FIRST DELAYED NEUTRON EMISSION MEASUREMENTS AT ALTO WITH THE NEUTRON DETECTOR TETRA

D. TESTOV[1,2], S. ANCELIN[2], J.BETTANE[2], F. IBRAHIM[2], K. KOLOS[2],
E. KUZNETSOVA[1], G. MAVILLA[2], M. NIIKURA[2], Yu. PENIONZHKEVICH[1],
V. SMIRNOV[1], E. SOKOL[1], D. VERNEY[2], J.WILSON[2]

1) Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia
2) Institute de Physique Nucleaire d'Orsay, France

Beta decay properties are among the easiest and therefore, the first ones to be measured to study new neutron rich isotopes. Eventually it could be sufficient just a few number of nuclei to estimate its lifetime and neutron emission probability. With the new radioactive beam facilities which have been commissioned recently (or will have been constructed shortly) new areas of neutron rich isotopes are becoming reachable. To study beta decay properties of such nuclei at IPN Orsay in the frame of collaboration with JINR, Dubna a new experimental setup including the neutron detector TETRA of high efficiency was developed and commissioned.

1. Beta-decay properties for the nuclear structure studies and astrophysical r-process calculations

The ^{78}Ni is hypothetically considered as a double magic nucleus whose structure is the key ingredient for the shell-model calculations. Although this nucleus already has been synthesized its structure and excitation modes are not obvious and the knowledge of it is currently based on the extrapolations of the properties of its neighbors. Even though in the recent papers [1 – 4 and others] published by different groups the structure of neutron rich Ga isotopes in the very vicinity of ^{78}Ni have been intensively discussed there have been no final agreement, and additional studies are required.

Going further away from the valley of stability to the neutron rich side, where the Q_β increases simultaneously with the drop in the energy of neutron separation, a proper neutron detector becomes crucial. Furthermore, neutrons emitted after the β-decay can serve additional degree of selectivity. The aim of the present work was to build the powerful setup to study new neutron rich isotopes in conjunction with neutron detector of high efficiency to reveal its β-decay properties.

In the β decay for the allowed transitions orbital angular momentum is zero, whereas in transitions in which orbital angular is different from zero call forbidden. However, they are not forbidden in reality but occur with a much smaller probability.

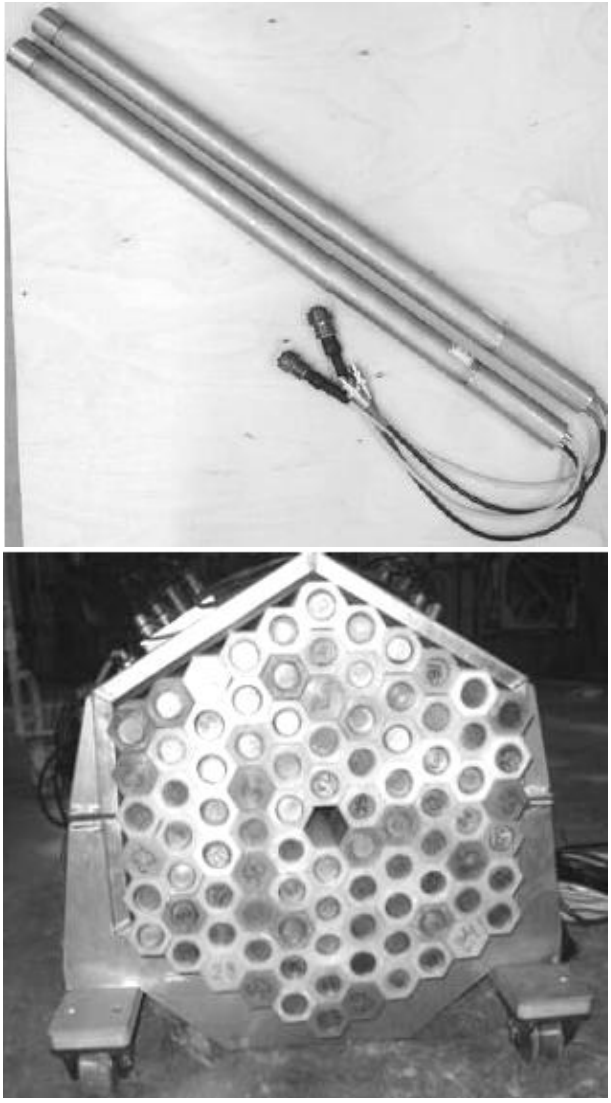

Figure 1: On the left side: the ^{3}He tubes; on the right: The schematic view of TETRA neutron detector before the update, see the text for details.

Moving away from the line of stability the Q_β value increases with the consequent increase in forbidden transition probability. Crossing the major shells N=28, N=50 the first forbidden decays give more noticeable contribution to the total half-life and probability of beta delayed neutron emission (P_n). Going beyond the allowed β-decay approximation in order to figure out the relative contribution of the Gamma-Teller and First Forbidden decays is an exciting experimental task [5].

In the case of delayed neutron emission, the (β-, 2n)-process occurs when $Q_\beta > S_{2n}$ (S_{2n} two-neutron separation energy). Originally this process was observed at CERN on ^{11}Li [6, 7] and then on 30, 32, 31 isotopes of Na [8]. Up to now where a few β- delayed multineutron emitters have been measured experimentally in the region of light nuclei. For the fission fragments such a process was experimentally observed only for the two nuclei: ^{98}Rb ($T_{1/2}$= 110 ms) and ^{100}Rb ($T_{1/2}$= 51 ms) [9, 10]. However there are theoretical predictions for β-delayed two-neutron emission for a series of isotopes in the range of medium and heavy masses [11, 12]. Multi-neutron emission can lead to wrong P_{n1} values which can result in errors of life-time determined from the decay by delayed neutron activity. Additionally, study correlations between neutrons emitted can give information about neutron clusters since neutron are not distributed by Coulomb force.

Neutron rich nuclei play a key role in the astrophysical rapid neutron capture process. The r-process constitutes one of the major processes in which elements heavier than iron are formed. It consists of a series of rapid neutron captures followed by β-decays and passes through a net of nuclei with the large Q_β value far from stability. The position of the r-process line depends on nuclear-structure properties and the stellar conditions under which it occurs: the temperature, density, and duration of the neutron flux. Magic neutron numbers play a special role in the r-process – after freeze out of the neutron flux, these nuclei β decay back towards the line of β stability.

A detailed study of the r-process involves the use both - theoretical and experimental data. Most of the data that is needed (nuclear masses, β-decay half-lives and β -delayed neutron emission probabilities) is currently derived from theoretical models due to the lack of measured β -decay properties of isotopes participating in the r-process. Studying these properties experimentally covering all “waiting-point" nuclei in the r-process path around double magic nuclei Z=28 et N=50 (^{78}Ni) and Z=50, N=82 (^{132}Sn) is extremely important for astrophysics [13, 14].

2. The TETRA neutron detector

Helium counters detect neutrons by inducing a reaction $^3\text{He} + \text{n} \rightarrow {}^3\text{H} + \text{p} +$ 780 keV (1), with a cross section of 5320 barns for a neutron of the thermal energy [15]. However, since neutrons are born "fast" they should be moderated. To achieve it a counter has to be placed in the high density polyethylene. Once a thermal neutron comes to the active volume of the detector it is lucky to be consumed in the reaction (1).

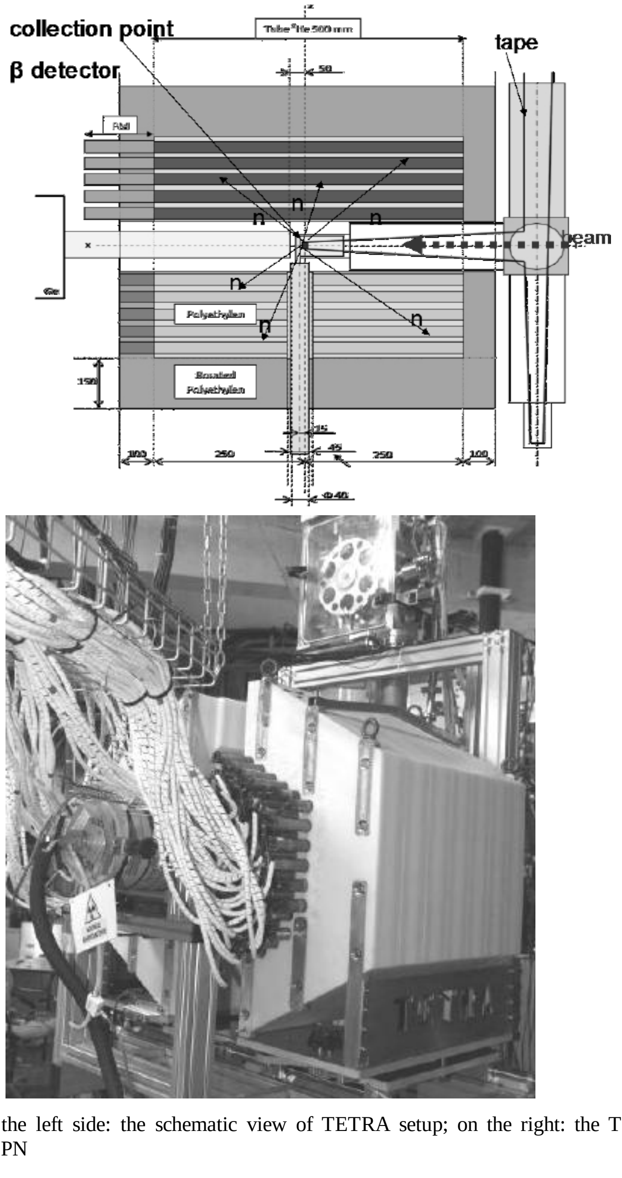

Figure 2: On the left side: the schematic view of TETRA setup; on the right: the TETRA/BEDO installation at IPN

The consumption of a neutron results in both – the almost zero-energy threshold for a neutron and eliminating the so-called cross talk effect. Even detectors of this type are sensitive to gamma rays, the energy disposed by gamma is significantly low in comparison to one released in the reaction (1) induced by a neutron which allows quite effectively to cut gammas by a threshold. These entire qualities discussed make a ^{3}He based neutron detector a nice tool to study beta decay properties of neutron rich nuclei.

In the frame of collaboration between JINR (Dubna), IPN (Orsay) it was decided to use the neutron detector TETRA build at JINR as a heart of future installation to study properties of neutron rich isotopes produced at ALTO. At ALTO, the ISOL type facility at IPN, Orsay [16], the electron driver delivers a primary electron beam at the energy of 50 MeV with a nominal intensity of 10 μA at the thick 238 UCx target. Fission fragments are extracted at 30 kV voltage towards the on-line isotope separator PARRNe or can be selectively ionized with a laser ion source. Currently the facility provides physicists with intensive exotic beams of neutron-rich nuclei in the regions of double magic ^{78}Ni and ^{132}Sn.

The TETRA is ^{3}He based neutron detector constructed at JINR, Dubna and consists of 90 counters 500 mm length and 32 mm in diameter filled by 3He at a pressure 7 atm with an admixture of 1 % of CO_2 [17]. In the basic configuration served by JINR counters were arranged in 5 layers in a hexagon with the central hole about 5 cm. Each tube was placed in its individual hexagon brick of moderator, the distance between centers of tubes was 5 cm. As it was shown during the test experiment performed with a neutron wall and reported in [18], a ^{3}He detector had to include as many as 4 layers of counters placed in moderator to have the efficiency flat up to neutron energy of 1.5 MeV. No shielding from background neutrons was applied. The overall view is shown in the Fig. 1 Efficiency for the single neutron registration (ε_{1n}) measured was for a spontaneous fission source ^{252}Cf (by the method described in [19]) placed at the center of the detector was $\varepsilon_{1n} = 70\pm2\%$.

The first attempt to study the β delayed properties, with the help of TETRA was undertook long ago in 2009 and reported in [20]. Although it was proven the workability of the installation, during the experiment it came out the limitations of the setup performed. To avoid or at least to minimize the constrains the installation suffered, tremendous up-grade during 2010-11 was performed. Completely new design was developed and applied to the practice. The main difficulty came from the requirement that TETRA had to work in the conjunction with 4π beta detector as well as with a gamma detector but remaining in the same time its efficiency for neutron registration high and flat. Furthermore, the detector must have had a proper shielding from backgrounds neutrons (cosmic, β decay of isotopes stopped at the separator). It gave strict geometrical constraint on the whole installation.

In the picture 2 it is presented the overview of the new setup performed. The nuclei of interest are finally collected at the Mylar tape. The collection point (in red) is surrounded by 4π β-detector (in yellow) and by 4 layers of neutron counters placed in the single piece of high-density polyethylene, and a germanium detector which is put from the back on the beam axis. The collected nuclei, whose lifetime is relatively short undergo β decay. In its turn the daughter nuclei also suffer from β decay however, since it get closer back to the stability, with a longer half-life. In order to evacuate unwilling radioactivity of these nuclei the tape is moved with the period depended on a particular isotope to be studied.

To protect the neutron counters from background neutrons a pie shielding was applied. The outer part is 15-cm thick borated polyethylene slice which gives almost total suppression of the background. The inner part is the 5-cm slice of high density polyethylene which increases probability of neutron registration from the source at the center of the detector since neutrons, which have passed the detector without interaction, are lucky, with the certain probability, to be reflected and to come back to the detector. Since the inner raw of counter was removed to increase the diameter of the central hole up to 11 cm the efficiency of single neutron registration suffered. The efficiency measured in the present geometry for ^{252}Cf neutron source at the centre is ε_{1n} = 52±2 % (MCNP calculations 49%). In contrary, the flatness of the efficiency as a function of neutron energy was saved due to thickness of the detector.

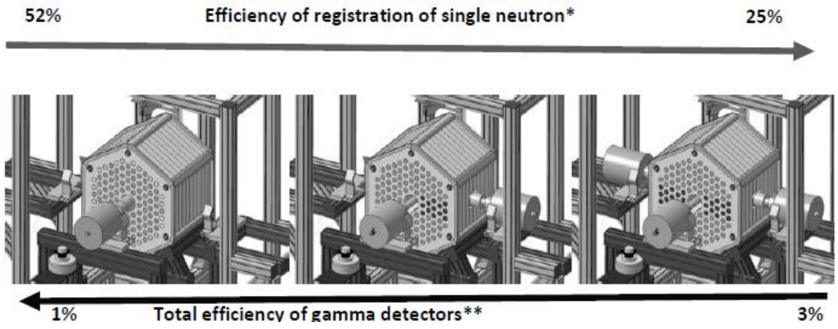

Figure 3: Three available configuration to operate BEDO-TETRA installation. On the left-hand the "1n is maximum, whereas efficiency of gamma registration is the minimum (experimentally measured values). On the right-hand the gamma efficiency is higher at the expense of ε_{1n} (calculated value). At the center the "transition" configuration is presented. * - for the 1 MeV neutron energy; ** - for the 1 MeV gamma energy.

More details concerning neutron detectors development and employment at JINR are found in [17, 21]. The installation assumes three basic type of configurations to be run. For pure Pn - measurements the maximum ε_{1n} is required. In contrast, the gamma registration acts complementary role and only serves identification isotopes on-line and, consequently, can be sacrificed (Fig. 3 on the left).

Whereas for nuclear structure studying in which the overall gamma efficiency plays the major part, and neutron channel is used as a marker for the coincidence, the high ε_{1n} is not of crucial importance (Fig. 3 on the right). To achieve the 3^{d} configuration two additional germanium detector have to be added, meantime 26 neutron counters have to be replaced from its original locations to the outskirt which definitely results in lower ε_{1n}.

3. Towards new experiments

For commissioning of the setup the ^{123}Ag was chosen since its P_n value is well-know [22]. Fission fragments were produced at ALTO via photo-fission and then separated on-line by mass-separator PARNNe and finally collected by mylar tape. The plasma ion source MK5-ISOLDE [23] was used. The tape system was employed to remove the longer-lived radioactivity from the detection system. The delayed neutron emission from ^{123}Ag was observed. Since on its isobar ^{123}Ag was the single neutron emitter all neutron registered were attributed either to the background or to the β-n decay of 123Ag. The efficiency of TETRA measured via P_n of ^{123}Ag coincided with one measured with ^{252}Cf source.

Within 2 years time the new installation was made from the scratch to its first experiment. There will be series of publication describing into details the setup and first experiments performed. Nowadays there a few (acted recently) setups of the same type of neutron detector employed (NERO - [24], BELEN - [25]). Competitiveness of its teams gives a huge impact on the research which definitely leads towards new breathtaking discoveries.

On behalf of the collaboration I would like to thank both - Dubna and Orsay teams working hardly under realization of the project.

References

1. O. Perru, D. Verney, F. Ibrahim et al, *Eur.Phys.* **J28** 307 (2006).
2. M. Lebois, D. Verney, F. Ibrahim et al *Phys. Rev*. **C80** 044308 (2009).
3. J. A. Winger, K. P. Rykaczewski, C. J. Gross, *Phys. Rev*. **C81** 044303 (2010).
4. M. Madurga, R. Surman, I. N. Borzov *Phys. Rev. Lett*. **109** 112501 (2012).
5. I. N. Borzov *Phys. Rev*. **C71** 065801 (2005).
6. H. R.E. Azumaa, T. Bjornstadb, *Phys. Rev. Lett.* **B96** 31 (1980).
7. P. G. H. R.E. Azumaa, L. CC. Carraz, *Physics Letters* **B43** 1652 (1979).
8. D. G. C. DETRAZ, M. EPHERRE, *Physics Letters* **B94** 307 (1980).
9. M. S. R. E. Chrien, R. L. Gill, *Phys. Rev. Lett.* **47** 483 (1981).

10. B. Jomson et al Proc.Int.Conf.Nuclei Far from Stability,Helsingor, Denmark, vol. 1, 265 (1981).
11. K.-L. K. P. MOLLER, J.R. NIX, *Physics Letters* **B66,** 343 (1977).
12. Y. Lyutostansky, *Z. Phys.* **A313,** 235 (1983).
13. B. Pfeiffier, K.-L. Kratz, F.-K. Thielemann, and W. Walters, *Nucl. Phys.* **A693,** 282 (2001).
14. F. Montes, H. Schatz, A. Aprahamian, *Nucl. Phys.* **A758** 646 (2005).
15. K. A. E. R. Institut, Nuclear data evaluation laboratory, http://atom.kaeri.re.kr/, (2007).
16. M. C. M. et al *Nucl. Instr.& Meth.* **B266,** 4092 (2008).
17. D. Testov, C. Briancon, S. Dmitriev, *Phys. Atom. Nuc.* **72,** 1 (2009).
18. J. Cerny, Z. Dlouhy, Z. Dolezal, *Nucl. Instr. & Meth*. **A540,** 430 (2005).
19. M. Dakowski, Y. Lazarev, V. Turchin, and L. Turovtseva, *Nucl. Instr. & Meth*. **113,** 195 (1973).
20. D. Testov, S. Ancelin, F. Ibrahim, *AIP Conf. Proc*. **1224**, 568 (2010).
21. A. Svirikhin, A. Isaev, A. Yeremin, *Instr.& Exp. Techn.* **54,** 644 (2011).
22. P. L. Reeder, R. A. Warner, and R. L. Gill, *Phys. Rev.* **C27,** 3002 (1983).
23. S. Sundell and H. Ravn, *Nucl. Instr. & Meth*. **B70**, 160 (1992).
24. J. Pereira, P. Hosmer, G. Lorusso et al *Nucl. Instr. & Meth.* **A618,** 275 (2010).
25. M. Gomez-Hornillos, J. Rissanen, J. Tain, *Journal of Physics Conference Series* **312,** 052008 (2010).