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Influence of the n-p asymmetry on decay properties of palladium isotopes

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Summary. — The INDRA 4π-array was coupled with the high acceptance spectrometer VAMOS to study the decay of palladium isotopes with a large range of $N/Z = 1$–1.26, produced in the ^{34,36,40}Ar + ^{58,60,64}Ni reactions at $E/A = 13.3$ MeV. The coupling of both apparatuses gives the opportunity to detect complete events with light charged particles identified in INDRA and the compound nucleus residue in VAMOS. The detailed studies of this experiment put constraints on the N/Z effects in the statistical models.

1. – Introduction

The understanding of the role of the isospin degree-of-freedom in reaction dynamics is one of the major topic of current experimental and theoretical investigations in nuclear physics. In the Fermi energies regime violent nuclear reactions can produce one or more excited fragments which subsequently decay through evaporation of light particles [1, 2]. The excitation energy of these fragments can reach a value as high as 3 MeV/nucleon. To pin down the influence of the isospin in these multi-body reactions it is crucial to study the properties of the decay of primary fragments as a function of the N/Z (isospin). Fusion-evaporation reactions ($E/A < 15$ MeV) lead to the formation of mono-nuclear configurations and thus, it is a tool very well adapted to explore the decay properties in a controlled way.

Exclusive measurements and high-quality data on isotopic distributions of the residues and light particles are required to obtain valuable experimental information and to constrain the crucial ingredients of statistical models as for example the N/Z dependence of the level density parameter. To do so very sophisticated apparatuses are necessary. Taking advantage of the GANIL installation we have coupled the high acceptance VAMOS spectrometer with 4π INDRA detector and we have utilized the SPIRAL1 facility.

We will report on experiments leading to the formation of compound nuclei of palladium with a large range of neutron-proton ratio ($N/Z = 1$–1.26). In this contribution, we will focus on the location of the measured residues in the chart of nuclides with respect to the predicted attractor line (EAL) [3]. Other objectives of this experiment are described in refs. [4, 5].

2. – Experimental setup

The experiment was performed at the GANIL facility, where ^{34,36,40}Ar at $E/A = 13.3$ MeV impinged on ^{58,60,64}Ni targets placed inside the INDRA vacuum chamber. Notice that ^{34}Ar is a radioactive beam provided by the SPIRAL 1 facility. The combinations between the three projectiles and three targets can lead to the formation of five compound nuclei, namely palladium isotopes, ^{92,94,96,100,104}Pd, at the same excitation energy of about 2.9 MeV/nucleon. For these experiments the 4π INDRA detector was coupled to VAMOS spectrometer. The charged-particle multidetector array INDRA [6], in the setup used in this experiment, covers the polar angles from 7 to 176°, to allow the coupling with the VAMOS [7] spectrometer in the forward direction. The INDRA detector allows charge and isotope identification up to Be-B and only charge identification for heavier fragments. The VAMOS spectrometer is constituted by two large magnetic quadrupoles focussing the incoming ions in the vertical and horizontal planes, followed by a large magnetic dipole, which bends the trajectory of the ions. In the present setup, the spectrometer covers the forward polar angle for about $\delta\theta = \pm 4°$. The momentum acceptance was about $\pm 5\,\%$. The focal plane is located 9 m downstream and it is composed of two SED (Secondary Electron Detectors) which give the position of the reaction products, followed by a sandwich of detectors: an ionization chamber (7 modules), 500 μm thick Si-wall (18 independent modules). The charge identification of the residues is provided by ΔE-E (ionization chamber *vs.* the Si detector) technique. The time of flight base is long enough to allow resolution of all isotopes produced in the reactions of this experiment.

3. – Experimental results

Figure 1 (left panel) shows the mass number *vs.* the ratio A/Q of the residues detected in the focal plane of VAMOS. Q is the charge state of the residue of mass number A. A high resolution of the charge, mass of the residues is obtained. In the right panel of fig. 1 we present the invariant c.m. velocity of the α particles detected in INDRA in coincidence with the residues detected in VAMOS (fig. 1 (left panel)). In this plot we can clearly see an emission from a unique source centered at recoil velocity of the compound nucleus associated with the full momentum transfer. The kinetic energy distributions of the light charged particles (not shown here) have Maxwellian shape as expected. Brief quantitative analysis of these distributions indicates an evaporation character of the process. More details on these aspects will be given elsewhere.

Figure 2 represents the isotopic distributions (yield) of the residues with charges $Z = 33$ (left panel) and $Z = 34$ (right panel) for ^{94}Pd and ^{104}Pd. More than 12 isotopes with a good statistics are observed. This provides a good characterization of the shape of the distributions. As expected, the shape is Gaussian-like and the average value of the neutron-rich ^{104}Pd is shifted towards higher masses.

We have extracted the average value of these distributions and reported the corresponding neutron and proton numbers (N, Z) in the chart of nuclides in fig. 3 (star symbols). Let us first recall the EAL [3]. The evaporation attractor line is a line in the

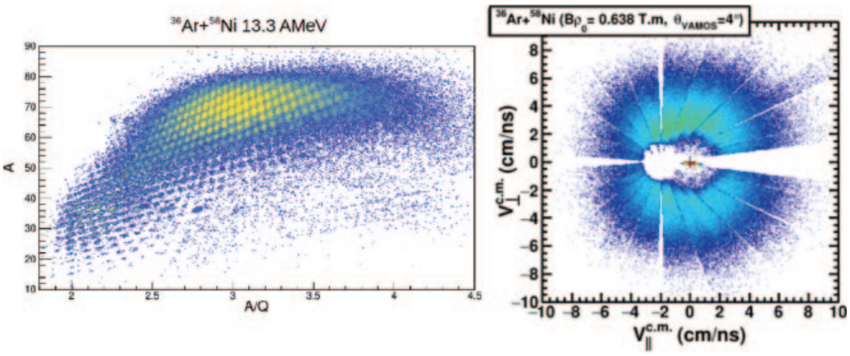

Fig. 1. – (Color online) The mass number (A) *vs.* the ratio A/Q of the residues detected in VAMOS (left panel) and invariant c.m. velocity plot of the α particles detected in INDRA (right panel) in coincidence with the residues of the reaction $^{36}\mathrm{Ar} + ^{58}\mathrm{Ni}$ at $E/A = 13.3\,\mathrm{MeV}$.

chart of nuclides towards which an evaporation residue of an excited source moves on average as it cools. At this line the neutron and proton partial decay widths are approximately equal at all excitation energies. This line is drawn using the parametrisation extracted from ref. [3] for $Z < 90$. For the neutron-poor initial compound nuclei (^{94}Pd) the location of the corresponding measured residues is close to the evaporation attractor line. On the contrary, in the case of neutron-rich CN (^{104}Pd), while the excitation energy is high the final distributions stay far away from the EAL. Indeed the N/Z of the residue has an N/Z close to that of the initial one. The difference between the EAL and the data points corresponding to ^{104}Pd is around 4 neutrons. However the data points remain parallel to the evaporation attractor line. It is worth noting that the four data points reported in fig. 3 for each system have originally the same excitation energy of the CN. They are represented by star symbols corresponding to $Z = 33$, 34, 35 and 36. The three other systems ^{92,96,100}Pd are under study and should provide a wide-ranging systematic.

Does this difference arise due to the N/Z dependence of the level density parameter?

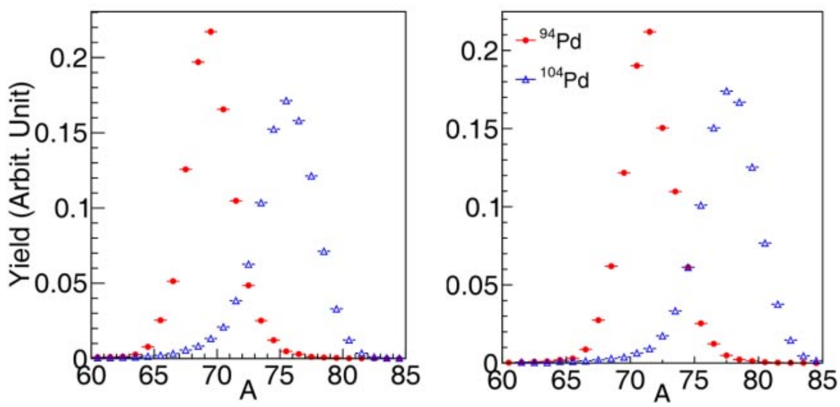

Fig. 2. – (Color online) Isotopic distributions of residues with charge $Z = 33$ (left) and $Z = 34$ (right) for ^{94}Pd (solid symbols) and ^{104}Pd (open triangles).

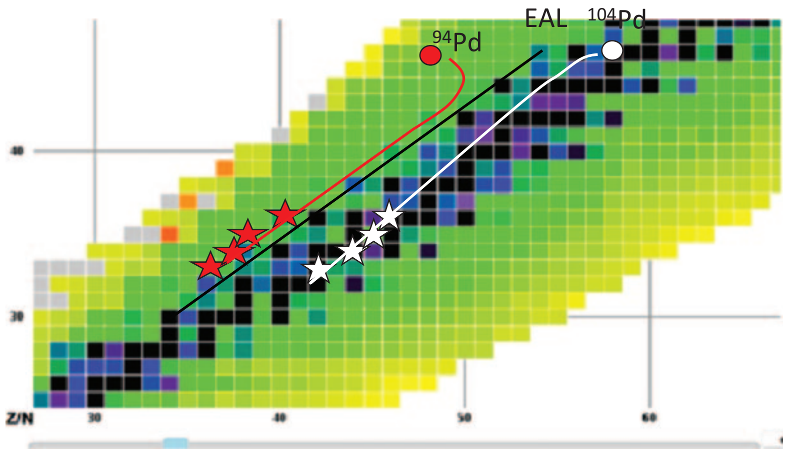

Fig. 3. – (Color online) A portion of the chart of nuclides, the EAL (thick-black-line) is extracted from ref. [3] eq. (1) for $Z < 90$. The location of the compound nuclei ^{94}Pd and ^{104}Pd is indicated by circles. The corresponding mean location of the measured residues are indicated by star symbols for $Z = 33$, 34, 35 and 36. The two lines connecting the data points are drawn to guide the eyes.

The main ingredient in the statistical models is the nuclear level density parameter. At low excitation energy the level density parameter is determined from the explicit counting of the resonances around $A/8$. At high excitation energy experimental studies utilizing the shape of evaporation spectra revealed that the level density parameter is reduced [8-10]. Moreover a parametrisation of the level density parameter dependence with the excitation energy was established in ref. [11].

In the Fermi gas model, the isospin dependence of the level density parameter is very small. This dependence is around $a = mA[1 - \frac{1}{9}(\frac{N-Z}{A})]^2$, where a, N and Z are respectively the level density parameter, neutron and proton numbers. A strong dependence on N/Z has been proposed in ref. [12] based on an extrapolation from the low energy level density data. Two cases are considered:

$$a = \alpha A/\exp[\beta(N-Z)^2], \tag{1}$$

$$a = \alpha A/\exp[\gamma(Z-Z_0)^2], \tag{2}$$

where α, β and γ are fit parameters. These parameterisations provide a significant variation of the level density parameter values. Charity *et al.* have performed GEMINI++ calculation testing both parametrisations for the ^{152}Yb and ^{160}Yb systems. They excluded case (2) since this case the evaporation path of n-poor CN (^{152}Yb) would cross the attractor line. For the n-rich CN (^{160}Yb) with parametrisation of case 1 the path of the evaporation line is moved towards the $N = Z$ line at high excitation energies crossing the attractor line as well. Similar GEMINI calculations for our palladium systems are necessary in order to confirm or infirm these conclusions of both level density parametrisations. Our measurements of (N, Z) of residues are straightforward and should bring stronger constraints on N/Z dependence on decay mode of CN. Moreover, the measured LCP in coincidence with the residues, will bring valuable information on properties of the disintegration process as a function of the n-p asymmetry.

4. – Summary and conclusions

In this contribution, we have presented exclusive measurements of fusion reactions of 5 systems ^{34,36,40}Ar $+^{58,60,64}$ Ni at $E/A = 13.3$ MeV leading to the formation of compound nuclei, $^{92-104}$Pd. For these experiments the 4π INDRA was coupled to VAMOS spectrometer. Isotopic distribution of the residues were obtained for a large range of charges. The average value of these distributions were extracted and then reported the correponding (N, Z) in the chart of nuclides. The location of the residue of n-poor system is close to the evaporation attractor line, in agreement with the previous finding of Charity [3]. On the contrary in the case of the n-rich system the location of the residues stay far away from the EAL. The three other systems ^{92,96,100}Pd are under study and will provide a wide-ranging systematic. We believe that the location of the residues in the chart of nuclides is a very interesting observable which can provide a crucial constraint for statistical models. Further theoretical and experimental analyses are in progress.

REFERENCES

[1] INDRA Collaboration (Marie N. *et al.*), *Phys. Rev. C*, **58** (1998) 256.
[2] INDRA Collaboration (Hudan S. *et al.*), *Phys. Rev. C*, **67** (2003) 064613.
[3] Charity R. J. *et al.*, *Phys. Rev. C*, **58** (1998) 1073.
[4] Ademard G. *et al.*, for the INDRA Collaboration, *Eur. Phys. J. A*, **50** (2014) 33.
[5] Ademard G. *et al.*, for the INDRA Collaboration, *EPJ Web of Conferences*, **88** (2015) 00030.
[6] Pouthas J. *et al.*, *Nucl. Instrum. Methods A*, **357** (1995) 418.
[7] Savajols H., for the VAMOS Collaboration, *Nucl. Instrum. Methods Phys. Res. B*, **204** (2003) 146.
[8] Hilscher D. *et al.*, *Phys. Rev. C*, **36** (1987) 208.
[9] Nebbia G. *et al.*, *Phys. Rev. C*, **39** (1989) 497.
[10] Chbihi A. *et al.*, *Phys. Rev. C*, **43** (1991) 666.
[11] Charity R. J. *et al.*, *Phys. Rev. C*, **82** (2010) 014610.
[12] Al-Quraishi S. I. *et al.*, *Phys. Rev. C*, **63** (2001) 065803.