The low-lying \(^{12}\text{C}\) excited states have been recently studied through different experiments \([1, 2, 3]\) which have pointed out the features of these states. In particular the Hoyle state at 7.65 MeV excitation energy \([4]\) has been interpreted as mainly instantaneous \([3]\) or sequential through an intermediate \(^{8}\text{Be}\) \(_{gs}\) decay \([2]\). Many efforts have been dedicated to model comparisons and most of the results indicate a nearly complete agreement with a sequential decay with a very small (around 0.3\%) contamination by the instantaneous one. A very recent review of the Hoyle state, together with implication on nuclear forces, structure and astrophysics, has been recently published \([5]\).

We have studied the reaction \(^{12}\text{C} + ^{12}\text{C}\) with a 95 MeV Carbon beam delivered by the Tandem accelerator of INFN Laboratori Nazionali di Legnaro (LNL) with the [GARFIELD + RCo] apparatus covering approximately 4\(\pi\) \([6]\). The collected data have been analyzed with the aim of selecting compound nucleus reactions and compared to a dedicated Hauser-Feshbach calculation \([HF]\), which includes excited states of light nuclei. The results, published in \([7]\), show a substantial good agreement with theoretical predictions except some discrepancies for even residues, showing contamination from clustering effects. In this report we will concentrate on the analysis of semiperipheral \(^{12}\text{C} + ^{12}\text{C}\) reactions and in particular reactions where the projectile interacts with the target, leaves the target in the ground or in a slightly excited state and decays in three \(\alpha\)-particles.

### Results

In Fig. 1 the energy spectrum of the reconstructed \(^{12}\text{C}\) quasi-projectile is shown, as calculated from the sum of the energy of the three \(\alpha\)-particles:

\[
E_{\text{tot}} = \sum_{i=1}^{3} E_i + E_{\text{rec}} = E_{\text{beam}} + Q
\]

where \(Q = -7.272\) MeV is the Q-value for the decay of \(^{12}\text{C}\) in three \(\alpha\)-particles and \(E_{\text{rec}}\) is the recoil of the \(^{12}\text{C}\) quasi-target. As it can be easily seen most of the energy corresponds to a negligible recoil energy and therefore a \(^{12}\text{C}\) quasi-target nearly at rest in the laboratory frame.

[Fig. 1 Total energy spectrum for \(\alpha\)-particles products. From right to left the peaks correspond to the ground and the first excited states of the recoil \(^{12}\text{C}\) nucleus.]
The excitation energy of the $^{12}$C quasi-projectile can be calculated as:

$$E^* = \sum_{i=1}^{3} E_i - \frac{p_C^2}{2m_C} + E_{th}$$

and is presented in Fig. 2 ($E_{th} = |Q| = 7.272$ MeV). Three excited $^{12}$C quasi-projectile levels are present for “true” $\alpha$-particles ($\approx 7.7, 9.6$ and $10.8$ MeV).

The lower peak in Fig. 2 corresponds to the well-known Hoyle state. Different observables have been proposed to determine if the decay of this state is instantaneous or sequential through the formation of $^8$Be$_{\alpha}$. The first is the minimum relative energy between a pair of the three $\alpha$. The presence of a peak at about 92 KeV is the first observable compatible with a prevalent sequential decay and it has been presented in the 2013 LNL Annual report [9].

A second observable which can contribute to the discussion is the deviation from the average center-of-mass energy:

$$E_{rms} = \sqrt{\left\langle E^2_{\alpha}\right\rangle - \left\langle E_{\alpha}\right\rangle^2}$$

here $E_{\alpha}$ represents the energy of the $\alpha$-particles in the $^{12}$C rest frame and the average is over the three $\alpha$-particles in each event. $\left\langle E_{\alpha}\right\rangle$ corresponds to $1/3$ of the $Q$-value for the Hoyle-state decay into three $\alpha$-particles (127 KeV).

The results are shown in Fig. 3 where the plot of $E_{rms}$ vs. the mean $\alpha$-particle energy is shown. As it can be easily inferred for Fig. 3 the simultaneous decay, corresponding to three $\alpha$-particles at nearly the same kinetic energy, i.e. at very low $E_{rms}$ values, is absent in our analysis, contrary to the bump at $E_{rms} < 25$ KeV obtained in Ref. [3].

Finally if we analyze the Dalitz plot (see Fig. 4) of the energies of the three $\alpha$-particles normalized to the total energy. We would expect that the simultaneous decay should result in 3 equal kinetic energies, i.e. an enhancement of the central part of the plot which is not the case of our data. On the contrary, it shows enhancements in the region where the energy of two $\alpha$-particles are very close one to the other an the third $\alpha$-energy is far from the two others.

This can be considered as a signal of the importance of the sequential decay.