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

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Тестов Д. и др. E15-2013-2
Первый эксперимент по измерению запаздывающей
нейтронной эмиссии на комплексе АЛТО
с использованием нейтронного детектора ТЕТРА

При изучении новых нейтроноизбыточных ядер исследование свойств их бета-распада дает информацию об их свойствах. Даже небольшого числа ядер может быть достаточно для измерения периода бета-распада и вероятности запаздывающей эмиссии нейтронов. Со строительством новых фабрик по производству экзотических пучков становятся доступными новые области нейтроноизбыточных изотопов. Для изучения свойств таких ядер в рамках сотрудничества ИПН (Орсэ) и ОИЯИ (Дубна) была создана и опробована в эксперименте новая установка, включающая нейтронный детектор высокой эффективности ТЕТРА.

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First Delayed Neutron Emission Measurements at ALTO
with the Neutron Detector TETRA

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

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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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-value 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 their 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 much smaller probability. 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 Gamow–Teller and first-forbidden decays, is an exciting experimental task [5].

In the case of delayed neutron emission, the $(\beta, 2n)$-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, a few β-delayed multi-neutron 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 lifetime determined from the decay by delayed neutron activity. Additionally, study of correlations between neutrons emitted can give information about neutron clusters since neutrons are not distributed by the 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 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 on: 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 decay towards the line of β stability.

A detailed study of the r-process involves the use of both — theoretical and experimental data. The most of the needed data (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 of these properties, experimentally covering all «waiting-point» nuclei in the r-process path around double magic nuclei $Z = 28$, $N = 50$ (^{78}Ni) and $Z = 50$, $N = 82$ (^{132}Sn), is extremely important for astrophysics [13, 14].

THE TETRA NEUTRON DETECTOR

Helium counters detect neutrons by inducing the reaction

$$^{3}\mathrm{He} + n \rightarrow {}^{3}\mathrm{H} + p + 780\ \mathrm{keV}, \tag{1}$$

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 captured in reaction (1). The capture of a neutron results in both — almost zero-energy threshold for a neutron and eliminating the so-called crosstalk 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 reaction (1) induced by a neutron which allows one quite effectively to cut gammas by a threshold. These entire qualities make a ^{3}He based neutron detector a nice tool to study beta-decay properties of neutron-rich nuclei.

In the framework of collaboration between JINR (Dubna) and 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 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 ^{3}He 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 a 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 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 flat efficiency up to neutron energy of 1.5 MeV. No shielding from background neutrons was applied. The overall view is shown in 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 $\varepsilon_{1n} = 70 \pm 2\%$.

Fig. 1. The ^{3}He tubes (left). The schematic view of TETRA neutron detector before the update (right). See the text for details

The first attempt to study the β-delayed properties, with the help of TETRA, was undertook long ago, in 2009, and reported in 2010 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 constraints the installation suffered, tremendous upgrade during 2010–2011 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 a proper shielding from background neutrons (cosmic, β decay of isotopes stopped at the separator). It gave strict geometrical constraint on the whole installation.

In Fig. 2 is presented the overview of the new setup performed. The nuclei of interest are finally collected at the mylar tape. The collection point (*6*) is surrounded by 4π β-detector (*7*) and by 4 layers of neutron counters (*2*) placed in the single peace of high density polyethylene, and a germanium detector (*3*) 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

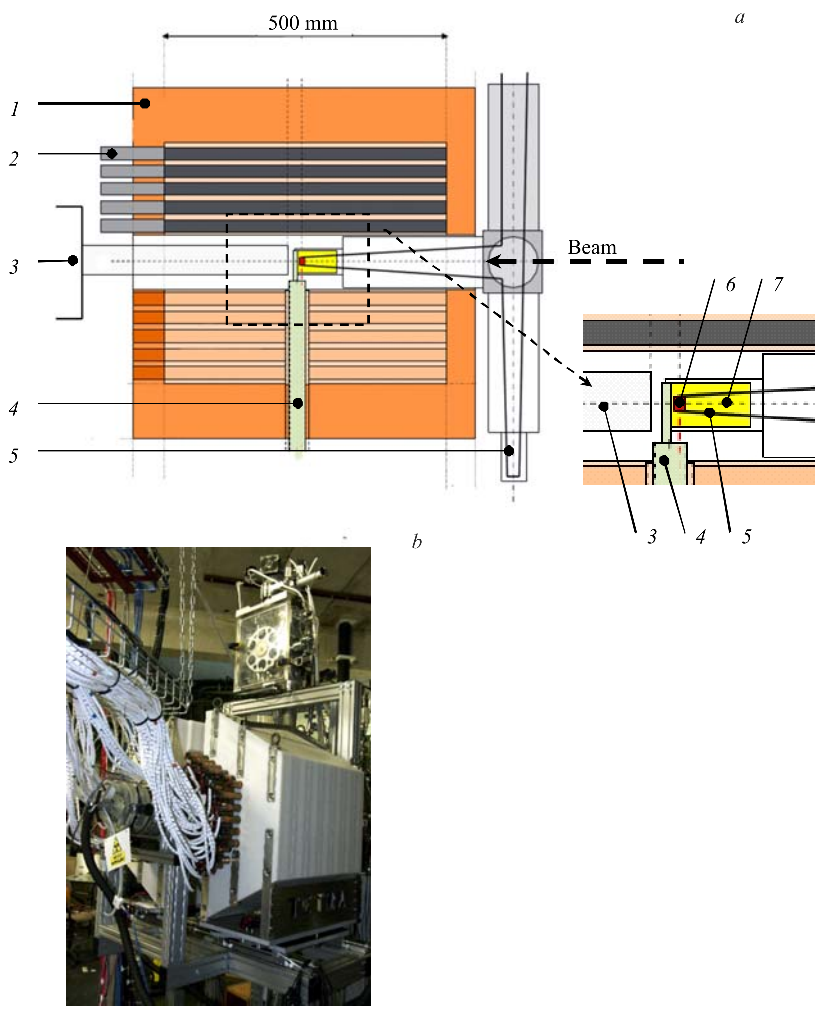

Fig. 2. The schematic view of TETRA setup (*a*): *1* — shielding borated polyethylene; *2* — ^{3}He with preamplifier placed in moderator; *3* — germanium detector; *4* — light guide; *5* — tape; *6* — collection point; *7* — 4π beta detector. The TETRA/BEDO installation (*b*)

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 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 registration efficiency of single neutron suffered. The efficiency measured in the present geometry for ^{252}Cf neutron source at the centre is $\varepsilon_{1n} = 52 \pm 2\%$ (MCNP calculations 49%). In contrary, the flatness of the efficiency as a function of neutron energy was saved due to thickness of the detector. More details concerning neutron detectors development and employment at JINR are found in [17, 21].

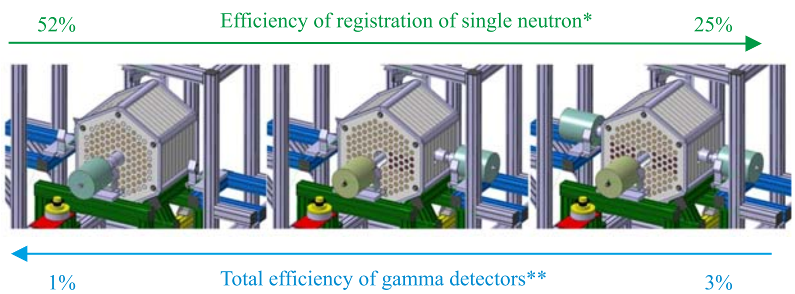

Fig. 3. Three available configurations to operate BEDO–Tetra installation. On the left-hand side — the $1n$ is maximum, whereas efficiency of gamma registration is the minimum (experimentally measured values). On the right-hand side — the gamma efficiency is higher at the expense of ε_{1n} (calculated value). In the center — the transition configuration is presented. * — for the 1 MeV neutron energy; ** — for the 1 MeV gamma energy

The installation assumes three basic types 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 for identification isotopes on-line and, consequently, can be sacrificed (see Fig. 3, 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 (see Fig. 3, right). To achieve the 3D configuration, two additional germanium detectors have to be added, mean time of 26 neutron counters have to be replaced from their original locations to the periphery which definitely results in lower ε_{1n}.

TOWARDS NEW EXPERIMENTS

For commissioning of the setup, the ^{123}Ag was chosen since its P_n value is well known [22]. Fission fragments were produced at ALTO via photofission 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 longe-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 neutrons registered were attributed either to the background or to the β–n decay of ^{123}Ag. The efficiency of TETRA measured via P_n of ^{123}Ag coincided with that one measured with ^{252}Cf source.

Within two years, the new installation was made from the scratch to its first experiment. There will be series of publications describing in detail the setup and first experiments performed. Nowadays, there are a few setups (acted recently) of the same type of neutron detector employed (NERO [24], BELEN [25]). Competitiveness of their 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 the Dubna and Orsay teams working hardly under realization of the project.

REFERENCES

1. *Perru O. et al.* // Eur. Phys. J. 2006. V. 28. P. 307.
2. *Lebois M. et al.* // Phys. Rev. C. 2009. V. 80. P. 044308.
3. *Winger J. A., Rykaczewski K. P., Gross C. J.* // Phys. Rev. C. 2010. V. 81. P. 044303.
4. *Madurga M., Urman R., Borzov I. N.* // Phys. Rev. Lett. 2012. V. 109. P. 112501.
5. *Borzov I. N.* // Phys. Rev. C. 2005. V. 71. P. 065801.
6. *Azuma R. E., Bjornstad T.* // Phys. Rev. Lett. B. 1980. V. 96. P. 31.
7. *Azuma R. E., Carraz L. C.* // Phys. Lett. B. 1979. V. 43. P. 1652.
8. *Détraz C., Epherre M.* // Phys. Lett. B. 1980. V. 94. P. 307.
9. *Reeder P. L. et al.* // Phys. Rev. Lett. 1981. V. 47. P. 483.
10. *Jonson B. et al.* // Proc. Intern. Conf. «Nuclei Far from Stability», Elsinore, Denmark, 1981. V. 1. P. 265.
11. *Moller K.-L. K. P., Nix J. R.* // Phys. Lett. B. 1977. V. 66. P. 343.
12. *Lyutostansky Y.* // Z. Phys. A. 1983. V. 313. P. 235.
13. *Pfeiffier B. et al.* // Nucl. Phys. A. 2001. V. 693.P. 282.
14. *Montes F., Schatz H., Aprahamian A.* // Nucl. Phys. A. 2005. V. 758. P. 646.
15. Korea Atomic Energy Research Institute (KAERI), Nuclear data evaluation laboratory. http://atom.kaeri.re.kr/, 2007.
16. *Cheikh Mhamed M. et al.* // Nucl. Instr. Meth. B. 2008. V. 266. P. 4092.

17. *Testov D., Briancon C., Dmitriev S.* // Phys. At. Nucl. 2009. V. 72. P. 1.
18. *Cerny J., Dlouhy Z., Dolezal Z.* // Nucl. Instr. Meth. A. 2005. V. 540. P. 430.
19. *Dakowski M. et al.* // Nucl. Instr. Meth. 1973. V. 113. P. 195.
20. *Testov D., Ancelin S., Ibrahim F.* // AIP Conf. Proc. 2010. V. 1224. P. 568.
21. *Svirikhin A., Isaev A., Yeremin A.* // Instr. Exp. Techn. 2011. V. 54. P. 644.
22. *Reeder P. L., Warner R. A., Gill R. L.* // Phys. Rev. C. 1983. V. 27. P. 3002.
23. *Sundell S., Ravn H.* // Nucl. Instr. Meth. B. 1992. V. 70. P. 160.
24. *Pereira J. et al.* // Nucl. Instr. Meth. A. 2010. V. 618. P. 275.
25. *Gomez-Hornillos M., Rissanen J., Tain J.* // J. Phys. Conf. Ser. 2010. V. 312. P. 052008.

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