

REPORT

**concerning a Thesis work
for acquiring of a Degree of Doctor of Philosophy
in the professional field 4.1. Physics Science,
within the Thesis defense procedure
of the Faculty of Physics at Sofia University
„St. Kliment Ohridski“**

The report has been prepared by Assoc. Prof. Dr. Elena Aleksandrova Stefanova, Institute for Nuclear Research and Nuclear Energy, from her position as a member of the scientific jury, with respect to the Order № ПД 38-335 / 16.07.2021. г. of the Rector of Sofia University.

Title of the Thesis: “Studies on the Applications of the Triple-to-Double Coincidences Ratio Method for Primary Activity Standardization using Liquid Scintillation Counting”

Author of the Thesis: Chavdar Chavdarov Dutsov

I. Overview description of the presented documents.

1. The documents

The Ph.D. candidate Chavdar Dutsov has provided his thesis work in English language and the authors summary of the thesis in Bulgarian, the other required documents are also available.

The documents presented by the candidate fulfill the requirements of acquiring the degree of Ph.D from the Sofia University „St. Kl. Ohridski“, Sofia, Bulgaria.

2. The candidate

The candidate Chavdar Dutsov has received his secondary education from the National High School of Mathematics and Science, Bulgaria, Profile: Physics and Astronomy. He has won awards from International Olympiads in Astronomy and Astrophysics, as well as awards from National Olympiads in Math and Computer's Math. His Bachelor's and Master's degrees are in Medical Physics from the Sofia University „St. Kl. Ohridski“. He took part in a number of scientific projects. Within the work on the thesis, he has also worked at CEA Saclay, French National Laboratory “Henri Becquerel” CEA Saclay, France .

3. Overview of the scientific contributions of the candidate.

The scientific research in the thesis represents a significant contribution to the field of applied science and especially providing new knowledge in the studies of the measurement of the absolute

activity of radionuclides when using liquid scintillation counting with the triple-to-double-coincidences counting method (TDCR).

The main studies and contributions in the thesis are published in 5 (five) publications, which are the base of the thesis. With no exceptions, all they are published in refereed journals having an impact factor. One of them is in **Scientific Reports by Nature Research, which is a journal with impact factor of 4.379 for 2020**, and **Q1**, two publications are in **Nuclear Instruments and Methods in Physics Research, A, with impact factor of 1.445 for 2020 and Q1 for 2020** and two publications are in **Applied Radiation and Isotopes** with impact factor of **1.513 for 2020 and Q2** estimation. The Ph.D. candidate is the first author in four of the publications and in one of the papers he is a second author. Taking into account all these together with the opinion of the scientific supervisor Assoc. Prof. Krasimir Mitev and Prof. Phillippe Cassette from CEA Saclay, the significant contribution of the candidate to the research work is definitely revealed.

Within the work, several computer codes have been developed, including a Monte Carlo code for simulation of the time distribution and the number of detected events within liquid-scintillation measurements.

In the thesis, an application performed at the MIL Laboratory at Sofia University, based on the results of the scientific work, is also presented.

Chavdar Dutsov is a coauthor in 6 more publications.

The Investigations and the results of the investigations, included in this thesis, exceed the requirements of obtaining of the educational and the scientific degree of „Doctor of Philosophy“.

Indeed, for the first time are proposed methods of estimation of accidental coincidences within the TDCR method. The cross-correlation distribution of the time intervals between detected scintillation events within a coincidence window, has been analytically derived. The possibility to use the cross-correlated distributions for an estimation of the detection efficiency and to obtain the activity of the sample has also been studied. Two coincidence counting algorithms for applying artificial dead-time after each detected signal in the counters used with TDCM technique were compared and studied. An influence of the delayed fluorescence on the measured activity of an radioactive sample through the TDCM method was found. Using liquid-scintillation techniques and methods, half-lives of some long-living excited states in several nuclei have been measured more precisely than with previous measurements using different techniques.

The journals, in which these investigations were published, to large extent ruled out the possibility of repeating another work or plagiarism. These are journals in which results from forefront research obtained for the first time are published. In addition, the candidate and his supervisor has signed the corresponding declarations.

4. Analysis by content of the scientific and applied scientific achievement of the candidate.

In the thesis are presented achievements of applied science, science and pure application. The main contribution is applied science methodology together with new knowledge concerning the measurement of the absolute activity of radionuclides using liquid-scintillation counting through the method of triple-to-double coincidences.

The liquid-scintillation counting is a technique of measurement of the absolute activity of alpha and beta emitters, through measurement of the counting rate of emitted photons. For this purpose, the sample is dissolved in a liquid scintillator, where via decay and the following interaction of the emitted particles with the scintillator, photons are emitted. Because the radionuclides are within the active volume of the detector, the efficiency of detection of the emitted particles is higher than with other methods. It is basically 100 % for alpha decay and for higher energy beta particles. The efficiency of registration of low-energy beta particles is not that high. The liquid-scintillation counting is a technique with many practical applications. Several methods are available for measurement of the absolute activity using this technique. One such method is based on the counted triple to double coincidences ratio. In the present thesis, considerable development of this method is presented, which certainly represents a significant new knowledge in this field.

Two different algorithms for counting coincidences within TDCR measurements are studied. These algorithms of counting are connected with the need of applying dead time after each detected signal in order to avoid the delayed fluorescence. Two algorithms are compared – of the Common Dead Time (CDT) and of the individual dead time (IDT). The results are published in the journal **Applied Radiation and Isotopes, having an impact factor 1.513 for 2020 and rating Q2 for 2020**. Chavdar Ducov is the first author in this work.

An analytical equation for the distribution of the time intervals between the signals of two photomultiplier tubes (cross-correlation distribution) – one giving „start“ and the other one giving „stop“, has been derived. The dependence of the light yield of the scintillator from the deposited energy is experimentally studied. A dependence of the height of the distribution from the deposited energy has been found, which can give the connection of the height of the cross-correlated distribution from the efficiency of detection. This is a new approach in the measurement of the absolute activity. The obtained results are published in the journal **Scientific Reports in Nature Research, which is a journal with relatively high impact factor of 4.379 for 2020, and respectively Q1**. Chavdar Ducov is the second author in this work.

Using the liquid-scintillation techniques and methods the half-lives of excited states in few nuclei are measured more precisely than in previous different measurements. This shows that the methods of liquid scintillation can be used for measuring half-lives of excited states up to 8 ns. This study is published in **Applied Radiation and Isotopes with impact factor 1.513 for 2020 and factor Q2**. Chavdar Ducov is the first author in this work.

For the first time, methods for estimation of accidental coincidences in TDCR measurements are developed. Two methods are presented – experimental and analytical. The experimental method is used in order to derive analytical equations for calculating the counting rate of the accidental

coincidences. The derived equations can be used in all available TDCR systems. This study has an important contribution to the science and applied science as it allows measurement of samples with very high activity. The given corrections for accidental coincidences allowed to perform studies with long coincidence windows, which is important for studying the time dependence of delayed fluorescence. These studies are published in **Nuclear Instruments and Methods in Physics Research A, which has an impact factor of 1.445 for 2020 and Q1 for 2020**. Chavdar Ducov is a first author in this work.

A dependence of measured counting rates in channels of double and triple coincidences from the widths of coincidence windows was studied. Because of the delayed fluorescence in the scintillators it is possible for some of the scintillation photons to be emitted with delay. The study shows that indeed the delayed fluorescence does influence the measurement of the activity through the TDCR method and a correction has to be applied in order to decrease this influence. The results are published in **Nuclear Instruments and Methods in Physics Research A, which is with impact factor 1.445 for 2020 and Q1 for 2020**. Chavdar Ducov is the first author in this work.

A new Compton-TDCR system has been built with aim to overpass the delayed fluorescence with wider windows. The system has been built in the French National Laboratory “Henri Becquerel” CEA Saclay, France. The work on this study continues.

In Chapter 11 from the thesis, practical applications of TDCM method are given. They are made at the MIL Laboratory at Sofia University.

5. Personal impression of the candidate

My only personal impressions of the candidate are from the preliminary defense of the thesis. The candidate was confident, competent and demonstrating his first-hand experience in the work he has done. Highly impressing was the fact, that Prof. Phillipe Cassette from CEA Saclay, France, who has guided the candidate while he worked in France, has arrived in Sofia especially for the preliminary defense of the thesis. He spoke in great detail about the huge amount of work the candidate has done as well as of his substantial contributions to the achievements in the presented work.

6. Conclusion

After I had checked the presented thesis, the author's summary of the thesis, and the other materials, and analysed their importance and their scientific, applied scientific and application-oriented contributions, I **claim** definitely and with confidence that the scientific contributions not only satisfy, but exceed the requirements of acquiring Ph.D degree in the Sofia University “St. Kl. Ohridski“. Particularly, the work the candidate has performed exceed the national requirements in the field. No plagiarism has been found in the thesis, the author's summary and in the papers.

I give with confidence a **positive** estimation of the thesis.

II. FINAL CONCLUSION

Based on all above, I **definitely recommend** to the scientific jury to award the educational and scientific degree „Doctor of Philosophy“ in the professional field 4.1 „Physics Science“ to Chavdar Ducov.

23.08.2021 г.

The report is prepared by: Assoc. Prof. Elena Stefanova