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G. Calvi, S. Cavallaro, A. S. Figuera and M. Sandoli :

ANGULAR CORRELATIONS AT $E_d = 1.6$ MeV IN THE $^{19}F(d, p_1 \gamma)^{20}F$ REACTION. -

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ABSTRACT. -

(d, p γ) angular correlations of the proton group corresponding to the 0.65 MeV level of ^{20}F produced in the reaction $^{19}F(d, p_1)^{20}F$ have been measured at $E_d = 1.6$ MeV.

The measurements have been carried out in the reaction plane and in two azimuthal planes for a proton emission angle of 45°.

The experimental points have been fitted by a sum of even order Legendre polynomials. The best fits obtained including polynomials to the 6th order seem to agree better with the experimental points.

Taking into account this result a possible presence of more reaction mechanism is suggested.

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INTRODUCTION. -

One of the most powerful tools for the study of the reaction mechanism and of the spectroscopic parameters is given by the measurements of the angular correlation between the reaction products.

Most of the theoretical work published in the last years on this subject is concerned with deuteron induced reactions proceeding through direct mechanism[1,2].

The angular correlation between the protons and relative γ-rays going to the ground level in ^{20}F for the reaction $^{19}F(d,p\gamma)^{20}F$ has been studied by P. R. Chagnon[3] and R. W. Newsome Jr.[4] at a bombarding energy of about 0.5 MeV. These Authors performed the analysis of their experimental data in terms of a direct interaction mechanism, but they did not give a unique assignment to the J value of the first excited level of ^{20}F.

The present measurement of angular correlation between the protons going to the first excited level of the ^{20}F and the subsequent 0.65 MeV γ-rays was done at $E_d = 1.6$ MeV in the attempt to gain more information on this level.

EXPERIMENTAL SET-UP. -

Fluorine targets obtained by vacuum evaporation of PbF_2 on Ni backing were used, their thickness was about 0.25 mg/cm^2. The backing thickness was 1.25 μm.

The target chamber was a brass cylindrical shell 1 mm thick by 25 cm high and approximately 11 cm in diameter with a Faraday cup, for beam current measurements, in the beam direction.

The protons were detected by a solid state counter 500 μm thick and 50 mm^2 of sensitive surface. Its front face was shielded by a Ni foil 10 μm thick to prevent the scattered deuterons from reaching the counter area.

This detector placed at 4.5 cm from the center of the target could be rotated around a vertical axis going through this center and perpendicular to the reaction plane.

The γ-rays detector was a scintillation counter, mounting a 7.5 cm x 7.5 cm NaI(Tl) crystal, and was placed at a distance of 21 cm from the center of the target. It could be rotated around this center either on the reaction plane or on the azimuthal ones.

The half angles subtended by the detectors at the target were respectively 10° for the NaI(Tl) crystal and 5° for the solid state detector.

The electronics block diagram is shown in Fig. 1. The solid state detector was connected both to a 512 channels analyser and to a single channel discriminator. The latter was used to gate on the p_1 protons group, in such a way that, on the first 256 channels it was possible to see the total proton spectrum minus the p_1 group, and on the second 256 channels the p_1 group (see Fig. 2).

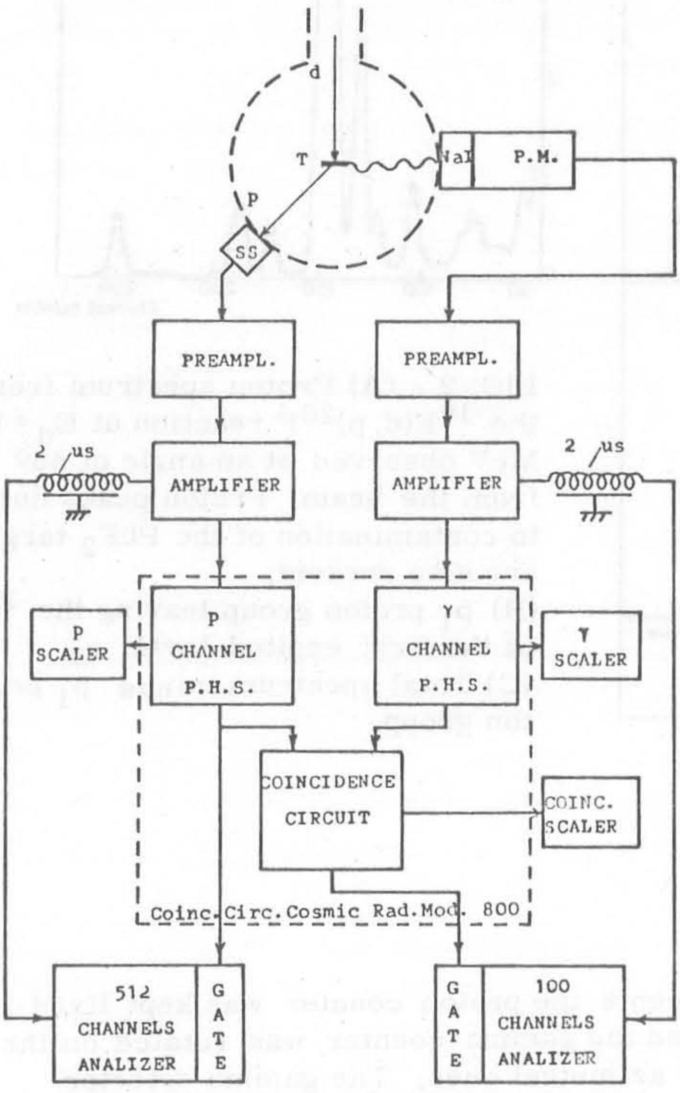

FIG. 1 - Schematic diagram of the electronics.

This set-up allowed to control continuously the stability of the whole apparatus.

The γ-rays counter was connected to a 100 channels analyser and to a single channel discriminator. The latter gated on the photoelectric peak of the γ-rays coming from the first ^{20}F excited level, and gave a signal for the (p, γ) coincidence circuit.

The coincidence circuit was a commercial model and had a measured resolution time of 35 ns.

The gate of the 100 channels analyser was driven by the signal coming out from the coincidence circuit, so that just the γ-rays photoelectric peak in coincidence with the p_1 protons group could be seen.

The linearity of both the multichannel analysers was checked by a precision pulser.

The proton window position was fixed by looking at the proton p_1 group itself while the gamma rays window was fixed by looking at the photoelectric peak of the γ-rays of a ^{137}Cs source having about the same value as the excitation energy of ^{20}F first level.

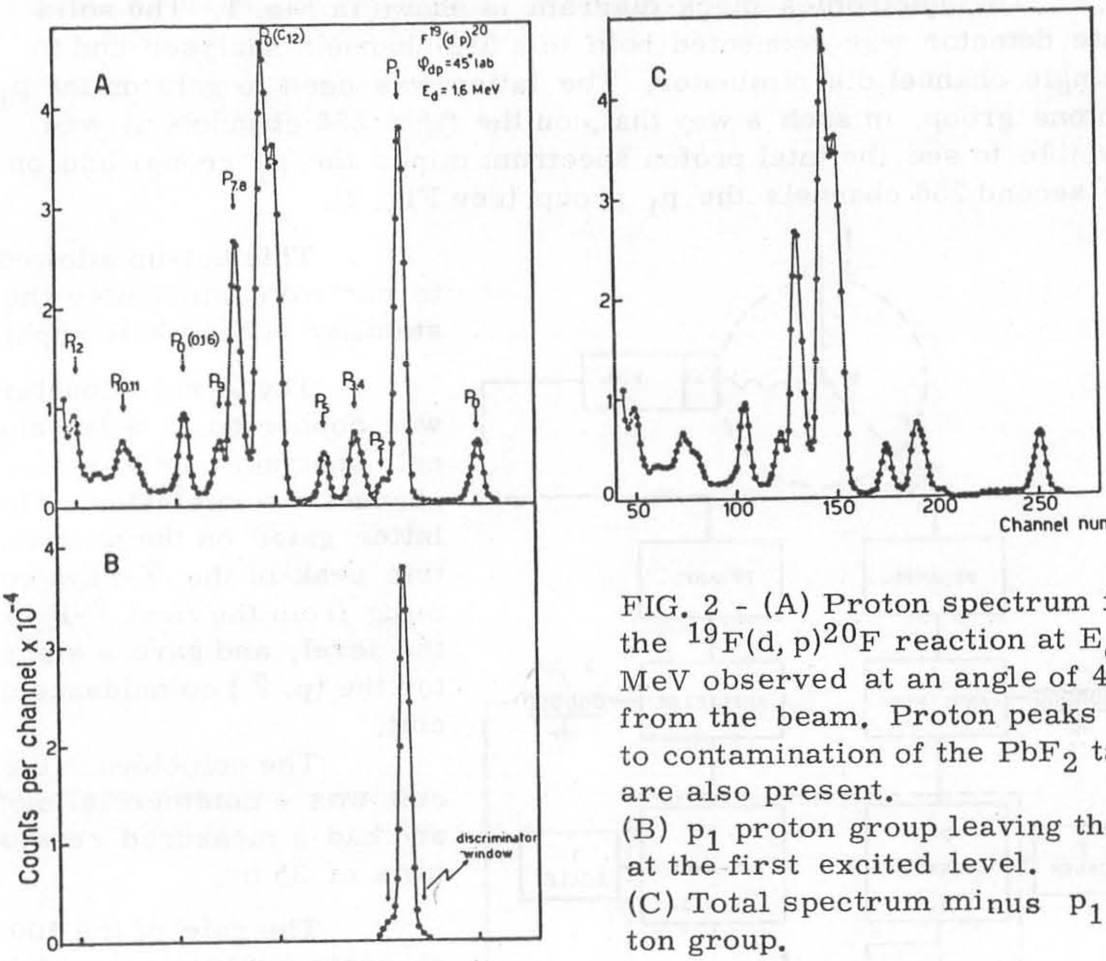

FIG. 2 - (A) Proton spectrum from the $^{19}F(d, p)^{20}F$ reaction at $E_d = 1.6$ MeV observed at an angle of 45° from the beam. Proton peaks due to contamination of the PbF_2 target are also present.
(B) p_1 proton group leaving the ^{20}F at the first excited level.
(C) Total spectrum minus p_1 proton group.

RESULTS AND DISCUSSION. -

In each set of measurements the proton counter was kept fixed in the direction $\theta_{dp} = 45^o$ (lab) and the gamma counter was rotated on the reaction plane or on one of the azimuthal ones. The gamma detector angles were chosen in random order to minimize any possible drift.

The gamma absorption due to the target holder, to the solid state detector and to the Faraday cup (expecially at 0° and 45° from the beam) was not negligible, so it needed correction. The correction factor has been determined recording counts from a ^{137}Cs gamma source having the same size as the cross section of the beam. This source was mounted on a backing similar to those of the targets. Corrections were also applied for the analyser dead time and for random coincidences.

The angular correlation between the protons and the γ-rays following a (d, p) reaction takes the form

(1) $$W(\theta_\gamma, \varphi_\gamma) = \sum_{kq} A_{kq} C_{kq} (\theta_\gamma, \varphi_\gamma)$$

where $C_{kq}(\theta_\gamma, \varphi_\gamma)$ are the spherical armonics normalized so that $C_{oo} = 1$, $C_{k0} = P_k(\cos\theta_\gamma)$. $(\theta_\gamma, \varphi_\gamma)$ refer to the center-of-mass system.

In the reference frame (see Fig. 3A) with the x axis in the recoil direction and the z one perpendicular to the reaction plane, q can take only even values, while assuming that the reaction proceedes through definite parity states, also k must have only even values.

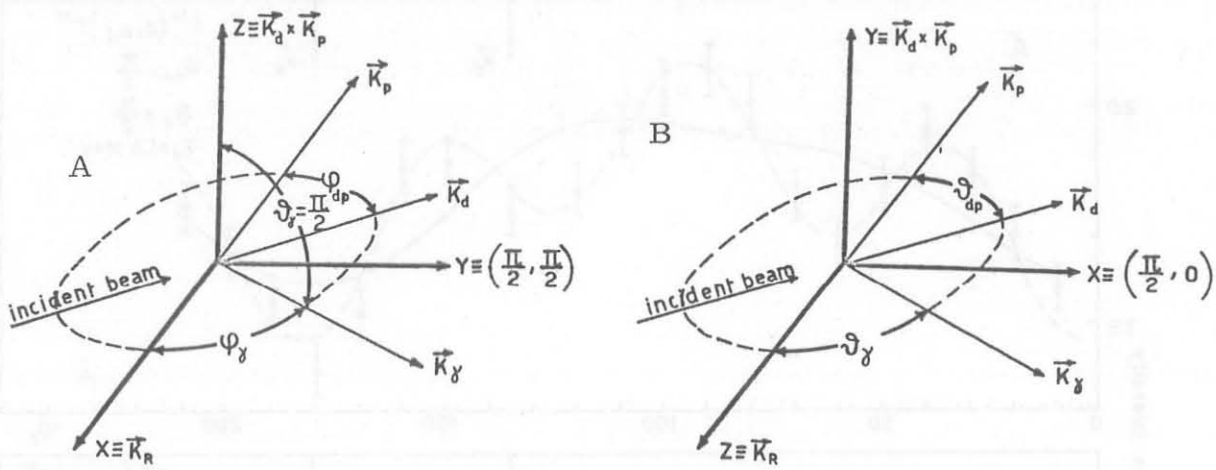

FIG. 3 - Angular correlation geometry.

With this assumption the formula (1) can be written:

(2) $$W(\frac{\pi}{2}, \varphi_\gamma) = A_o + \sum_{q=0}^{k} \left[A_q \cos q\varphi_\gamma - B_q \operatorname{sen} q\varphi_\gamma \right]$$

in the reaction plane and

(2) $$W(\theta_\gamma, 0) = \sum_k \sum_{q=0}^{k} A_{kq} P_k^q (\cos\theta_\gamma)$$

$$W(\theta_\gamma, \frac{\pi}{2}) = \sum_k \sum_{q=0}^{k} (-1)^{q/2} A_{kq} P_k^q (\cos\theta_\gamma)$$

in the azimuthal planes $\varphi_\gamma = 0$ and $\varphi_\gamma = \pi/2$ respectively. If we assume for the (d, p) reaction a stripping mechanism and only one l value for the captured neutron, the k value must satisfy the following limitations:

$$k \leq 2l; \quad k \leq j_1 + j_1'; \quad k \leq L+L'; \quad k \leq 2J$$

where j_1, j_1' are two possible values for the total angular momentum of the captured neutron, J is the intermediate nucleus spin, and L, L' two possible values for the multipolarities of the γ-rays emitted.

The proton detector was placed at an angle of 45° from the deu teron beam in order to get the maximum yield for the p_1 protons(5). Fig. 4A shows the experimental points from the measurements with the

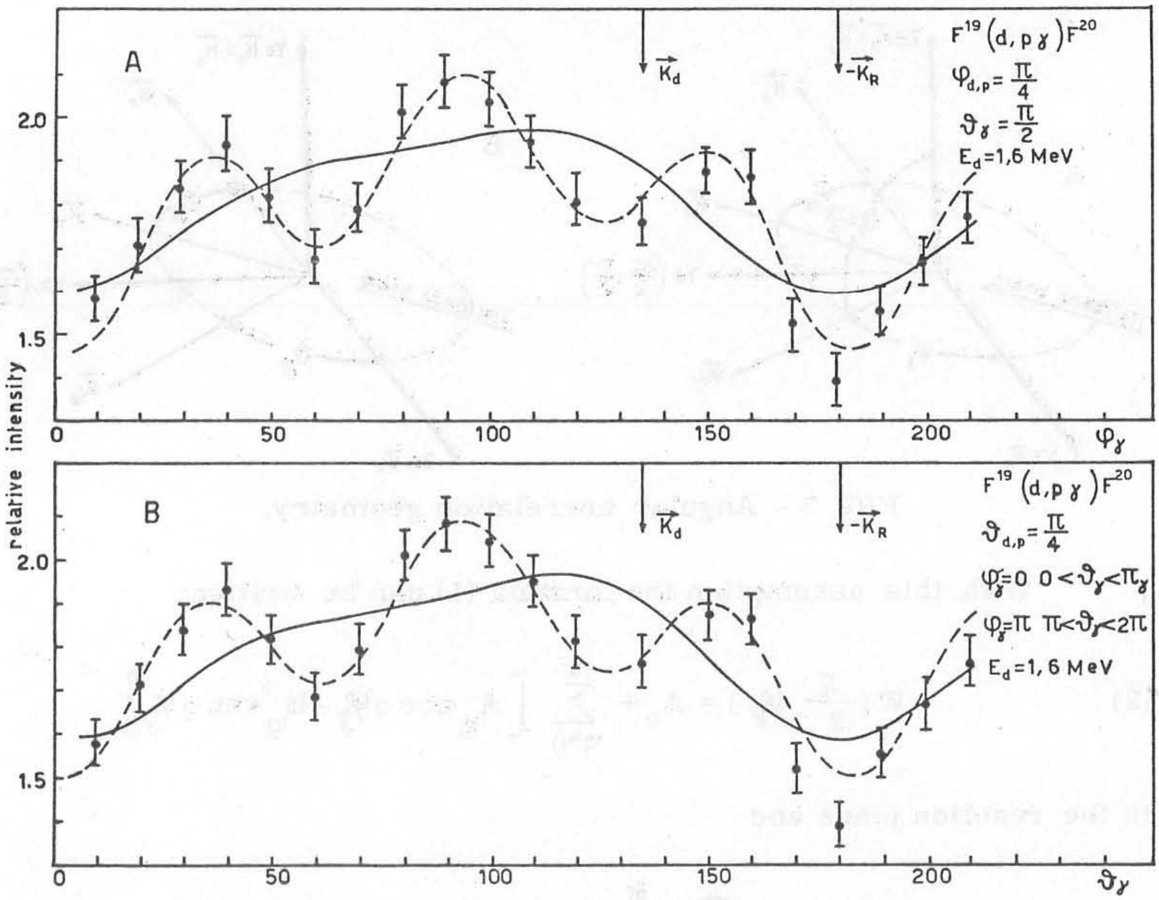

FIG. 4 - Proton- γ reaction plane angular correlation through the first excited levels of ^{20}F. The curves are the least squa re fits of the experimental points to the function (2), A ; to the function (3), B. The continuous and the dashed curves are the best fits with $k_{max} = 4$ and $k_{max} = 6$ respectively. The ^{20}F re coil axis is indicated by k_R.

proton detector placed at 45° from the deuteron beam, and the gamma detector rotating on the reaction plane. In the same figure the continuous curve represents the best fit of the experimental data to the function (2) with k having 4 as maximum value, while the dashed curve has $k_{max} = 6$.

Figure 5 shows the experimental points from the measurements with the proton detector placed at 45° from the deuteron beam, and the gamma detector rotating on the azimuthal planes $\varphi_\gamma = 0°$; $\varphi_\gamma = 90°$. As in Fig. 4 the continuous and the dashed curves correspond to the best fits with $k_{max} = 4$ and $k_{max} = 6$ value respectively.

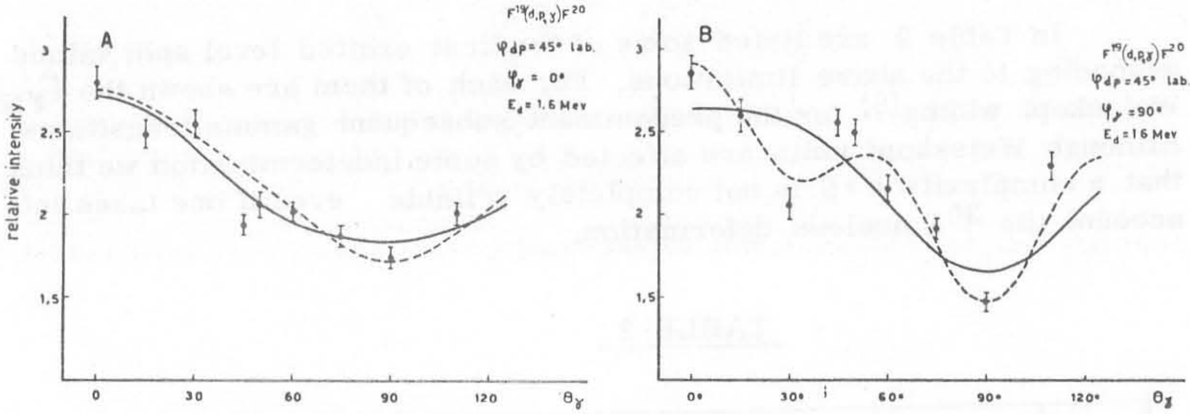

FIG. 5 - Proton-γ angular correlation on the azimuthal planes $\varphi_\gamma = 0$ (A), $\varphi_\gamma = \pi/2$ (B). The continuous and dashed curves are the least square fits based on eq. (2') with $k_{max} = 4$ e $k_{max} = 6$.

The comparison between the two fits was performed by the standard χ^2 test. The definition we have used is

$$\chi_o^2 = \sum_i \frac{(Y_{exp.} - Y_{calc.})_i^2}{Y_{calc.\,i}}$$

where: Y_{exp} is the number of coincidences and Y_{calc} is the corresponding value from the calculated curve.

The χ^2 test of fits corresponding to measurements on the azimuthal planes $\varphi_\gamma = 0°$; $\varphi_\gamma = 90°$ (see Fig. 5) does not allow a sharp choice between k = 4 and k = 6 complexities. Nevertheless the χ_o^2 values corresponding to measurements on the reaction plane show that $k_{max} = 4$ has to be rejected (see Fig. 4) as can be seen in Table 1.

If one assumes 6 as the k_{max} value, the correlation function complexity limits the spin of ^{20}F first excited level to values $J \geq 3$, and also the L multipolarities of subsequent gamma transition to values $L \geq 3$.

TABLE 1

k_{max}	degrees of freedom	χ^2_o	$P(\chi^2 \geq \chi^2_o)$
4	15	63	.01
6	13	12.5	.5

In Table 2 are listed some of the first excited level spin values according to the above limitations. For each of them are shown the $\Gamma_{\gamma N}$ Weisskopf widths(6) for the predominant subsequent gamma transitions. Although Weisskopf units are affected by some indetermination we think that a complexity k = 6 is not completely reliable even if one takes into account the ^{20}F nucleus deformation.

TABLE 2

J	Transitions and Weisskopf widths		
3^+	M1 (6.1×10^{-3})	E2 (3.4×10^{-7})	M3 (2.1×10^{-9})
3^-	E1 (1.4×10^{-1})	M2 (1.4×10^{-8})	E3 (5.1×10^{-9})
4^+	E2 (3.4×10^{-7})	M3 (2.1×10^{-9})	
4^-	M2 (1.4×10^{-8})	E3 (5.1×10^{-9})	
5^+	M3 (2.1×10^{-9})	E4 (4.8×10^{-19})	
5^-	E3 (5.1×10^{-9})	M4 (2.6×10^{-19})	

As suggested by Satchler et al.(2) we studied the correlation function also changing the reference frame in order to test the independence of the k value of the complexity from it. In the second set of axes (see Fig. 3B) the z axis is taken in the recoil direction, and the y one is normal to the reaction plane. In this reference frame the formula (1) in the reaction plane may be written:

$$W(\theta_\gamma, 0) = \sum_k A_{k0} P_k(\cos\theta_\gamma) + 2 \sum_k \sum_{q>0} \sqrt{\frac{(k-q)!}{(k+q)!}} P_k^q(\cos\theta_\gamma) \qquad (3)$$

for $0 < \theta_\gamma < \pi$

$$W(\theta_\gamma, \pi) = \sum_k A_{k0} P_k(\cos\theta_\gamma) + 2 \sum_k \sum_{q>0} (-1)^q \sqrt{\frac{(k-q)!}{(k+q)!}} P_k^q(\cos\theta_\gamma) \quad (3)$$

for $\pi < \theta_\gamma < 2\pi$

Where k assumes only even values while q can take both odd and even values. The Fig. 4B shows the same experimental points as Fig. 4A. The continuous curve represents the best fit of these experimental data to the function (3) with k having 4 as maximum value, while the dashed curve has $k_{max} = 6$. The comparison of the results in Fig. 3A and Figure 3B confirms the k = 6 value of the complexity.

In order to justify such a complexity a J value at least equal to 5 should be necessary. The presence of dipole and or quadrupole radiations for $J < 5$ would predominate so that the octupole radiation would be hidden.

Recently it has been suggested[7] a $J^\pi = 3^+$ with the transferred neutron angular momentum $l_n = 2$.

Although most of previous papers agrees to interpretate the first excited level as populated through a pure stripping mechanism[7], we believe the complexity we observed could be accounted for by a not pure direct interaction mechanism at our energy.

Furthermore the behaviour of the excitation function[8] for the concerned level at our deuteron energy shows strong fluctuations pointing to a possible statistical mechanism.

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