IL NUOVO CIMENTO **41 C** (2018) 172
DOI 10.1393/ncc/i2018-18172-x

COLLOQUIA: IWM-EC 2018

Isotopic composition of quasi-projectile fission fragments for the systems ^{40,48}Ca + ^{40,48}Ca at 35 AMeV

A. CAMAIANI(1)(2)(*) G. CASINI(2), S. PIANTELLI(2), E. BONNET(3), R. ALBA(4), S. BARLINI(1)(2), M. BINI(1)(2), B. BORDERIE(5), R. BOUGAULT(6), M. BRUNO(7)(8), A. BUCCOLA(1)(2), A. CHBIHI(9), M. CICERCHIA(10)(11), M. CINAUSERO(10), D. DELL'AQUILA(12), J. A. DUENAS(13), Q. FABLE(6), D. FABRIS(14), L. FRANCALANZA(12), J. D. FRANKLAND(9), C. FROSIN(1)(2), F. GRAMEGNA(10), D. GRUYER(6), M. HENRI(6), A. KORDYASZ(15), T. KOZIK(16), N. LE NEINDRE(6), I. LOMBARDO(17), O. LOPEZ(6), C. MAIOLINO(4), T. MARCHI(10), L. MORELLI(9), A. OLMI(1)(2), P. OTTANELLI(1)(2), G. PASQUALI(1)(2), G. PASTORE(1)(2), M. PARLOG(6)(18), G. POGGI(1)(2), D. SANTONOCITO(4), A. A. STEFANINI(1)(2), S. VALDRÉ(2), E. VIENT(6), G. VERDE(17) and M. VIGILANTE(12)

(1) *Dipartimento di Fisica, Universitá di Firenze - Firenze, Italy*
(2) *INFN, Sezione di Firenze - Firenze, Italy*
(3) *SUBATECH UMR 6457, IMT Atlantique, Universitè de Nantes, CNRS-IN2P3 - 44300, Nantes, France*
(4) *INFN, Laboratori Nazionali del Sud - Catania, Italy*
(5) *IPN, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay - F-91406 Orsay Cedex, France*
(6) *Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen - F-14000 Caen, France*
(7) *Dipartimento di Fisica, Università di Bologna - Bologna, Italy*
(8) *INFN, Sezione di Bologna - Bologna, Italy*
(9) *GANIL, CEA/DRFCNRS/IN2P3 - Bvd. Henri Becquerel, 14076 Caen, France*
(10) *INFN, Laboratori Nazionali di Legnaro - Legnaro(PD), Italy*
(11) *Dipartimento di Fisica, Università di Padova - Padova, Italy*
(12) *Dipartimento di Fisica and Sezione INFN, Università di Napoli - I-80126 Napoli, Italy*
(13) *Departamento de Fisica Aplicada, FCCEE Universidad de Huelva - 21071 Huelva, Spain*
(14) *INFN, Sezione di Padova - Padova, Italy*
(15) *Heavy Ion Laboratory, Warsaw University - Warsaw, Poland*
(16) *Jagiellonian University - Cracow, Poland*
(17) *INFN, Sezione di Catania, Catania, Italy*
(18) *"Horia Hulubei" National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) - P.O. BOX MG-6, Bucharest Măgurele, Romania*

received 3 December 2018

(*) E-mail: alberto.camaiani@fi.infn.it

Summary. — In this paper, preliminary results for the reactions ^{40,48}Ca + ^{40,48}Ca at 35 MeV/u in the framework of the FAZIASYM experiment are discussed. FAZIASYM experiment was performed at the LNS cyclotron with 4 blocks of the FAZIA apparatus. We will focus on the quasi-projectile fission events. After a brief overview on the various analysis steps, we will show some results on the isospin content of both fission-like fragments, comparing the cases of the two extreme n-rich and n-deficient systems also by exploiting a recently introduced order variable.

1. – Introduction

In the past years the FAZIA Collaboration developed and built a new modular detector aimed at investigating nuclear reactions in the Fermi energy domain (25–50 MeV/u): after a long R&D phase, some physics campaigns at the INFN Laboratori Nazionali del Sud (LNS) were carried out. In this proceeding we are going to talk about preliminary results from the second experiment of the first campaign, devised to explore the reactions ^{40,48}Ca+^{40,48}Ca at 35 MeV/u.

The so-called FAZIASYM experiment was proposed in order to complete a study on the symmetry energy term of the nuclear Equation of State (EoS) started using the INDRA + VAMOS setup at GANIL [1, 2]. A limit of the latter measurement, due to the presence of the spectrometer, is the lack of coincidence among quasi-projectile (QP) and light charged particles (LCP) or intermediate mass fragments (IMF) at forward angles. Such a limit could be overcome by a modular detector like FAZIA. However, in this paper we mainly focus on a subject that recently became of interest to our collaboration, following previous ideas and analyses with FAZIA [3,4] and also supported by some recent literature [5, 6], *i.e.*, the investigation of the isospin content of both fission fragments coming from the QP, detected in coincidence.

2. – Experimental apparatus

The experimental apparatus consists of 4 blocks of the FAZIA detector, located in the Ciclope Scattering Chamber of LNS; a complete description of the features of the telescopes, in particular for what concerns the Z, A identification can be found elsewhere [7-10]. A block of FAZIA consists of 16 Si-Si-CsI telescopes fully equipped with digital electronics; each layer has a thickness of 300 μm, 500 μm and 10 cm, respectively. The fragments can be isotopically identified exploiting the Si-Si and Si-CsI ΔE-E correlations up to $Z \approx 25$ and the Pulse Shape Analysis (PSA) techniques (the latter for the particles stopped in the first Silicon layer) up to $Z \approx 20$ with low identification thresholds as reported in [10]; LCPs are mainly identified in charge and mass in the CsI detector by means of conventional fast-slow PSA.

The four blocks were placed 80 cm far from the target, covering the polar angles from 2° up to 8° with respect to the beam axis. Each block covers a surface of about 9×9 cm^2 and an active solid angle of $\sim$0.01 sr.

Since the angular acceptance of our experimental apparatus is small, it is extremely important to discuss any result by comparing it with the distributions obtained via realistic simulations of the considered reactions. As conventionally done in this research field, the reactions are simulated in two steps. The first one is the nuclear collision itself and the second is the de-excitation process which brings the initially excited fragments towards the ground or low-lying states. For the description of the dynamical phase we adopted the AMD model [11], choosing a stiff parametrization of the symmetry energy term ($L = 108$) and stopping the calculations at 500 fm/c. As afterburner we have chosen the statistical model GEMINI++ [12]; for sake of brevity in the following we label the AMD + GEMINI simulated data simply as “AMD”. The AMD events have then been filtered via a software replica of the apparatus, including the efficiencies, the resolutions and the identification thresholds of the various detectors. We refer to these filtered data as “AMD geo”, while “AMD 4π” means a sample of events that does not consider the apparatus efficiency at all.

3. – Event selection: Fission of the quasi-projectile

The selection of the QP fission-like events has been done via software gates: in the following we will discuss these criteria using the n-rich system as an example. The same selections have been applied to the n-deficient one.

To disentangle peripheral and central events we exploit the correlation between the total detected charge (Z_{TOT}) and the flow angle (θ_{flow}), in events where the number of detected fragments (with $Z \geq 3$) is greater than one. As shown in literature, while the most strongly dissipative collisions produce a flat θ_{flow} distribution, the more peripheral collisions are mainly located at low angles [13]. In our case due to the low multiplicity of the events, because of the limited geometrical efficiency, θ_{flow} is dominated by the direction of the biggest fragment.

The results are shown in the left panel of fig. 1: a clear accumulation of events is present at small angles. We have verified by means of the simulation that such an accumulation corresponds to peripheral events in which the QP has been detected. Thus we define peripheral events (black rectangle in fig. 1) as those with $2° < \theta_{flow} < 20°$ and $12 \leq Z_{TOT} \leq 20$ (which represents a reasonable domain for the QP charge).

The selection of the QP fission can be done assuming a two step process: the QP formed in semi-peripheral collisions, as selected before, can undergo a further break-up in two fragments. Such fragments can thus be selected with proper conditions. In particular we can exploit the correlation between the System Center of Mass (SCM) relative angle

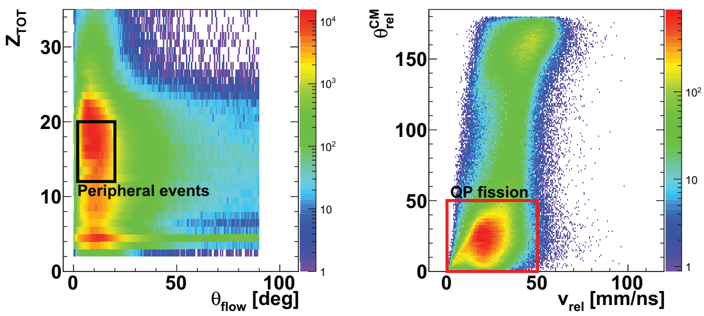

Fig. 1. – Left panel: correlation between the flow angle and the total detected charge. Right panel: correlation between the SCM relative angle of the two biggest fragments and their relative velocity. Both correlations are for the n-rich system.

of the two biggest fragments (θ_{rel}^{CM}), and their relative velocity (v_{rel}). Indeed, if the two detected fragments are produced in the QP fission, θ_{rel}^{CM} must be much smaller than 180°, meaning that both are forward emitted with respect to the SCM, and v_{rel} has to be compatible with the Viola systematics [14].

A class of events that meets these criteria can be found in the right panel of fig. 1 (red rectangle), where the correlation θ_{rel}^{CM} *vs.* v_{rel} is shown for the peripheral events selected as described above with two detected fragments.

4. – Results

First information can be extracted from the average neutron number per charge unit ($\langle N \rangle / Z$) of the fission fragments as a function of their charge. The results are shown in fig. 2, both for the ^{48}Ca+^{48}Ca and ^{40}Ca+^{40}Ca systems, where the first and the second biggest fragments of each event, assumed to be the remnant of the QP fission, are shown, labelled as "BIG" and "small", respectively, according to the legend.

The different neutron richness of the systems causes a net shift, approximately of 0.1, between the n-rich and the n-deficient system, but the behavior is almost the same. In both systems the values clearly oscillate below Ne ions and then they flatten; such a trend is quite similar to that observed in other systems [15, 16]

Recently Jedele *et al.* [5] associated the isospin content of the QP fission fragments to the timescale of the rupture of the excited (and deformed) QP after the interaction with the target nucleus introducing an ordering variable (studied system ^{70}Zn+^{70}Zn at 35 MeV/u). Such a variable is the angle (labelled as α) between the center-of-mass velocity of the original fissioning QP (reconstructed as the CM of the fission pair) and the relative velocity of the two fragments after the split ($\alpha = 0$ means that the two fragments are aligned along the direction of their center of mass, with the light one toward the target side). The faster the fission mechanism, the smaller the α angle [17, 18]. In ref. [5] a regular trend of the fragment isospin content is shown as a function of the α angle for a given fission pair: the isospin content tends to exponentially decrease (increase) with increasing α for the smaller (bigger) fragment of the pair. After deducing the decay constant for this trend the authors of [5] could extract the fission time scale.

Following [5, 6] we started a similar analysis for the QP fission fragments. First of all we needed to understand the effect of our limited angular acceptance. For such a purpose we investigated the cos(α) distributions, shown in fig. 3. Our distributions do

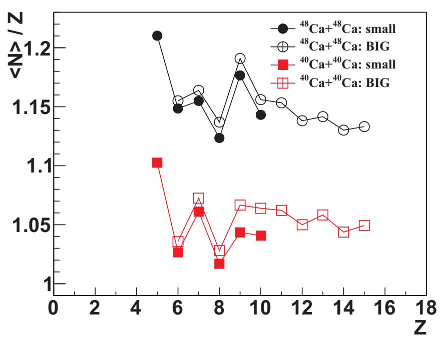

Fig. 2. – Average neutron number per charge unit of the fission fragments as a function of their charge. Statistical errors are smaller than the marker size.

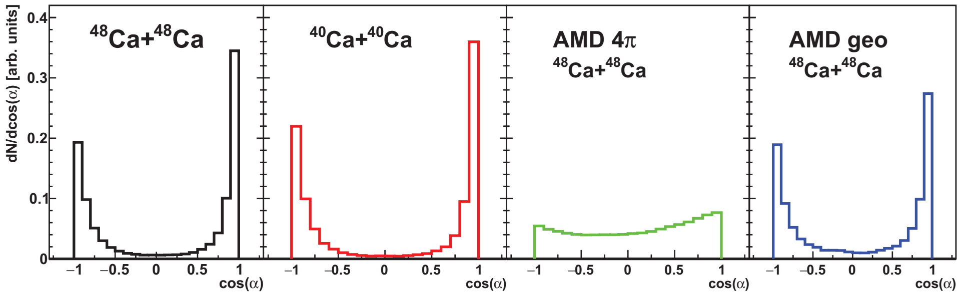

Fig. 3. – Experimental and simulated distributions of $\cos(\alpha)$. All the histograms are normalized to unity.

not manifest a shape similar to that often observed by other experiments [5, 6, 16] with a pronounced peak at $\cos(\alpha) = 1$. However, an aligned emission seems favored, with a slight preference for the smaller fragment emitted towards midvelocity.

By means of the reaction simulations we verified that the geometry significantly affects the shape of the measured $\cos(\alpha)$ distribution. This is shown for the n-rich system in the third and fourth panel of fig. 3; the labels refer to the convention introduced in sect. **2**. As we can see the effect of the geometry is mainly to deplete the distribution around $\cos(\alpha) \sim 0$, as also observed in other experiments with limited angular coverage [19].

In fig. 4 the isospin content (here quoted as $\Delta = \langle\frac{N-Z}{A}\rangle$ for an easier comparison with [5, 6]) is reported for many fission pairs as a function of the α angle. Due to the low statistics collected for the n-deficient system, here we limit ourselves to show only the data of the n-rich one. Data are organized in the following way: each row represents classes of events with fixed sum of the "small" and the "BIG" fragment (Z_{QP}), decreasing from $Z_{QP} = 20$ (top) to $Z_{QP} = 12$ (bottom); in some sense moving down a column we are going from peripheral events to more central ones. Moreover, moving horizontally, from left to right, the event asymmetry decreases (left are the most asymmetric break-ups). The Δ values of the "small" and the "BIG" fragment of the pair are represented as blue and magenta dots, respectively.

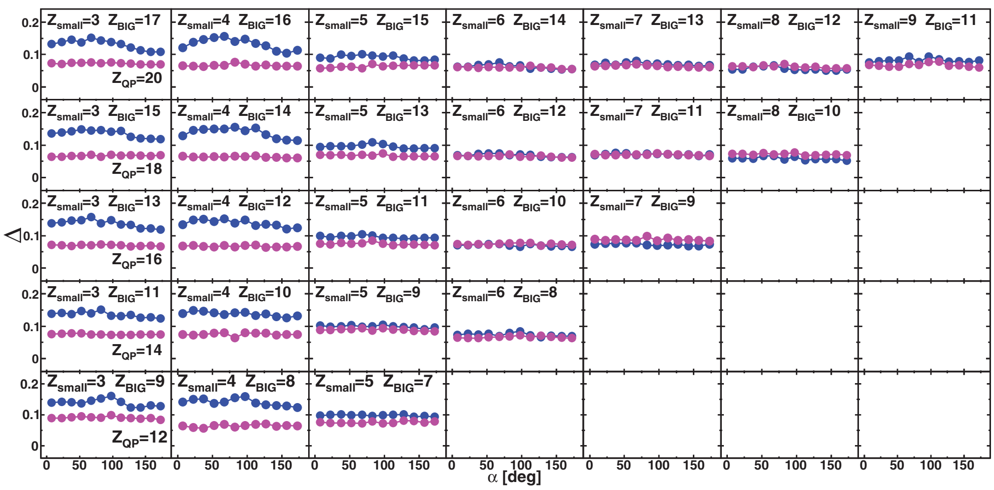

Fig. 4. – Δ as a function of the α angle for the n-rich system. Blue dots: Δ value for the small fragment. Magenta dots: Δ value for the BIG fragment. See the text for the panels displacement.

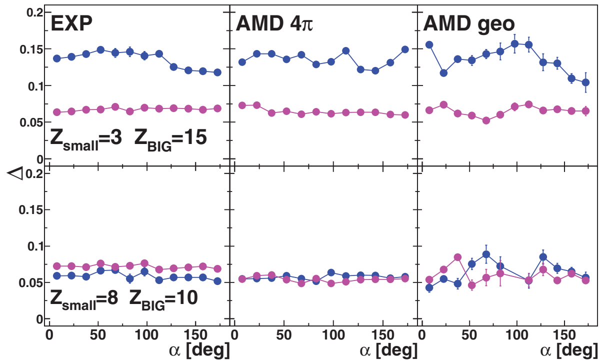

Fig. 5. – Isospin content as a function of the α angle for the fission pairs $Z_{small} = 3$, $Z_{BIG} = 15$ and $Z_{small} = 8$, $Z_{BIG} = 10$. The panels are organized as follow: in the first column the experimental plots, in the second the 4π original AMD simulation, in the third column the AMD results after the geometrical filter.

Some observations can be made looking at fig. 4. First, an equilibration of the isospin content as the symmetry increases is clear, independently of the Z_{QP} value: indeed, the Δ gap between the "BIG" and the "small" fragment decreases moving toward symmetric events. Second, in every panel, a clear decrease/increase of Δ as a function of α, as reported for instance in [5, 6], does not appear. A weak decreasing trend of Δ with increasing of α for Z_{small} seems visible for the pairs involving $Z_{small} = 3$ and 4, but not with the evidence found in [5, 6]. Mostly for asymmetric splits, a slight and broad Δ increase around 90° seems apparent. This can be an artifact due to the the limited coverage of the blocks and will be thoroughly verified in our next analysis with the help of the AMD simulation.

A first indication in this sense can be seen in fig. 5. Here the filtered events (AMD geo) present a broad irregular bump at 60–120°, not present in the original simulation (AMD 4π). However, the geometry effects do not change too much the main trends of the figure: the Δ gap between the "small" and "BIG" fragment is preserved for all the fission directions (no clear tendency to isospin equilibration when α increases). Indeed, an important observation is that not even the AMD 4π simulation predicts an evolution of Δ as a function of α, at variance with the experimental results of [5, 6], and it is qualitatively in agreement with our findings of fig. 4. The lack of an evolution of Δ *vs.* α could signal some differences in the time scale of the break-up process according to the scenario proposed in [5, 6]. These subjects will be carefully investigated to understand the reasons of the apparent different behavior of the splitting of Zn QP [5, 6] and Ca QP. This might be related to the different size of the two systems. The work is still in progress.

5. – Conclusion and prospectives

We have presented some preliminary experimental results concerning the analysis of the systems ^{48,40}Ca+^{48,40}Ca at 35 MeV/u on data collected with the FAZIA apparatus at the INFN Laboratori Nazionali del Sud (Italy). Motivated by the recent results on the quasi-projectile fission obtained in our previous FAZIA experiment [3, 4] and in similar systems [5, 6], we started a study of the isospin dynamics for the QP fission events.

The main preliminary results are the following: as expected, the neutron richness of the original systems reflects in the neutron richness of the fission fragments. For these fragments the mean N/Z difference between the ^{48}Ca+^{48}Ca and ^{40}Ca+^{40}Ca is 0.1, and shows a behavior quite similar to that observed in other experiments [15, 16]. The found dependence of the isospin content as a function of the fission step alignment presents differences with respect to published results for ^{70}Zn+^{70}Zn at similar bombarding energies. This interesting result, which seems supported by our transport model simulations will be further investigated. We are also planning some dedicated experiments with a reduced FAZIA setup coupled to other detectors such as OSCAR [20] in order to detect also the QT to obtain an estimate of the event centrality.

* * *

Thanks are due to INFN-CNAF and GARR for providing the computing resources to perform Monte Carlo simulations.

REFERENCES

[1] Fable Q., Universitè de Caen Normandie, PhD Thesis (2018).
[2] Wigg P. C. *et al.*, *EPJ Web of Conferences*, **31** (2012) 00015.
[3] Pastore G., Univeristà degli studi di Firenze, PhD Thesis (2017).
[4] Piantelli S. *et al.*, *these proceedings*.
[5] Jedele A. *et al.*, *Phys. Rev. Lett.*, **118** (2017) 062501.
[6] Rodriguez Manso A. *et al.*, *Phys. Rev.*, **95** (2017) 044604.
[7] The FAZIA Collaboration and Bougault R. *et al.*, *Eur. Phys. J. A*, **50** (2014) 47.
[8] Carboni S. *et al.*, *Nucl. Instrum. Methods A*, **664** (2012) 251.
[9] Le Neindre N. *et al.*, *Nucl. Instrum. Methods A*, **701** (2013) 145.
[10] Pastore G., *Nucl. Instrum. Methods A*, **860** (2017) 42.
[11] Ono A. *et al.*, *Phys. Rev. C*, **53** (1996) 2958.
[12] Charity R. J., *Phys. Rev. C*, **82** (2010) 014610.
[13] Frankland J. D. *et al.*, *Nucl. Phys. A*, **689** (2001) 905.
[14] Viola V. E. *et al.*, *Phys. Rev. C*, **31** (1985) 1550.
[15] Barlini S. *et al.*., *Phys. Rev. C*, **87** (2013) 054607.
[16] De Filippo E. *et al.*, *Phys. Rev. C*, **86** (2012) 014610.
[17] Casini G. *et al.*, *Phys. Rev. Lett.*, **71** (1993) 2567.
[18] Stefanini A. A. *et al.*, *Z. Phys. A*, **251** (1995) 167.
[19] McIntosh A. B. *et al.*, *Phys. Rev. C*, **81** (2010) 034603.
[20] Dell'Aquila D. *et al.*, *Nucl. Instrum. Methods A*, **877** (2018) 227.