particle and the nucleon, can change the state of their relative motion during the reaction.

In the following we shall call this mechanism "uncorrelated transfer", while "correlated transfer" will indicate the transfer of five nucleons, i.e. a cluster having the quantum numbers of ^5He or ^5Li in their ground states.

From the study of five-nucleon elastic transfer process in the $^{11}B + ^{16}O$ system[18], it was found that the dominant process is the *simultaneous* (α-p) transfer.

As a matter of fact, the correlated transfer gives the largest cross section than the other contributions, thus giving quantitative information on the clusterization of ^{16}O nuclei. In this frame, the study of the five-nucleon transfer mechanism was performed, with the aim of investigating into detail this process checking, in particular, the validity of such an interpretation. In the case of $^{12}C(^{11}B,^6 Li)^{17}O$ the ^{11}B nucleus plays the role of a donor for the neutron and α-particle.

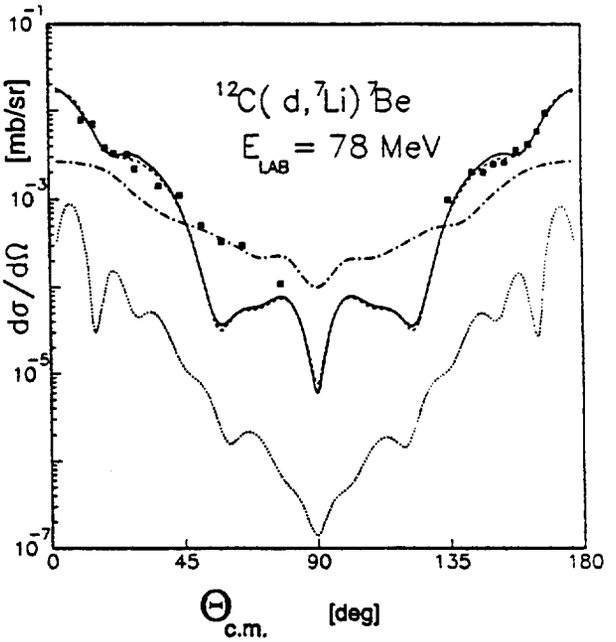

Fig. 7

We studied the angular distributions of $^{12}C(^{11}B,^{6}Li)^{17}O$ at three ^{11}B beams: 28,35 and 40 MeV, following the experimental procedure already described [19] . As an example, Fig. 3 already showed the ^{6}Li (together to ^{7}Li) ion spectrum obtained at ϑ_{lab}=14° and E_{beam} = 40 MeV.

The theoretical analysis performed to analyze the experimental data is based DWBA formalism, used at the first order for n and α-particle simultaneous transfer [18], as shown by Fig. 6.

In particular, two kinds of calculations were performed: a simultaneous transfer one, by evaluating both correlated and uncorrelated transfers, and a *sequential transfer* one, seen as two-step processes by means of the JUPITER-5 code [20].

The results of calculations of simultaneous transfer of five-nucleons seen as an α-particle and a neutron in $^{12}C(^{11}B,^{6}Li)^{17}O$ are shown in Fig. 7 for ^{11}B 40 MeV laboratory energy.

One can easily see that the contribution of correlated transfer (dashed line) of a neutron and an α-particle is larger than the uncorrelated one (dotted line) by a factor 3-4, while experimental data are well reproduced by a coherent sum of correlated (dashed line) and uncorrelated (dotted line) simultaneous transfer [21].

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