IL NUOVO CIMENTO **48 C** (2025) 34
DOI 10.1393/ncc/i2025-25034-1

Colloquia: WPCF-Resonance 2023

The OSCAR correlator for low energy nuclear reactions and heavy-ion collisions

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received 23 July 2024

Summary. — The OSCAR array (hOdoscope of Silicons for Correlations and Analysis of Reactions) is a modular detector designed to perform two- and multi-particle correlation measurements in heavy-ion collisions and direct nuclear reactions at low beam energies. The main features of the OSCAR detector will be presented in this manuscript, including its present and future scientific programs. Correlation measurements with OSCAR allow to study the decay of resonances produced during nuclear reactions, providing information about the structure of unbound particle states in both stable and exotic light nuclei. As an example, the reconstruction of the Hoyle state in ^{12}C via 3-α particle correlations and invariant mass spectroscopy is shown. Possible applications on Femtoscopy studies of low energy heavy-ion collisions are also discussed.

1. – Introduction

Studies in the nuclear physics fields of Resonance Decays and Femtoscopy need instrumentation able to perform precise and thorough particle correlation measurements to extract information, *e.g.*, on the branching ratio of certain decay mechanisms or on the correlation function for the emission of two particles from an evaporating source. To this aim, thanks to its modularity, adaptability and performance features, the OSCAR detector has already been exploited to study the mechanism of the Hoyle state resonance decay in ^{12}C, which has paramount importance in the field of nuclear astrophysics. The main strengths of the OSCAR detector, apart from the low threshold and high energetic resolution for the detection of charged particles, are the high compactness and modularity: in fact, different modules can be used together, or even combined with other detectors. Its high performance have also been proved true with other experiments, such as in refs. [1], where an array of four different OSCAR modules was used, in a very compact geometry, to measure the cross section of the $^3He(^{13}C,\alpha)^{12}C$ reactions, with excellent results in

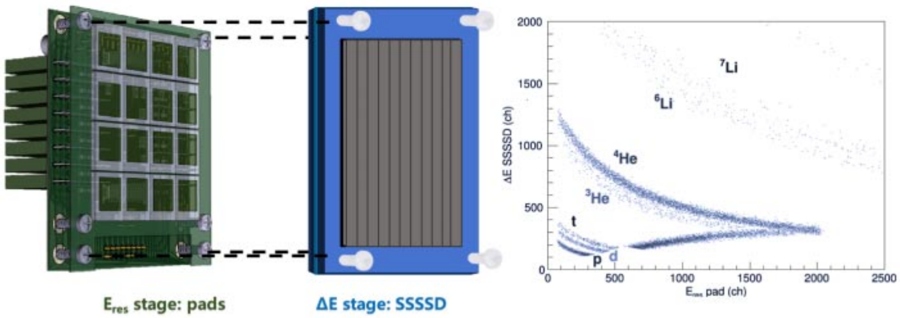

Fig. 1. – (*Left*): Schematic depiction of the two stages of the OSCAR detector, with the sixteen 500 μm-thick silicon pads in the second (E_{res}) stage and the sixteend strips in the first (ΔE) stage; (*Right*): example of a $\Delta E - E$ spectrum obtained for one single pseudo-telescope for different kinds of particles with charge Z = 1, 2, 3 in [5].

the discrimination of the elusive α_2 channels (where the residual ^{12}C nucleus is left in the *Hoyle* excited state, [2]), a *golden way* to highlight the presence of cluster structures in ^{16}O, as well in other experimental situations [3, 4]. In this manuscript, further applications in correlation studies in the field of low-energy femtoscopy, both with stable and radioactive ion beams, are proposed to be performed in actually or soon available experimental facilities.

2. – Experimental features

A full OSCAR unit is composed of two independent stages (as explained in a more detailed way in ref. [5]). The first one is a Single Sided Silicon Strip Detector (SSSSD), an array of sixteen adjacent 20-μm thick silicon strips, with a very low detection threshold (*i.e.*, 500 keV/A), capable of identifying even the slowest particles. The second stage consists of sixteen independent ceramic-framed silicon pad detectors, with variable thickness (usually 300-500 μm) with an active area of 1 cm^2 each. The overlap between the sixteen strips from the first stage and the sixteen pads from the second stage produces sixty-four $\Delta E - E$ pseudo-telescopes, and grant very high angular resolution (of $\sim 1°$ at about 55°) and granularity, thus being highly sensitive to particles' incident positions, a parameter which is, of course, fundamental for correlation studies. As shown in fig. 1, which represents a $\Delta E - E$ spectrum obtained for one of the pseudo-telescopes, OSCAR is capable of separation and identification of particles, in charge and mass, of Z = 1, 2, 3, up to ^{7}Li, with incident energies as low as 1.2 MeV/nucleon.

3. – The study of the Hoyle state decay in ^{12}C

The existence of the Hoyle state, *i.e.*, the first 0^+ excited state in ^{12}C level scheme, has been suggested to be the main explanation for the enhanced nucleosynthesis rate of ^{12}C (and, thus, heavier elements) in stars, thought to happen through the fusion of three α particles. To highlight the mechanism of this process, it is important to understand and define if it happens via a direct three-body capture process (DD), an event which should be extremely unlikely to happen without the existence of a resonance, or via a sequential process, by which a wandering α particle is captured by a ^{8}Be nucleus in the short time-span of its life (SD). To experimentally discriminate between these two mechanisms, and to identify which one is dominant, it is useful to look at the decay of the aforementioned Hoyle state, by the means of α-particles angular correlation analyses in the framework of nuclear reaction experiments.

Up to today, contradictory results have been found for the branching ratio of the DD to the SD mechanisms, when different interacting physical systems were used for the measurements. In the case of nuclear reactions, such as in refs. [4, 6, 7], where a smaller number of degrees of freedom is present, the obtained branching ratio is very low (DD/SD = 0.043 %). When the same parameter is obtained by analyses from heavy-ion collisions [8], the obtained value is much higher (DD/SD = 17%); this discrepancy is thought to be due to effects induced by the reaction mechanism by in-medium modifications of the nuclear structure.

An experimental set-up constituted by four OSCAR second stages (a total of sixty-four silicon pads) was exploited in [1] to measure the angular correlation of the three α particles which were hypothesized to be emitted by the excited $^{12}C_{Hoyle}$ nucleus formed by the $^{14}N(d,\alpha)^{12}C_{Hoyle}$ direct reaction at E_{beam} = 10.5 MeV. The OSCAR detector was chosen because of the high resolution and background-to-noise ratio it shows in the region of the ^{12}C Hoyle peak, at $E_x \sim 7.65$ MeV.

The experiment has been performed to discriminate between the occurrence of the direct or the sequential process for the decay of the Hoyle state resonance. To this aim, two different kinds of Montecarlo simulations have been performed, each of them assuming a 100% contribution of the sequential process (100% SD) or of the direct process in the phase space (100% DDΦ), in order to be compared with the obtained experimental data. The first kind of Montecarlo simulation has been presented in the form of Dalitz plots, and shows how the experimental data are better explained if a fully sequential decay process is taken into account. The same conclusion can be extracted by looking at the energy distribution for the largest of the three α particles normalized energies (ϵ_i), which also perfectly follows the simulated curve for the sequential decay: the plot is peaked at ϵ_i = 0.5, meaning that in most cases, the normalized energy of the most energetic α particle is half of the total, suitable with the explanation of a sequential decay in which the first step involves the emission of an α particle and a ^8Be nucleus; otherwise, the plot would show a more diffuse distribution between ϵ_i =0.33 and ϵ_i= 0.67, which is what one would expect for a decay process in which the parent state decays in three different particles, where each one of these particles get the same kinetic energy. By the analysis of these data, it has been possible to extract, with a confidence level of 95%, the aforementioned value of 0.043% for the upper limit of the branching ratio of the DDΦ to the SD.

4. – Low energy femtoscopy with the OSCAR correlator

The study of emitting sources, produced during heavy ion collisions, is mainly complicated by the charateristic sizes (of about 10^{-15} m = 1 fm) and timescales of the phenomenon ($\sim 10^{-23}$ s). It is thus necessary to extract information through indirect observations, using Femtoscopy and imaging techniques ([9-11] To do so, it is necessary to measure the relative momenta of the emitted particles, to construct the correlation function. This correlation function is then used as input data in the Koonin-Pratt equation to extract information on the particles' relative distance distribution (at the moment of the emission of the second particle), and thus on the source size, and its dynamical evolution.

OSCAR may be, indeed, used in low-energy femtoscopy studies. In this way, through the study of peripheral and central heavy-ions collisions at E/A lower than 15 MeV, in which the main processes are, respectively, the production of evaporating quasi-projectile and quasi-target and fusion or evaporation processes, it should be possible to have a deeper understanding of the systems lifetimes, the emission of resonances or the eventuality of final state interactions between the emitted particles.

Few attempts to measure emission times in evaporation sources have been performed in ref. [12], exploiting the ^{129}Xe + ^{27}Al reaction. OSCAR may help to improve the description of states of different nuclei, already seen in previous experiments [13] which, although were using old telescope detectors, with only 4° of angular resolution, were able to see the states of the various nuclei, but not precise enough to extract information and disentangle the occurrence of the decay of pre-formed clusters or the independent emission of particles and the consequent final state interaction.

5. – Conclusions

Experiments as the ones mentioned in the previous sections may be performed by the means of stable or radioactive ion beams, available at SPIRAL1 (and SPIRAL2, in the near future) at GANIL, FRIB at Michigan State University and SPES at Laboratori Nazionali di Legnaro. The experiments will need a suitable and modern particle correlator, which could provide high and precise angular resolution and an adequately low threshold for low energy studies, especially if one wants to better understand emissions from long-lived evaporating sources.

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