## HNPS Advances in Nuclear Physics

Vol 2 (1991)

HNPS1991


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doi: 10.12681/hnps.2859

# THE $^{16}O+^{12}C$ RESONANCES INVESTIGATION BY THE pn TO d COMPETITION RATIO TECHNIQUE.

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## 1. Introduction

Pronounced oscillations in the $^{16}O+^{12}C$ system, have been observed in angle-integrated elastic and inelastic scattering [1], as well as in complete fusion excitation function and various exit channels of the system [2].

Quasi-molecular and three-body $^{12}C$-$\alpha$-$^{12}C$ molecular states have been observed in the $^{12}C+^{16}O$ system, indicating an $\alpha$-cluster structure for the entrance channel resonance, in consistency with experimental data [3].

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Due to the existence of interference effects between true resonances and compound nuclear states, it is very difficult to deduce partial widths $\Gamma_j$ of individual exit channels for the true resonances.

The study of the $^{16}O+^{12}C$ excitation functions of light charged particle reaction channels p,d and $\alpha$ [4], showed strong evidence for a large statistical compound-nucleus contribution with additional indications of a nonstatistical reaction mechanism involved.

The present work is trying to shed some light on the $^{16}O+^{12}C$ resonance mechanism behavior and possible by applying a new technique, which is the measurement of the cross section ratio $\sigma_{pn}/\sigma_d$ at the vicinity of the three well known resonances 11.85, 12.79 and 19.7 MeV.

The competition ratio between the pn and d emission leading to the same residual nucleus, in a series of heavy-ion induced nuclear reactions, has been extensively studied at various bombarding energies [5-8].

The deduced $\sigma_{pn}/\sigma_d$ ratios have been found to follow a systematic trend utilized to extract an empirical equation:

$$\sigma_{pn}/\sigma_d = 0.83 \exp [0.19 (E_{c.m.}+Q_{pn})] \qquad (1)$$

where the quantity $(E_{c.m.}+Q_{pn})$ is expressed in MeV.

The empirical relation has been applied to describe the competition in reactions different from those by which it was derived, extended for each reaction at several bombarding energies.

Good agreement between the experimental values and Hauser-Feshbach calculations have been obtained for many nuclear systems [8], where the primitive role of the compound nucleus process, has been estimated, in the measured relative cross sections for pn and d emission.

The 11.85 and 12.79 MeV resonances of the $^{16}O+^{12}C$, with similar others have been studied experimentally by γ-ray yield measurement, or by heavy residue nuclei detection, at energies below the Coulomb barrier of the $^{16}O+^{12}C$ system.

The intermediate-type resonance at $E_{c.m.}$=12.79 Mev has also been observed in the excitation function of the n, p, d and α exit channel [9].

The 19.7 MeV resonance of the $^{16}O+^{12}C$, has been studied extensively at elastic, inelastic scattering [1], $\alpha+^{24}Mg$ and other light particle evaporated exit channels. The 19.7 MeV resonance has been considered as one of the prime examples of a "molecular resonance", coming from the determination of its physical origin.

Actually, we proceeded through a detailed scanning of bombarding energy of the resonances 11.85 ($8^+$), 12.79 ($7^-$) and 19.71 MeV ($14^+$) to obtain the $\sigma_{pn}/\sigma_d$ cross section expecting not necessarily similar behaviour of this quantity.

## 2.Experiment

Thin natural carbon targets of 20 μg/cm$^2$, with Au backing have been bombarded with $^{16}O$ beams supplied by the Tandem T11/25 Van der Graaff accelerator of N.C.S.R."Demokritos".

A ΔE-E counter telescope of silicon detectors has been used, covered about 37 mSr, for light charged particle detection in a D-shape scattering chamber.

Measurements at the higher bombarding energies has been carried out at the MP Tandem Van der Graaff accelerator at Garching.

Particle identification with pile up rejection and fast coincidence circuitry for charged particle-$\gamma$ coincidences has been employed. The raw data have been stored event by event on magnetic tape by an on-line PDP-11/15 computer at Demokritos and a PDP-15/PDP-10 system at Garching.

## 3. Results

The obtained $\sigma_{pn}/\sigma_d$ ratio for the region $E_{c.m.}$=(10.5-13.5) MeV and $E_{c.m.}$=(17.5-21.5) MeV is shown in fig. 1, deep minima appear in the vicinity of the 12.79 MeV(c.m.) ($7^-$) and the 19.71 MeV (c.m.)

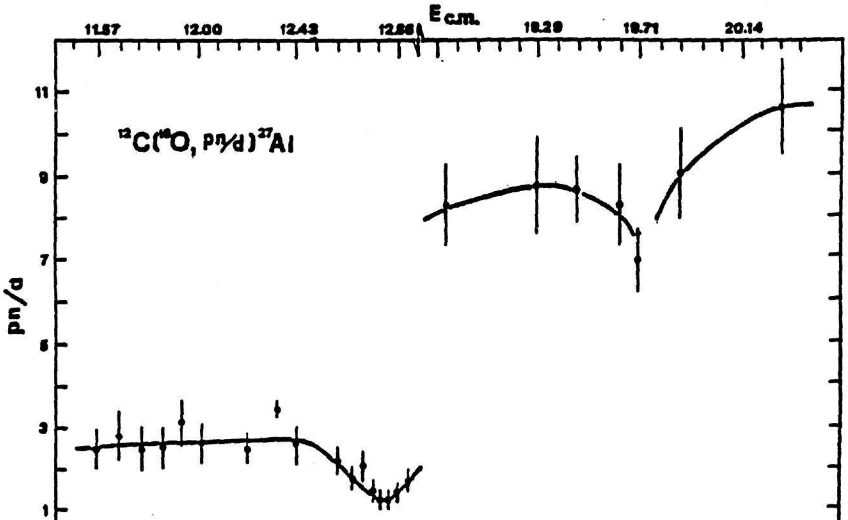


Fig. 1 The experimental data $\sigma_{pn}/\sigma_d$ emission ratio versus incident energy is plotted for the $^{12}C+^{16}O$ system at the 11.85, 12.78 and 19.71 MeV resonance energy region. The full and dashed lines are Hauser-Feshbach predictions, assuming that all possible l values or up to l=7 have been taken into account respectively.

$(14^+)$ resonances, where no evidence of any structure appears at the 11.85 MeV (c.m.) resonance.

It is obvious that the pn over d ratio behaves with specific sensitivity in this area and registers the 12.79 MeV resonance, recording a minimum of the ratio at the resonance energy, with a width of about 500 keV, two times greater than those reported by Frohlich [10].

It is important to underline that there is no evidence of any kind of structure of the excitation function yielding the $^{26}$Al as a compound nucleus exit channel $^{12}$C($^{16}$O, pn(d))$^{26}$Al, as it has, already, been reported by γ-ray yield measurement [11] or by deuteron detection [4], or by the residual nucleus $^{26}$Al measurement [12].

The measured width $\Gamma_{c.m.}$=150 keV of the 12.79 MeV resonance by the $\sigma_{pn}/\sigma_d$ ratio, indicates directly a decay from its doorway-state structure, confirming a dinuclear molecular or an α-cluster configuration [11].

The pn over d emission cross section ratio in the center of mass energy region (17.5 - 21.5) MeV was measured. A similar minimum of the $^{16}$O+$^{12}$C system, obtained like the 12.8 MeV, as it is shown in fig. 1, with a width of about 600 keV.

The 19.7 MeV resonance with $J^{\pi} = 14^+$ has been reported many times by elastic, inelastic scattering measurement of the system $^{12}$C+$^{16}$O [1,2], either in fusion excitation, as an intermediate resonance, populated directly via the entrance channel through some doorway mechanism e.g. quasimolecular, rotational band or α-cluster states.

A detailed measurement of the pn to d emission cross section ratio has been performed at the vicinity of the resonance 11.85 MeV, giving no corresponding structure as we have found in the other two resonances.

However, a broad width (290 keV) resonance of $J^P=8^+$ spin has been reported as a dinuclear structure by the Erlangen group [10].

Hauser - Feshbach calculations, by code STAPRE, are plotted in fig. 1. They cannot take into account resonance phenomena, as it is expected, giving simply an increasing ratio $\sigma_{pn}/\sigma_d$ by the relative increase of the incident energy in agreement with the increase of the fusion cross section of the system.

The results do not agree with the up to now [6,7] concluded remarks about the $\sigma_{pn}/\sigma_d$ competition ratio of the compound nucleus equivalent exit channels, where a universality of reaction system indepedence has been published [7,8] for this ratio as a function of the incident energy.

The measured minima at the corresponding resonances diverges also from the phenomenological line produced by the equation (1). So, we can assume the candidate direct non-statistical nature for the 12.79 and 19.7 MeV resonances, something which is in agreement with refs. [8,9] for the character of dinuclear molecular resonances of $^{16}O+^{12}C$.

There is no explanation for the missing minimum of the $\sigma_{pn}/\sigma_d$ cross section ratio at the 11.85 MeV resonance by this technique, except that this resonance is produced by different mechanism, non detectable by our technique.

Further investigations are needed to $^{12}C+^{16}O$ resonances below and above this energy for additional information.

An indepedent way, has been used, in order to investigate the three resonances, where different thickness of the target $^{12}C$ has been bombarded. In fig. 2 the $\sigma_{pn}/\sigma_d$ ratio is plotted versus the incident energy in the 12.79 MeV resonance, where the deep minimum appears strongly eventhough different $^{12}C$ target thicknesses 20, 50, 100 $\mu g/cm^2$ have been used. It is worthwhile, to underline the reductance of the deep width by the 20 $\mu g/cm^2$ thickness measurement.

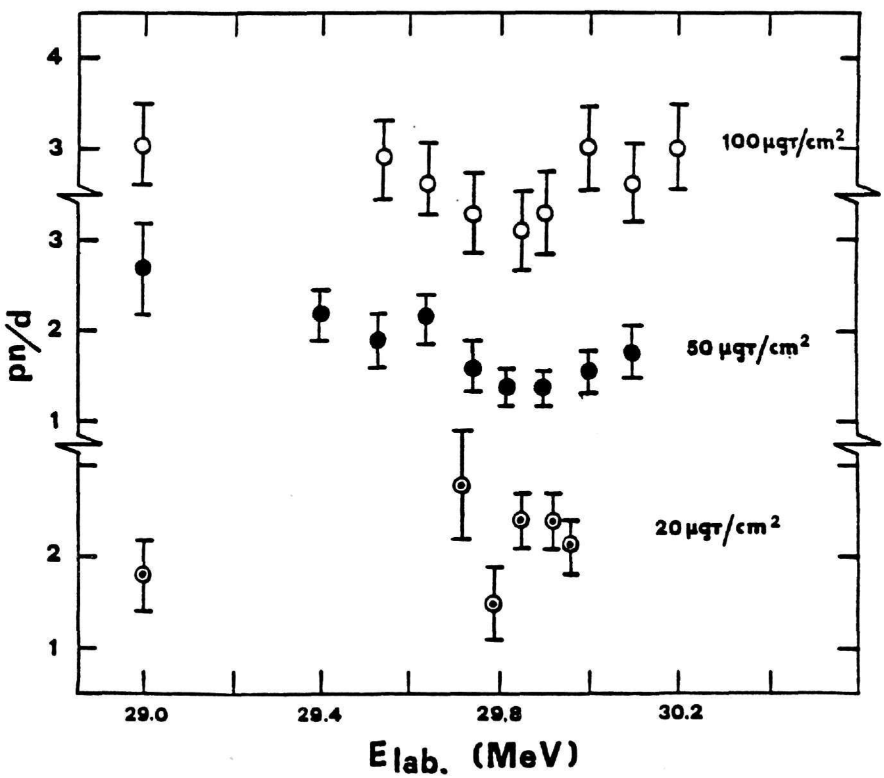


Fig. 2 The experimental data $\sigma_{pn}/\sigma_d$ versus incident energy is plotted for the $^{12}C+^{16}O$ system at the 12.78 MeV resonance energy region, obtained by different $^{12}C$ target thickness 20, 50 and 100 $\mu g/cm^2$.

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