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Decay modes of ^{24}Mg excited at 46.4 MeV

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Abstract. $^{8}Be_{gs}$ coincidences with ^{12}C, $^{8}Be_{gs}$ and α-particles produced in the $^{12}C+\ ^{12}C$ interaction at 65 MeV have been measured in a wide in-plane angular range. The 3- $^{8}Be_{gs}$ final state is found to be produced, even if poor statistics prevent any identification of the ^{16}O states involved in the first stage of the process. The $^{8}Be_{gs}-\alpha$ and $^{8}Be_{gs}-\ ^{12}C$ coincidence yields are found to be due to ^{12}C and ^{16}O excited states, decaying into the $^{8}Be_{gs}+\alpha$ and $^{12}C+\alpha$ systems, respectively.

PACS. 25.70.Ef Resonances – 21.60.Gx Cluster models – 27.30.+t $20 \leq A \leq 38$

1 Introduction

Several recent experiments on the $^{12}C+\ ^{12}C$ reaction [1-11] have shown the excitation of a unusually wide resonance around 32.5 MeV of *c.m.* energy (46.4 MeV in ^{24}Mg excitation energy), whose origin and characteristics are still matter of debate.

The first findings [1,2] on the $^{12}C[0_2^+]+\ ^{12}C[0_2^+]$ exit channel seemed to be in favour of a description of ^{24}Mg in terms of a linear chain of six α-particles, predicted by the Cranked Cluster Model [12].

Later experiments, performed on many other exit channels, casted serious doubts on the early interpretation of the 6-α linear chain. On one side the decay into two $^{12}C[0_2^+]$, whose description in terms of three loosely bound α-particles is widely accepted, seemed to indicate the symmetric breaking of a 6-α chain-like configuration. On the other hand this description hardly fits the observed decay of the resonance into channels involving very compact nuclei like $^{16}O_{gs}$ [5-8] or $^{12}C_{gs}$ [9,10] or even non α-nuclei such as ^{10}B, ^{11}C, ^{13}C and ^{14}N [10]. Moreover the resonance shows up with very different shapes and cross section absolute values in the many different channels so far investigated.

If a stretched configuration of ^{24}Mg made of six α-particles is produced during the interaction of two ^{12}C ions, it is expected to break up into different systems, all of them still retaining a high degree of deformation. This is the case of the $^{12}C[0_2^+]+\ ^{12}C[0_2^+]$ channel so far widely investigated, but it can also be the case of asymmetric fission into $^{8}Be+\ ^{16}O^*$ or $\alpha+\ ^{20}Ne^*$. A six α final state could then be achieved by sequential decay through ^{8}Be, ^{12}C and ^{16}O states. The large deformation of the primary ^{24}Mg should enhance production of intermediate systems with extended α-cluster configurations.

So far only little evidence is reported [3] for ^{16}O states excited in the $^{12}C+\ ^{12}C$ interaction and decaying into 4-α through formation of $^{12}C^*+\alpha$ or $^{8}Be+\ ^{8}Be$ intermediate systems. However, no definite conclusion is drawn about $^{8}Be+\ ^{8}Be$ final state in [3] because of the very poor statistics even if the data at three different energies are summed together. Also a rough indication of emission of ^{16}O and ^{20}Ne excited at the relevant energies, where large deformations are expected, can be found in the inclusive spectra of the $^{12}C+\ ^{12}C\rightarrow\ ^{8}Be+\ ^{16}O$ [5-8] and $^{12}C+\ ^{12}C\rightarrow\alpha+\ ^{20}Ne$ [11] reactions.

From the theoretical point of view it is to be mentioned that improved versions of both the Cranked Cluster Model [13] and the Band Crossing Model [14] have been developed in the meanwhile, leading to prediction of resonances in this region of ^{24}Mg excitation energy even without the assumption of extremely deformed configurations.

In the present paper an experimental study of further decay modes of ^{24}Mg at the excitation energy of 46.4 MeV is reported.

2 The experiment

The experiment was performed at the Laboratori Nazionali del Sud in Catania using the SMP Tandem Van de Graaff accelerator to produce a beam of ^{12}C with an energy of 65 MeV. The beam was accurately collimated in order to have a spot diameter of 1 mm on a natural Carbon target.

The detection set up consisted of five Dual Position Sensitive Detectors (DPSD) placed on both sides of the beam direction. Two were placed on one side at laboratory angles of 20^o and 35^o and three on the opposite side, at 17^o, 32^o and 47^o. Each of them covered an in-plane angular range around 9^o.

Each DPSD is made of two Position Sensitive Detectors mounted on opposite sides of the horizontal plane in close geometry. They are specially suitable for the identification of ^8Be through the detection of the two α-particles coming from its decay. On the spectrum of the relative energy of two particles hitting in coincidence the two halves of one DPSD, the peak around 90 keV allows for the identification of $^8Be_{gs}$. The detection efficiency for excited ^8Be nuclei is a few order of magnitude lower than for the ground state, due to the much larger emission cone.

The data acquisition was triggered by the coincidence of at least one pair of particles hitting one DPSD and another particle hitting one half of another DPSD. In this way coincidence events between one $^8Be_{gs}$ and any other particle (including another $^8Be_{gs}$) were recorded. Notice that with the present set-up no particle other than $^8Be_{gs}$ can be identified.

3 Data analysis and results

3.1 $^8Be_{gs} -\ ^8Be_{gs}$ coincidences

The analysis of $^8Be_{gs} -\ ^8Be_{gs}$ coincidences was performed by gating on the relevant peak around 90 keV of the relative energy spectra of the two particles detected in coincidence in each DPSD (Fig. 1). A low long-tailed background due to the coincidence of particles other than α's on the DPSD's is also present on these spectra, affecting to a small extent the peak of interest.

The total Q spectrum built with data coming from all the combinations of DPSD's is shown in Fig. 2. The peak close to -15 MeV is due to the emission of three ^8Be in their ground state, while the wide bump at more negative values can be partly due to the reaction producing two $^8Be_{gs}$ and a third ^8Be excited at 3 MeV; moreover the detection of particles other than α's on the PSD's, as well as processes with more than three bodies in the final state (for instance two ^8Be's and two uncorrelated α-particle) and reactions on the small ^{13}C component of the target could also contribute to this region of the Q spectrum.

As it can be seen from the Q spectrum, statistics is poor and prevents the extraction of any information from the spectra of the $^8Be_{gs} -\ ^8Be_{gs}$ relative energy. Such events are indeed spread over the full range of $^8Be_{gs} -\ ^8Be_{gs}$ relative energy covered by the experiment (under 17 MeV), without any evidence for meaningful structures. The only conclusion to be drawn from these data is then that the final state with three $^8Be_{gs}$'s is indeed produced in the interaction of two ^{12}C's at the energy corresponding to excitation of ^{24}Mg at 46.4 MeV. Knowing that in three body reactions the sequential emission is in principle much more favoured than the direct break up, one can only argue that the ^{24}Mg breaks into $^8Be_{gs} +\ ^{16}O^*$ and the last one in turn decays into two $^8Be_{gs}$'s.

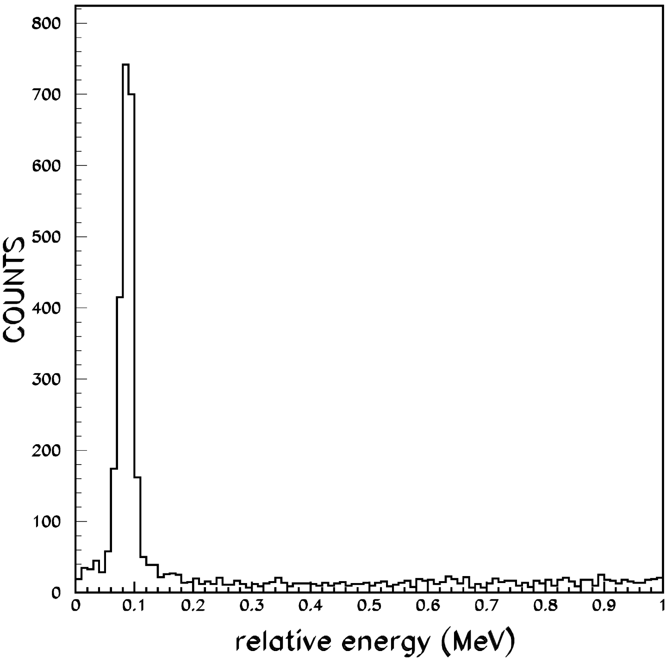

Fig. 1. Typical spectrum of the relative energy of two particles detected in coincidence in the two halves of a DPSD. The peak at 90 keV comes from the 2-α decay of $^8Be_{gs}$

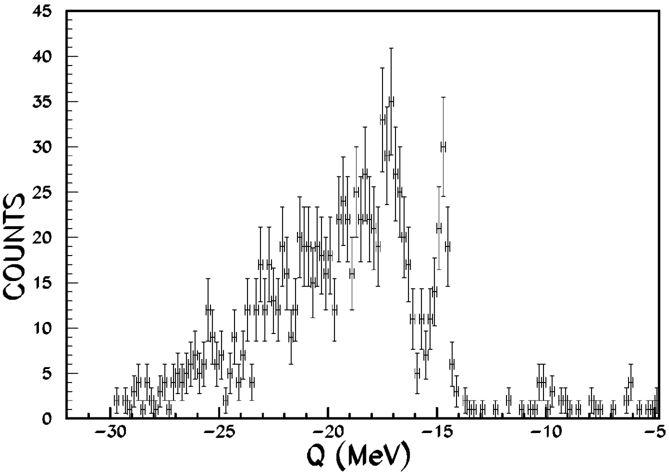

Fig. 2. Q spectrum deduced from the coincidence detection of two $^8Be_{gs}$

3.2 $^{8}Be_{gs}-\alpha$ and $^{8}Be_{gs}-\ ^{12}C$ coincidences

By selecting events of the 90 keV relative energy peak of one DPSD only and requiring coincidence with a single PSD, one selects the events due to coincidence of $^{8}Be_{gs}$ with another (stable) particle. Only kinematical identification of this particle is possible in this case.

It is known [15] that if one plots the coincidence events on the (E_3-Q) *vs* P_3^2 plane, P_3 E_3 and Q being the momentum and the energy of the undetected particle and the Q-value of the three body reaction respectively, the events fall on a straight line having a slope proportional to the inverse of the mass of the undetected particle A_3, and an offset given by $-Q$.

We can assume a given mass for the unidentified particle and calculate event by event the quantities (E_3-Q) and P_3^2 from energy and momentum conservation, respectively. In the (E_3-Q) *vs* P_3^2 plane, only the events for which the assumed mass value is correct fall on straight lines and assuming in turn mass 4 and mass 12, we obtain a way to separate part of the contribution of the $^{8}Be_{gs}+\ ^{4}He+\ ^{12}C$ final state from the other possible reaction channels. It is to be stressed that this procedure does not apply to all the data, since for some angular configurations it is not able to separate the relevant data from background. For this reason, the information deduced from the two kinds of analysis is not fully equivalent.

Examples of Q spectra obtained through this procedure are reported in Fig. 3, for the two values of the mass assumed for the unidentified particle. Of course they reflect the excitation spectrum of ^{12}C.

The data were corrected for the out-of-plane average angle of the stable particle detected in coincidence with $^{8}Be_{gs}$. In spite of the small value of this azimuthal angle, around 1^o, the introduction of such correction turns out to noticeably improve the overall energy resolution, mainly when a mass value of 12 is assumed for the unidentified particle.

We like to stress that, in spite of a residual background due to the ambiguity in particle identification, the resolution of the Q spectra obtained through this analysis makes us quite confident on the quality of the experiment and thus on the information deduced above from the fully identified 3- $^{8}Be_{gs}$ channel.

The Q spectrum of Fig. 3*a* is collected by assuming that an α-particle is detected in coincidence with $^{8}Be_{gs}$. Mainly pairs of adjacent detectors, placed on the same side with respect to the beam direction, contribute to this spectrum. The figure shows that the undetected ^{12}C is mainly produced in its ground state, in the $[2_1^+]$ state at 4.43 MeV or in the $[3_1^-]$ state at 9.63 MeV. Also a weak contribution from excitation of the $[0_2^+]$ state at 7.65 MeV appears in such spectrum. The position of the peaks in the figure is few hundreds keV shifted from the expected value, probably due to the dependence of energy response of detectors on the charge of the hitting particle.

By gating in turn on each peak of this Q spectrum, we calculated the relative energies of any two of the three final particles, for a fixed state of the residual ^{12}C. The spectra so obtained were then divided by the detection efficiency spectra, calculated by a Monte Carlo simulation code.

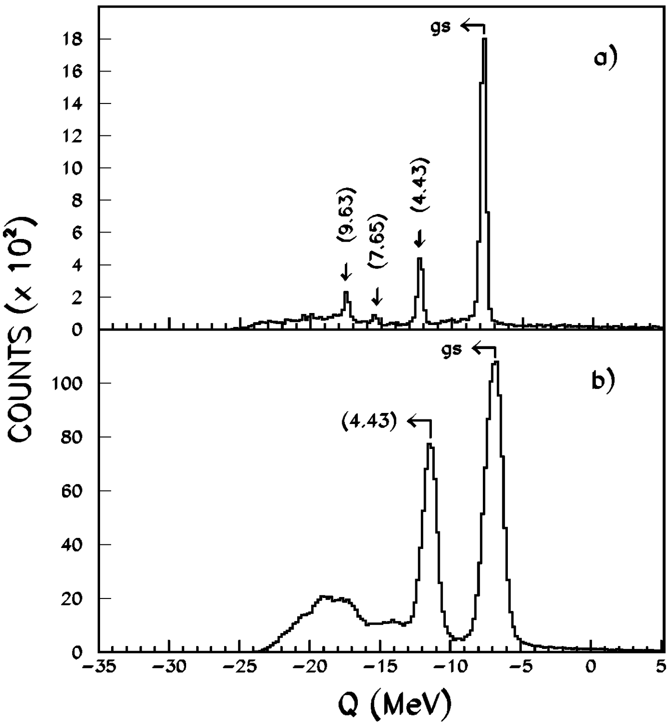

Fig. 3. Examples of Q spectra deduced from coincidences of one $^{8}Be_{gs}$ with one stable unidentified particle detected in one half of a DPSD. In Fig. 3*a* (3*b*) kinematics has been reconstructed and events have been selected under the assumption of mass 4 (12) for the unidentified particle

For each angle pair the efficiencies were calculated as a function of the relative energy E_{a-b}, a and b being in turn two of the three final particles. The reaction was assumed to proceed sequentially through formation of the intermediate nucleus $(a+b)$, followed by its decay into a and b. The simplified assumptions were made of *i*) isotropic angular distribution of $(a+b)$ in the general center of mass system and *ii*) isotropic emission of a and b in the frame of their center of mass. We checked that such calculation is only slightly sensitive to different shapes of angular distribution and correlation.

Figs. 4*a* through *d* report examples of the resulting $^{8}Be_{gs}-\alpha$ relative energy spectra. The dominant process turns out to be the sequential decay of ^{12}C from the unbound states at 7.65 and 9.63 MeV into $^{8}Be_{gs}+\alpha$, while the recoil ^{12}C is left in all the possible states under 10 MeV of excitation. A study of the many inelastic channels of the reaction was already reported in [9] at several energies around the resonance. The relative weights of these channels here deduced, roughly agree with the cross sections measured in [9], even if they refer to different angular ranges.

When mass 12 is assumed for the unidentified particle, the corresponding Q spectrum (Fig. 3*b*) shows, of course, only peaks corresponding to the particle-stable ^{12}C states,

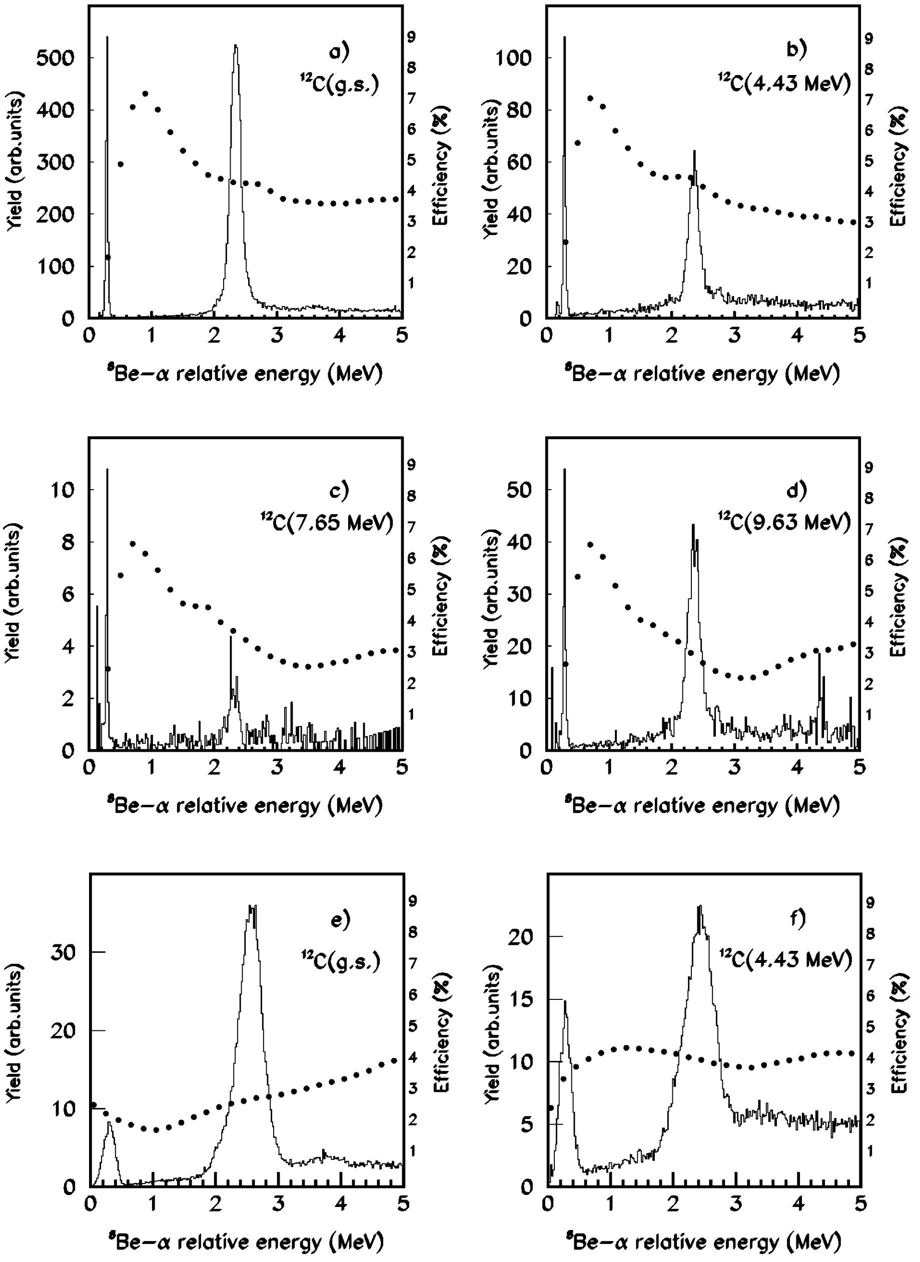

Fig. 4. $^8Be_{gs} - \alpha$ relative energy spectra deduced from $^8Be_{gs} - \alpha$ (*a* through *d*) and $^8Be_{gs} -$ ^{12}C (*e* and *f*) coincidences, by gating on the different peaks of the relevant Q spectrum. Spectra are divided by the detection efficiency. Dots show how efficiency varies with relative energy

namely the ground state and the 4.43 MeV state. Contributions to this spectrum mainly come from pairs of detectors placed on opposite sides with respect to the beam direction, which is simply a consequence of momentum conservation.

Here, too, $^{12}C^*$ break up largely contributes to the coincidence yield, but an important background in the $^8Be - \alpha$ relative energy spectra (Figs. 4e and 4f) reveals the presence of different mechanisms.

These events were then plotted on the $^{12}C - \alpha$ relative energy *vs* $^8Be_{gs} - \alpha$ relative energy plane. In this representation events falling on vertical straight lines reveal the formation and decay of ^{12}C states, whereas a horizontal alignment of events should indicate contribution due to production and decay of ^{16}O states. The excitation of ^{20}Ne states and their following decay into the $^{12}C +$ $^8Be_{gs}$ system should show up with preferential grouping of events along tilted lines. Therefore from these spectra obtained for each Q peak, one can deduce which mechanism is responsible for the $^8Be_{gs} -$ ^{12}C coincidence yield.

Examples of such representation are shown in Fig. 5 for events falling under each one of the two Q peaks of Fig. 3*b* corresponding to $^{12}C_{gs}$ (*a*) and $^{12}C[2_1^+]$ (*b*). In this figure the ^{16}O excitation energy was reported instead of the $^{12}C - \alpha$ relative energy in order to allow for an easier comparison of the ^{16}O states involved in the two cases.

Besides the vertical lines due to ^{12}C break up, whose projections give raise to the peaks of Figs.4*e* and 4*f*, hor-

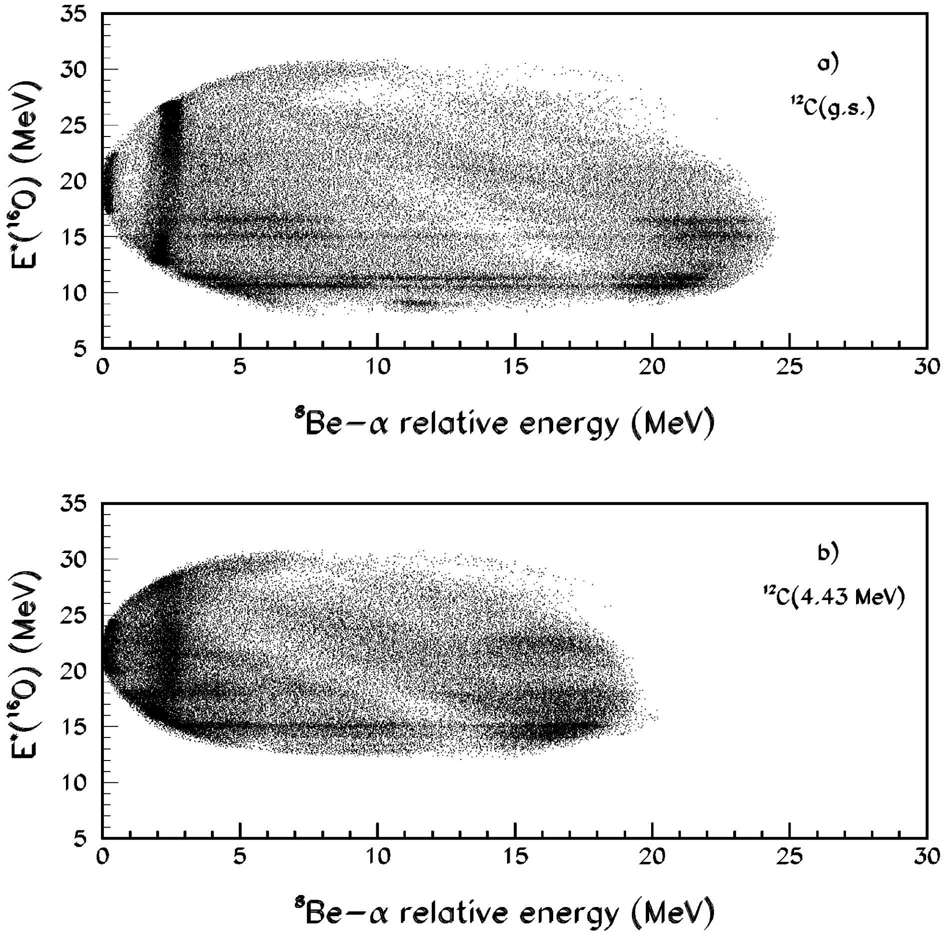

Fig. 5. ^{16}O excitation energy *vs* $^8Be_{gs} - \alpha$ relative energy plots for events falling under the $^{12}C_{gs}$ *a*) and $^{12}C[2_1^+]$ (*b*) Q peaks for the $^8Be_{gs} -$ ^{12}C coincidences

izontal ridges indeed show up, due to formation of the $^{16}O^* +$ $^8Be_{gs}$ intermediate system, subsequently decaying into the $^{12}C + \alpha +$ $^8Be_{gs}$ channel.

The matrices were then projected on the ^{16}O excitation energy (Fig. 6), with the condition of $^8Be_{gs} - \alpha$ relative energy larger than 2.8 MeV, which allows to exclude the dominant contribution due to $^{12}C^*$ break up. Looking at the same time both at matrices and at projections allows for a more reliable identification of the states contributing to the reaction. In order to have a better definition of such peaks the ^{16}O excitation energies were calculated retaining only the information on energy and angle of the first emitted ^8Be, regardless of energy and angle of the coincident particle. This reduces the effect of calibration shifts on the calculated excitation energies.

Several ^{16}O states appear to be excited in the reaction. The peaks occurring in most of the angular conbinations fall at ^{16}O excitation energy of about 10.6, 11.3, 14.3, 15, and 16.5 MeV when the ^{12}C is produced in its ground state. Decay into $^{12}C[2_1^+]$ occurs from ^{16}O states at 14.3, 15, 16.5 and 18.2 MeV, with a fair overlapping with three of the states producing $^{12}C_{gs}$. In both projections the cross section enhancement around 13 MeV comes from an unique detector pair and thus is not considered here as indication of a ^{16}O state.

Even if some states above the 4-α threshold appear to contribute to the spectra, there is no clear correspondence with the states belonging to the very deformed rotational band which have been recognized to decay into four α's, through formation of unbound ^8Be or $^{12}C^*$ systems [3]. This result is not unexpected, because of the very different degree of deformation of the final states investigated here and in [3].

On the other hand we must remark that involvement of other ^{16}O states, even at higher energy, cannot be ruled out, since the procedure of identification of the particle coincident with $^8Be_{gs}$ still leaves a residual background which limits the investigation of weak contributions.

No indication of ^{20}Ne states decaying into $^8Be_{gs} - ^{12}C$ pairs can be observed in the present data.

4 Conclusions

The present data bring further information on the decay of ^{24}Mg from the resonance energy of 46.4 MeV. The evidence of production of unbound ^{16}O states adds to the known modes of decay of ^{24}Mg into the many inelastic and transfer channels so far investigated.

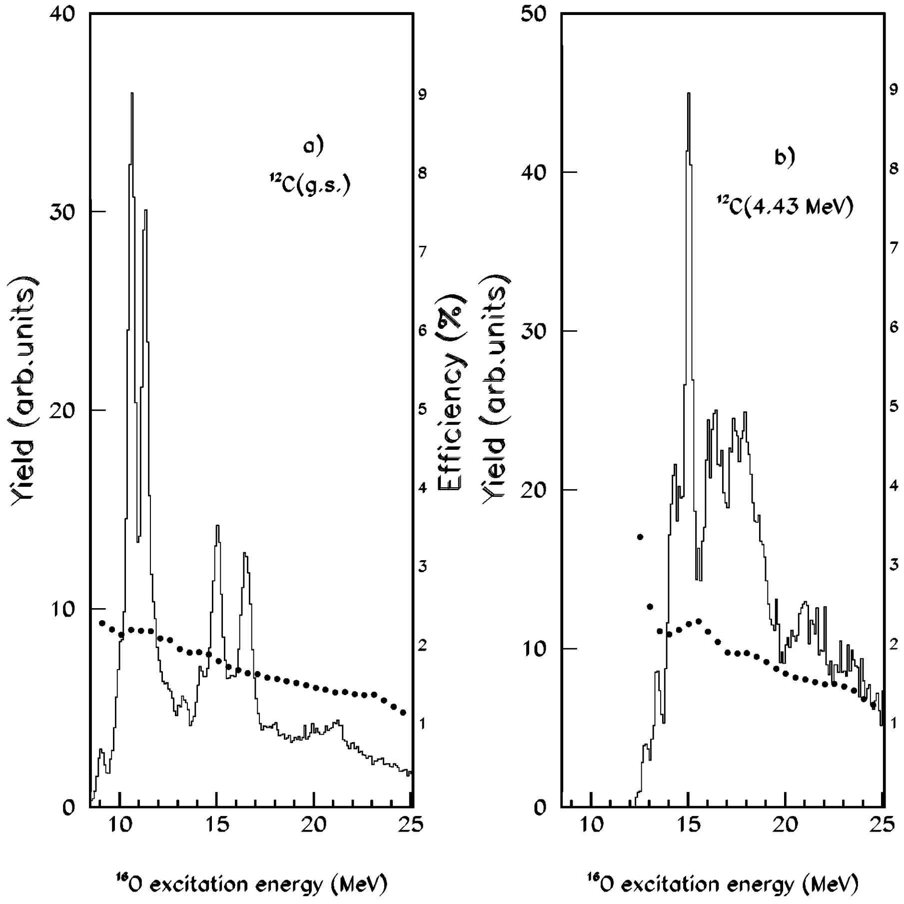

Fig. 6. Projections of the matrices of Fig. 5 (*a* and *b* correspond to figs.5*a* and 5*b* respectively) on the ^{16}O excitation energy axis, for events with $^{8}Be_{gs}-\alpha$ relative energy larger than 2.8 MeV. Dots show how efficiency varies with relative energy

Many questions are still open concerning the interpretation of all the data now available from the decay of the 46.4 MeV resonance and on the nature of such resonance.

Depending on the exit channel investigated, ^{24}Mg appears to be excited with very different probabilities, the largest being related to the less deformed configurations. This is evident from the comparison of the cross sections measured in all the experiments so far performed on this system [1-10]. One can take all these observations as an indication that in the interaction of two ^{12}C's at 32.5 MeV *c.m.* energy, two different resonances can be excited, at about the same energy, associated with different degrees of deformation, consistently with the Cranked Cluster Model prediction of a crossing of the six α's linear chain band with other ^{24}Mg bands [12].

In this picture one resonance, connected with a moderately deformed configuration, decays into rather compact systems, with similar values of the cross section and width around 1 MeV. It is the case of the $^{8}Be_{gs}+{}^{16}O^{*}$ channel [10] where ^{16}O is produced in states associated with more or less compact shapes [17] as well as the inelastic channels involving poorly deformed ^{12}C states [9,10]. This was also the case of the $^{12}C+{}^{12}C\rightarrow{}^{8}Be_{gs}+{}^{16}O_{gs}$ reaction, whose excitation function [18] showed a resonance at 32.5 MeV just as one of the many resonances of the rotational band associated with the D1 $(\alpha-^{16}O-\alpha)$ configuration [12], with cross section and width comparable to those of the other members.

The other resonance, associated to a more stretched configuration, decays into six α's through the symmetric $^{12}C[0_2^+]+{}^{12}C[0_2^+]$ system, as it was shown since the first experiments, with a cross section which is lower by orders of magnitude and an anomalously large width, as a signature of a very short lifetime. In principle if it undergoes an asymmetric $^{8}Be+{}^{16}O^{*}$ and $\alpha+{}^{20}Ne^{*}$ break up one expects ^{16}O or ^{20}Ne be excited to the states associated with stretched configurations of four or five α-particles. In turn $^{16}O^{*}$ should preferentially decay into the *i)* $^{8}Be+{}^{8}Be$ or *ii)* $\alpha+{}^{12}C^{*}$ systems and $^{20}Ne^{*}$ into the *iii)* $^{8}Be+{}^{12}C^{*}$ or *iv)* $\alpha+{}^{16}O^{*}$ systems.

Actually the present data report evidence for the 3-$^{8}Be_{gs}$ decay of ^{24}Mg, but no information on the emitting ^{16}O states can be deduced.

Moreover the $\alpha+{}^{12}C$ decay from ^{16}O states lying on the highly deformed chain-like band starting from 17 MeV excitation energy [3,16] does not show any evident contribution to the $^{8}Be_{gs}-{}^{12}C$ coincidence yield, as can be expected for final states involving rather compact ^{12}C configurations. On the other hand there is no evidence of such decay even in the $^{8}Be_{gs}-\alpha$ coincidence yield leaving a residual unbound ^{12}C, where in principle it could be detected.

No indication of the decay mode *iii)* is present in the data, while contribution from the mechanism *iv)* cannot be found in the present experiment, in which the detection of at least one ^{8}Be is required.

A measurement of the excitation function of the 3-$^{8}Be_{gs}$ exit channel around the resonance, with large statistics, would be of interest, in order to establish the presence of the resonance also in this exit channel and identify the ^{16}O states involved in the intermediate stage of the reaction, by means of angular correlations. To this aim large beam time and high efficiency detectors are needed. Moreover mass or charge identification of the stable particles coincident with $^{8}Be_{gs}$ would be desirable in order to reduce background and make the experiment more sensitive to unfavoured processes.

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