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Molecular resonances and the Jacobi shape transition : the case of ^{24}Mg+^{24}Mg and ^{48}Cr

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A fast rotating ^{48}Cr is predicted to be highly prolate and deformed after a Jacobi shape transition and just before fission. In this article, it is proposed that a narrow and high spin ^{24}Mg+^{24}Mg resonance corresponds to the formation of this exotic ^{48}Cr. Therefore 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. To establish the connection between the resonance and a molecular state of ^{48}Cr, 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 γ array CLARA, and, for the fusion-evaporation channels, the Si array EUCLIDES and the γ array GASP. Strong resonant effects have been observed in the inelastic channels involving the 2^+ and 4^+ states of the ^{24}Mg ground state (g.s.) band. Weaker effects are also seen in certain fusion-evaporation channels. Both results will be discussed here.

1. Introduction

In light heavy-ion collisions, resonant phenomena have been established experimentally through the measurement of excitation functions for composite systems with A lower than 60. The most striking resonances have been observed in the collisions between identical even-even nuclei like the reactions ^{12}C+^{12}C, ^{14}C+^{14}C, ^{16}O+^{16}O, ^{24}Mg+^{24}Mg and ^{28}Si+^{28}Si. While the observation of resonances is well understood in terms of a small number of open channels, their connection to large cluster and molecular states in the composite system is still a debated question. Such a link can only be firmly established through measurements not only of their spins and parities, but also of their γ and fragment decay widths.

The best cases to study are those for which the resonance width is narrow (100 to 200 keV) and thus implies that the lifetime of the composite system is long. This

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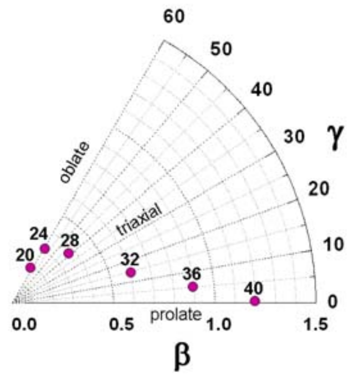

Fig. 1. Shape evolution in terms of the standard (β - γ) deformations according to the LSD approach[1] for the nucleus ^{48}Cr at spins J between 20 and 40.

would justify the assimilation of the formed dinucleus to a nuclear molecule. These conditions are fulfilled for some systems mentionned before and especially for the heaviest ones such as ^{24}Mg+^{24}Mg and ^{28}Si+^{28}Si. For both of them, narrow resonance phenomena have been observed and occur at high spins and high excitation energies, which could correspond to molecular states in ^{48}Cr and ^{56}Ni.

For the ^{24}Mg+^{24}Mg reaction, we have decided to focus on the decay of a resonance at a CM energy of 45.7 MeV (located at twice the Coulomb barrier), for which a spin-parity of $J^{\pi} = 36^{+}$ has been assigned from fragment-γ angular correlation work [2]. Despite the very high excitation energy of 60 MeV in the ^{48}Cr composite system, this resonance has a narrow total width of $\Gamma = 170$ keV. Thanks to the Heisenberg principle, this width corresponds to a lifetime of 4.10^{-21}s which is 10 times longer than a typical nuclear lifetime and corresponds to a rotation of about 2 turns of the composite system, which gives credit to the possible formation of a ^{48}Cr dinucleus in the resonance process. Therefore we suggest that there is a possibility of a strong overlap between the entrance channel ^{24}Mg+^{24}Mg resonance and the very deformed prolate ^{48}Cr nucleus at spin $J^{\pi} = 36^{+}$ and excitation energy of 60 MeV. If this scenario is correct, a signature of the deformation of the dinucleus should appear in the decay channels.

2. The fast rotating ^{48}Cr

Before going into the details of the ^{24}Mg + ^{24}Mg resonant reaction, let's first look at the shape evolution of a rotating ^{48}Cr nucleus. The resonance under study has a very high spin ($J^{\pi} = 36^{+}$) and it is known that for the ^{48}Cr the fission barrier vanishes at spin $\sim$40. For this relatively light nucleus, the rotational frequency close to the fission limit is very large and a Jacobi shape transition can be expected. Calculations of the ^{48}Cr shape evolution were performed using the LSD (Lublin

Strasbourg Drop) model [1], the results for ^{48}Cr can be seen in Fig. 1. For spin J = 20 to J = 24, the shape of the nucleus is oblate; from J = 28 to J = 32, the Jacobi transition takes place and the nucleus becomes triaxial; for J = 36 (the present resonance spin), the shape is strongly prolate and finally, for J = 40, the fission barrier gets small and the nucleus is about to fission. This model describes the shape of ^{48}Cr as a function of the angular momentum and explains why at a resonant spin of 36 the ^{48}Cr is prolate. But how can this deformed nucleus be formed? We believe that the resonance in the entrance channel is responsible for such a formation.

3. The ^{24}Mg + ^{24}Mg resonance

Experiments in Legnaro	First experiment	Second experiment
Channels explored	Inelastic channels	Fusion-evaporation channels
Goal	Resonant states in ^{24}Mg	Resonant residues
Detectors	PRISMA/CLARA	GASP/EUCLIDES
Measurements	fragment-γ coincidences	γ-light charged particle coincidences
Bombarding energies	ON resonance : 91.72 MeV - OFF resonance : 92.62 MeV	
Target	^{24}Mg : 40 μg/cm^2 on ^{12}C backing : 15 μg/cm^2	

Table 1. Experimental details concerning both experiments performed at the Legnaro Tandem on the ^{24}Mg + ^{24}Mg reaction.

In order to study the link between the ^{24}Mg + ^{24}Mg resonance and a molecular state in ^{48}Cr, two experiments have been performed ON and OFF resonance at the Legnaro Tandem. The first experiment has been focused on the decay of the resonance into the inelastic channels, whereas the second experiment has concerned the fusion-evaporation channels. Details concerning both experiments are given in Table 1. In Table 2 are given the results obtained concerning the inelastic channels. In order to determine which states carry away the resonant flux, the yields of the corresponding γ-ray transitions have been measured both ON and OFF resonance energies.

Transitions	$2^+ \to 0^+$	$4^+ \to 2^+$	$6^+ \to 4^+$ + transitions from the $K^\pi = 2^+$ band
R	1.82	1.87	1.09

Table 2. Results concerning the inelastic channels: ON/OFF resonance ratios R for the different transitions observed in ^{24}Mg.

If R equals 1, there is no resonant effect. As can be seen in Table 2, R equals

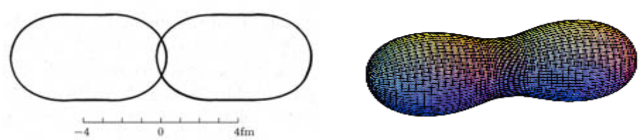

Fig. 2. Equilibrium shapes obtained, left, by the molecular model[3], and, right, by the LSD model[1] for the ^{48}Cr nucleus at an angular momentum of 36.

roughly 2 for transitions $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$. This implies that both 2^+ and 4^+ states of the g.s. band of ^{24}Mg are resonant states. On the contrary, R equals roughly 1 for the other transition which are therefore non resonant transitions and states. This is in agreement with the molecular model proposed by Uegaki and Abe [3] 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 looks like the ^{48}Cr shape obtained after a Jacobi transition and before fission (cf Fig. 2). The identification of the J^π=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. Concerning this excitation energy, the predictions by the molecular and LSD models are close to the experimental excitation energy which is of 60 MeV.

We would also like to mention that for the ^{24}Mg + ^{24}Mg system, the maximum calculated angular momenta transfer to each fragment in a sticking condition is J = 4 which is in agreement with our results.

As some resonant flux is missing in the inelastic channels, the fusion-evaporation channels have been investigated and the results are given in Table 3. At the used beam energy, the strongest channels produced via the ^{24}Mg + ^{24}Mg reaction go from ^{45}Ti up to ^{37}Ar. These residues are fed preferentially at high spins and high excitation energies as can be seen in Table 3. The ON/OFF resonance ratio (R) is lower than the one obtained for the inelastic channels, but in view of the care taken to extract this ratio, we think that the effect is real. As seen in Table 3, R varies from 0.83 to 1.07, 5 channels present a 'lack' of flux, whereas a resonant effect is observed for ^{45}Ti, ^{42}Ca and ^{39}K for which $R \geq 1$. 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 preequilibrium 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 $R < 1$. Of course, this hypothesis could be checked by measuring the angular and energy distributions of these light particles in coincidence with the residues of interest.

A more detail account and discussion of this work can be found in refs [4,5].

Nuclei	Channels	E (MeV)	Spins	$R_{ON/OFF}$
^{45}Ti	2pn	6,2	12	1,07 ± 0,02
^{44}Sc	3pn	3,6	11	0,96 ± 0,02
^{42}Ca	α2p	7,8	11	1,03 ± 0,01
^{41}K	α3p	2,8	7	0,83 ± 0,04
^{41}Ca	α2pn	5,9	9	0,92 ± 0,02
^{39}K	2αp	8	10	1,00 ± 0,01
^{38}Ar	2α2p	4,6	5	0,97 ± 0,03
^{37}Ar	2α2pn	6,5	8	0,88 ± 0,03

Table 3. Results for the fusion-evaporation channels. For each residue observed in the ^{24}Mg + ^{24}Mg reaction: channels, excitation energies and spins of favoured feeding, ON/OFF resonance ratios.

4. Conclusion

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^{π}=36^{+} resonance of the ^{24}Mg + ^{24}Mg reaction and corresponds to a ^{24}Mg - ^{24}Mg molecular state . In order to prove this statement, two experiments have been performed. Concerning the inelastic channels, the resonant flux is essentially carried away by channels involving the ^{24}Mg 0^{+}, 2^{+} and 4^{+} g.s. band members. This result is in good agreement with the molecular model and strengthens the argument in favor of the formation of a ^{48}Cr nuclear molecule. Concerning the fusion-evaporation channels, weak resonant effects have been discovered for ^{45}Ti, ^{42}Ca and ^{39}K. In conclusion, from the results obtained, it is obvious that there is still some resonant flux missing. It is possible that part of such flux [5] could be found in the decay of the resonance through the ^{48}Cr giant dipole resonance and also through interband E2 transitions between resonant molecular states.

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