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**Abstract.** The $^{24}$Mg + $^{24}$Mg reaction has been studied at the Legnaro Tandem at a CM bombarding energy of 45.7 MeV where a narrow and high spin resonance has been reported previously. The decay of the resonance into the inelastic and fusion-evaporation channels has been investigated. The ON and OFF resonance decay yields have been measured using, for the inelastic channels, the fragment spectrometer PRISMA and the $\gamma$ array CLARA, and, for the fusion-evaporation channels, the Si array EUCLIDES and the $\gamma$ array GASP. The resonant effects observed in both experiments are discussed and it is suggested that the resonance populates a deformed $^{48}$Cr after a Jacobi shape transition.

## 1. Introduction

Resonant phenomena are well established in light heavy-ion collisions. They have been mainly observed in the excitation functions for elastic and inelastic channels of reactions with composite systems between $^{24}$Mg and $^{56}$Ni. It has been shown that the observation of resonances in certain systems is well understood in terms of a small number of open channels, but the connection between resonances and molecular states in the composite system is still under question. To better establish this link, the best cases to study are the systems for which the resonance width is narrow (around 100 or 200 keV), which implies that the lifetime of the composite system is long.

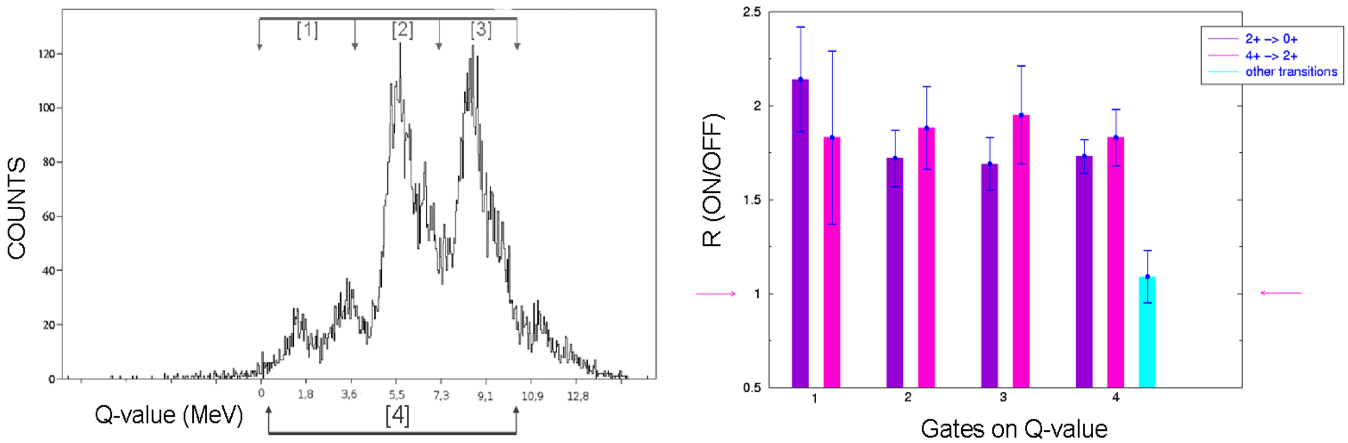


**Figure 1.** Left: Q spectrum of the $^{24}$Mg + $^{24}$Mg inelastic channels with indication of the different gates considered (see text). Right: ON and OFF yield ratios R for different $^{24}$Mg transitions and Q-value.

Our present study is focused on the decay of a narrow $^{24}$Mg + $^{24}$Mg resonance at a CM energy of 45.7 MeV, whose properties (spin and width) are well known: $J^{\pi} = 36^{+}$ and $\Gamma = 170$ keV [1, 2]. Moreover the resonance is located at twice the Coulomb barrier and the corresponding excitation energy of the $^{48}$Cr is around 60 MeV. The goal of our two experiments was to measure for this reaction the ON and OFF resonance decay yields into the various inelastic and fusion-evaporation channels.

The first experiment has been focused on the decay of the resonance into the inelastic channels, channels which are ten times stronger than the $\alpha$ transfer channel [3]. In order to see the effect of the resonance, the reaction $^{24}$Mg + $^{24}$Mg has been measured ON and OFF resonance at the Legnaro XTU Tandem using the PRISMA spectrometer for the detection of the $^{24}$Mg fragments and the CLARA array for the $\gamma$ emitted in coincidence.

In previous experiments [3, 4], it has been shown that resonant flux is missing in the $^{24}$Mg + $^{24}$Mg inelastic channels, therefore the fusion-evaporation channels have been investigated in a second experiment performed also at the Legnaro Tandem with the $\gamma$-array GASP coupled to the EUCLIDES detector for the detection of the evaporated light charged particles in coincidence with the $\gamma$ from the residues.

## 2. Experimental methods and results

As our two experiments on the deexcitation into the inelastic and fusion-evaporation channels are complementary, they have been done in the same conditions. Therefore both measurements were performed ON and OFF resonance with a beam and a target of $^{24}$Mg at a bombarding energy of $E_{CM}$=45.7 MeV.

Concerning the first experiment, the setup allowed to register coincidences between fragments and $\gamma$ rays using the PRISMA spectrometer and the CLARA array. The goal of this experiment was to determine which states in the fragments of the inelastic channels carry away resonance decay strength. Our main interest lays in the excitation energy range between 4.1 and 6.1 MeV, where there could be a competition between the g.s. band contribution and the contribution due to the $K^{\pi}$=$2^{+}$ band.

The Q-value spectrum of the $^{24}$Mg + $^{24}$Mg inelastic channels is represented on Fig. 1. From left to right, four different peaks can be observed and thus four different gates have been defined. In order to determine which states in the inelastic channels carry away the resonant flux, the yields of the corresponding $\gamma$-ray transitions have been measured both ON and OFF resonance energies. On Fig. 1 is also represented the ratio R of these yields for different transitions and selected Q-value gates, if R equals 1 there is no resonant effect. The first gate on Q corresponds to an inelastic excitation energy between 0.3 and 4.1 MeV and thus to the $^{24}$Mg channels ($2_1^+$, $0_1^+$), ($2_1^+$, $2_1^+$) and ($4_1^+$, $0_1^+$). For both transitions $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$, R equals approximately 2 and thus both $2_1^+$ and $4_1^+$ states are resonant states, the strongest contribution in this gate comes from the ($2_1^+$, $2_1^+$) channel. The second gate on Q-value corresponds to an excitation energy between 4.1 and 6.9 MeV. For this gate, a resonant effect is seen again in the yields of the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions. In this gate, the main contribution comes from the ($4_1^+$, $2_1^+$) channel. The third gate corresponds to an excitation energy between 6.9 and 10 MeV. As before, a resonant effect is seen in the yields of $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$, in this gate the main contribution comes from the ($4_1^+$, $4_1^+$) channel. Finally the fourth gate corresponds to the total excitation energy from 0.3 to 10 MeV. The $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ show strong resonant effects, the yields of the other transitions (transitions coming from the $K^\pi$=$2^+$ band and from the $6_1^+$ of the g.s. band) are weak and non-resonant (R $\sim$ 1).

It is known that the resonant flux in the inelastic channels represents only 30% of the total resonant flux [2, 4]. At the considered bombarding energy of the $^{24}$Mg + $^{24}$Mg reaction, the fusion-evaporation cross section is equivalent to 80% of the reaction cross section. This is the reason why a second experiment has been performed in order to search for missing flux in the strong fusion-evaporation channels. To look for the fusion-evaporation channels, the GASP array has been used to record the $\gamma$ rays from the residues in coincidence with EUCLIDES for the light charged particles emitted in the fusion-evaporation process. For the different $\gamma$ transitions observed, we have evaluated the ON/OFF resonance ratio R.

| Nuclei | Channels | E (MeV) | Spins | $R_{ON/OFF}$ |
|---|---|---|---|---|
| $^{45}$Ti | 2pn | 6,2 | 12 | 1,07 $\pm$ 0,02 |
| $^{44}$Sc | 3pn | 3,6 | 11 | 0,96 $\pm$ 0,02 |
| $^{42}$Ca | $\alpha$2p | 7,8 | 11 | 1,03 $\pm$ 0,01 |
| $^{41}$K | $\alpha$3p | 2,8 | 7 | 0,83 $\pm$ 0,04 |
| $^{41}$Ca | $\alpha$2pn | 5,9 | 9 | 0,92 $\pm$ 0,02 |
| $^{39}$K | 2$\alpha$p | 8 | 10 | 1,00 $\pm$ 0,01 |
| $^{38}$Ar | 2$\alpha$2p | 4,6 | 5 | 0,97 $\pm$ 0,03 |
| $^{37}$Ar | 2$\alpha$2pn | 6,5 | 8 | 0,88 $\pm$ 0,03 |

**Table 1.** For each residue observed in the $^{24}$Mg + $^{24}$Mg reaction: channels, excitation energies and spins of favoured feeding, ON/OFF resonance ratios.

Table 1 gives the strongest channels and nuclei produced via the $^{24}$Mg + $^{24}$Mg reaction, it gives also for each residue the excitation energy and spin corresponding to the favoured feeding and finally the ON/OFF resonance ratio. As seen in this table, the selective feeding of the nuclei by the fusion-evaporation process is at high excitation energy and high angular momentum as the $^{48}$Cr compound nucleus has an excitation energy of around 60 MeV and spins up to 36 that have to be evacuated into the deexcitation channels. This implies that for these channels the yrast states are preferentially populated.

If a resonant effect exists in the fusion-evaporation channels, the ratio will differ from 1. As can be seen in Table 1, the resonant effect is smaller than the one observed in the inelastic channels presented previously where the ratio equals roughly 2. But due to the experimental cautions taken, we believe that the deviations from 1 are significant and that a resonant effect is present in the fusion-evaporation channels. The ratio is higher or equals 1 for $^{45}$Ti, $^{42}$Ca and $^{39}$K and is lower than 1 for $^{44}$Sc, $^{41}$K, $^{41}$Ca, $^{38}$Ar and $^{37}$Ar. The maximum difference in R is $0.24 \pm 0.05$ between $^{45}$Ti and $^{41}$K. These results will be discussed in the next section.

## 3. Discussion

Concerning the results obtained for the inelastic channels, the $^{24}$Mg + $^{24}$Mg resonance decay flux is essentially observed in the $^{24}$Mg $4_1^+$ and $2_1^+$ states (present measurements) and also in the elastic channel [1, 2], i.e. in the first three members of the $^{24}$Mg $K^\pi$=$0^+$ g.s. band. This is in agreement with the molecular model proposed by Uegaki and Abe [5, 6] to describe the $^{24}$Mg + $^{24}$Mg high spin resonances. The equilibrium shape obtained in these calculations is a very deformed prolate pole-to-pole configuration which, as will be shown later, is very similar to the $^{48}$Cr shape obtained after a Jacobi transition and before fission. The identification of the $J^\pi$=$36^+$ resonance at $E_{CM}$=45.7 MeV with a $^{48}$Cr hyperdeformed molecular state is in agreement with the molecular model predictions what excitation energy, spin and decay are concerned. In this picture, the g.s. $^{24}$Mg rotational band and especially the $0_1^+$, $2_1^+$ and $4_1^+$ states play the dominant role in the description and in the decay of the resonance as demonstrated in our experiment.

The resonance under study has a very high spin ($J^\pi = 36^+$) and it is known that for the $^{48}$Cr nucleus the fission barrier vanishes at spin ∼40 [7]. For this relatively light nucleus, the rotational frequency close to the fission limit is very large and a Jacobi shape transition can be expected [8]. Calculations of the $^{48}$Cr shape evolution were performed using a new version of the liquid drop model that accounts explicitly for the nuclear surface curvature effects. Details concerning the Lublin - Strasbourg - Drop (LSD) approach can be found in Refs. [9] and [10]. The results for $^{48}$Cr can be seen on Fig. 2. For spin I=20 to I=24, the shape of the nucleus is oblate; from I=28 to I=32, the Jacobi transition takes place and the nucleus becomes triaxial; for I=36 (the present resonance spin), the shape is strongly prolate and the excitation energy predicted by this macroscopic model is close to the resonance excitation energy of 60 MeV. Finally, for I=40, the fission barrier gets small and the nucleus is about to fission. This model not only explains why at the resonant spin of 36 the $^{48}$Cr is prolate but also gives an equilibrium shape which is very similar to the one obtained through the molecular model by Uegaki and Abe [5, 6]. Such similarity of the shape suggests that there is an overlap between the resonance in our $^{24}$Mg+$^{24}$Mg entrance channel and the prolate $^{48}$Cr composite system after the Jacobi shape transition.

In the present work, new experimental results have been obtained concerning the inelastic channels selectively populated in the resonant process. Nevertheless these channels represent only 30% of the resonant flux [2, 4]. Therefore it was the goal of the second experiment to look at the fusion-evaporation channels to find missing flux. At the used beam energy, the strongest channels produced via the $^{24}$Mg + $^{24}$Mg reaction are given in Table 1. The ON/OFF resonance ratio (R) for the eight nuclei fed by fusion-evaporation is lower than the one obtained for the inelastic channels (R ∼ 2), but in view of the care taken to extract this ratio, we think that the effect is real. As seen in Table 1, the ratio varies from 0.83 to 1.07, R is lower than 1 for $^{44}$Sc, $^{41}$K, $^{41}$Ca, $^{38}$Ar and $^{37}$Ar, channels which present a 'lack' of flux, whereas a resonant effect is observed for $^{45}$Ti, $^{42}$Ca and $^{39}$K for which $R \geq 1$. The maximum difference in R observed is around 25% and we thus believe that a resonant effect is effectively there. We would like to propose a possible scenario, which is based on reaction dynamics considerations. In the $^{24}$Mg + $^{24}$Mg reaction, before complete fusion into a $^{48}$Cr nucleus, light particles could be emitted from the very deformed composite system. From such a pre equilibrium state, the flux evacuated could feed the residues with $R \geq 1$. On a longer time scale, complete fusion into $^{48}$Cr occurs and the subsequent evaporated particles are feeding the residues with $R < 1$. It is thus tentatively proposed that part of the resonant flux is carried away by this pre equilibrium emitted particles and there is thus a lack of flux in the other residues. Of course, this hypothesis could be checked

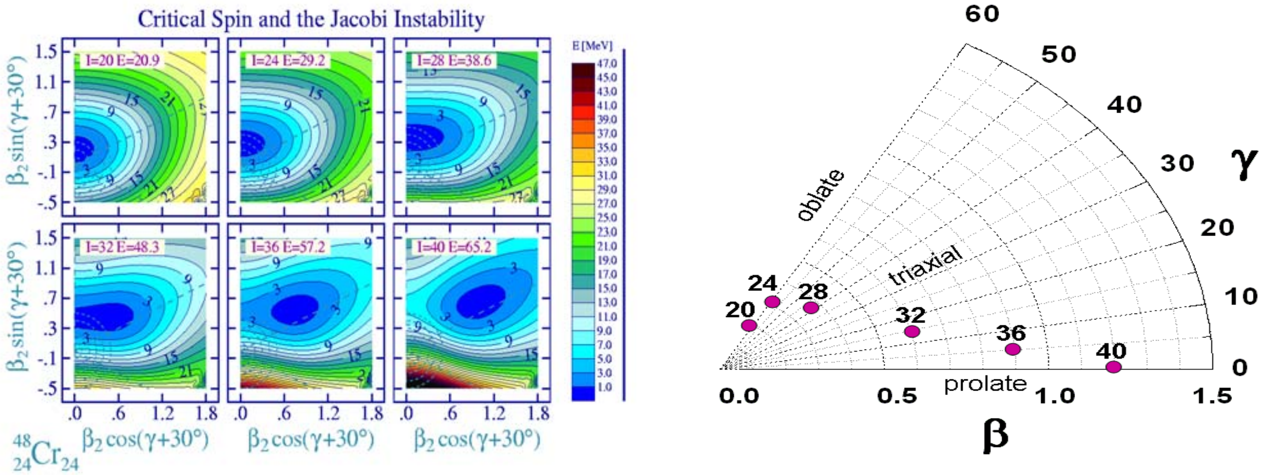


**Figure 2.** Total energy calculations in terms of the standard ($\beta$ - $\gamma$) deformations according to the LSD approach for the nucleus $^{48}$Cr at spins I between 20 and 40 [11].

by measuring the angular and energy distributions of these light particles in coincidence with the residues of interest, a similar effect has been seen in the decay of the neighbouring $^{46}$Ti [12].

## 4. Conclusion

The present work deals with the $^{24}$Mg + $^{24}$Mg system and especially with the J$^{\pi}$=36$^{+}$ resonance situated at E$_{CM}$=45.7 MeV. Two experiments were performed at the Tandem accelerator in Legnaro to look at ON and OFF resonance effects in the inelastic and fusion-evaporation deexcitation channels. Our main goal was to establish the connection of the resonance with molecular states of the deformed $^{48}$Cr composite system.

Concerning the inelastic channels, the results have been obtained using the PRISMA spectrometer in coincidence with the $\gamma$ CLARA array. For an excitation energy between 0 and 8 MeV, the resonant flux is essentially carried away by channels involving the $^{24}$Mg $0^+_1$, $2^+_1$ and $4^+_1$ g.s. members. This result is in good agreement with the molecular model proposed by Abe and Uegaki and strengthens the argument in favor of the formation of a $^{48}$Cr nuclear molecule.

As all the direct reaction channels absorb only 30% of the resonance flux [3, 4], a second experiment has been performed with the GASP $\gamma$ array coupled with the EUCLIDES Si detector on the fusion-evaporation channels. Weak resonant effects have been discovered for some of these channels such as $^{45}$Ti, $^{42}$Ca and $^{39}$K. In addition, the yrast states of the different residues are selectively populated by the fusion-evaporation process.

A fast rotating $^{48}$Cr undergoes a Jacobi shape transition which implies a very prolate shape for the nucleus just before the fission. We propose that this exotic $^{48}$Cr shape is populated by the J$^{\pi}$=36$^{+}$ resonance of the $^{24}$Mg + $^{24}$Mg reaction and corresponds to a $^{24}$Mg - $^{24}$Mg molecular state .

In conclusion, from the results obtained in the two experiments, it is obvious that there is still some resonant flux missing. It is possible that such flux could be found in the decay of the resonance through the giant dipole resonance as proposed in the case of the neighbouring fast rotating $^{46}$Ti nucleus [12] and also through eventual interband E2 transitions between resonant molecular states which in the case of the studied J$^{\pi}$=36$^{+}$ has been shown to be particularly enhanced [6]. A new detector, represented on Fig. 3, has been designed to fulfill this purpose. It is composed of 24 position sensitive Si detectors surrounded by a high efficiency $\gamma$ array.

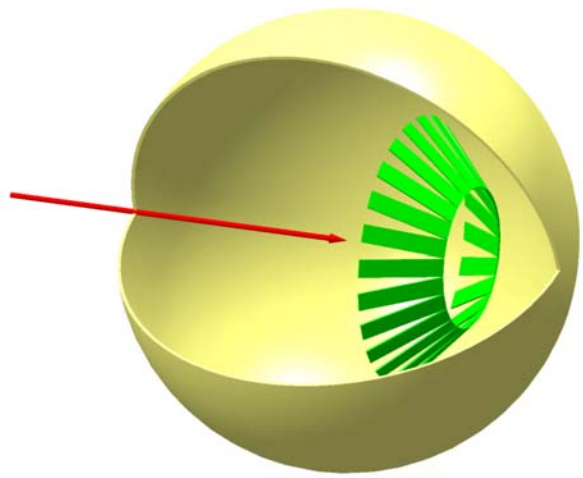

**Figure 3.** View of a new detector for the search of electromagnetic transitions between molecular states.


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