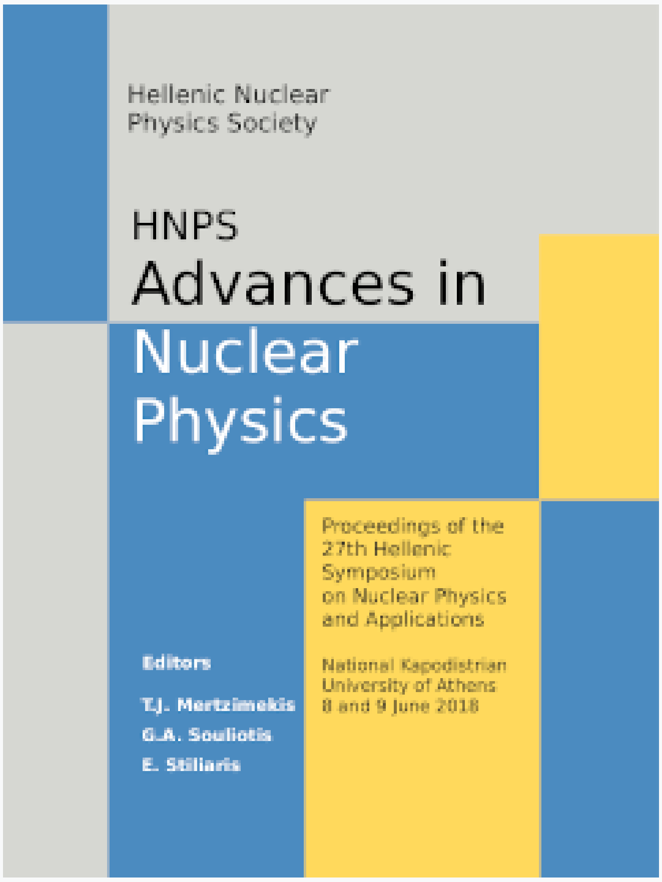
HNPS Advances in Nuclear Physics

Vol 26 (2018)

HNPS2018



Study and detection of relativistic Solar Neutrons at ground level with the Spherical Proportional Counter

D. Kyratzis, I. Savvidis

doi: [10.12681/hnps.1801](https://doi.org/10.12681/hnps.1801)

Study and detection of relativistic Solar Neutrons at ground level with the Spherical Proportional Counter

D. Kyratzis* and I. Savvidis

Department of Physics, Nuclear Physics Laboratory, Aristotle University of Thessaloniki, Greece

Abstract A novel method of high energy solar neutron detection is proposed with the Spherical Proportional Counter (SPC), taking advantage of the ^{209}Bi(n,f) reaction. This reaction, is considered as a standard for high energy neutron detection, due to large cross section values in the 100 MeV – 1 GeV energy interval, obtained in the n_TOF facility at CERN. A thin spherical shell of Bismuth will be situated in the large volume of the SPC, serving as target for high energy neutrons bombarding the detector, thus resulting in fission fragment emission. Detailed simulation of the ^{209}Bi(n,f) reaction with the INCL++ model, coupled with the ABLA07 de–excitation code is performed (cross section, mass & atomic number distribution, kinetic energy per fragment) in the 100 MeV – 10 GeV energy interval, together with SRIM for the fragments' projected range in ^{209}Bi. Experimental data from a ^{252}Cf source are obtained, in order to validate the SPC's efficiency in fission fragment detection. Calculations for the expected reactions in the ^{209}Bi shell have been performed in different atmospheric depths (700 & 1000 g/cm^2), and various spherical detector radii.

Keywords Spherical Proportional Counter, Solar neutron detection, high energy neutron – induced fission, ^{209}Bi(n,f), INCL++/ABLA07

INTRODUCTION

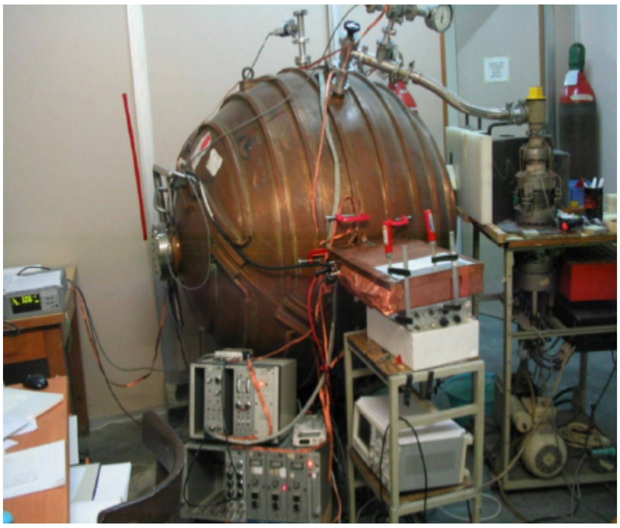
With the Sun being the starting point of the investigation considering nuclear interactions in stellar environments, valuable information can be extracted by studying the acceleration mechanism of highly energetic particles on the premises of solar eruptive phenomena. The particles of interest in that case are high energy solar neutrons, produced in flares, within the interaction of energetic ions (mainly protons and α–particles) with the solar photosphere. Biermann et al. [1] was the first to introduce the idea of a neutron flux produced in nuclear reactions of highly energetic protons with the solar photosphere. In this work, a novel method of high energy neutron detection is proposed, by utilizing the Spherical Proportional Counter (SPC). In the following section, a brief description of the SPC will be presented along with few of its prominent features. Afterwards, the interaction of interest is introduced, followed by the simulations performed with the INCL++/ABLA07 model.

Consequently, an enhanced version of the SPC is proposed, specifically optimized for the detection of high energy neutrons propagating through the atmosphere, complemented with the expected reactions for various atmospheric depths and detector sizes. The detection efficiency of the SPC is validated through experimental data obtained from a ^{252}Cf source.

* Corresponding author, email: dkyratzi@physics.auth.gr

SPHERICAL PROPORTIONAL COUNTER

The detector developed by I. Giomataris et al. [2], is illustrated in Figure 1, and consists of a spherical vessel made of copper, which is grounded and filled with a gas mixture. The large vessel has a diameter of 1.3 m, and 6 mm thickness, surrounding the spherical electrode (anode) of varying diameters (from 1 to 14 mm). The anode which consists of a metallic or a resistive material, is situated at the center of the vessel, supported by a grounded metallic rod, through which positive high voltage is applied. The SPC operates in sealed mode; the large volume of the detector is pumped out and then filled with the desirable gas at pressures up to 5 bar. The detector's most prominent applications include neutron and low–energy X–ray detection and spectroscopy, while promising results are expected from neutrino searches and dark matter studies. Moreover, benefiting from the natural spherical geometry, both collection and amplification of the deposited charges can be manifested by a single electronic channel that reads out a large gaseous volume. The spherical geometry results in very low capacity, allowing extremely low levels of electronic noise. Performance–wise, the SPC can be a unique detector in radiation measurements in both high and low energy region.



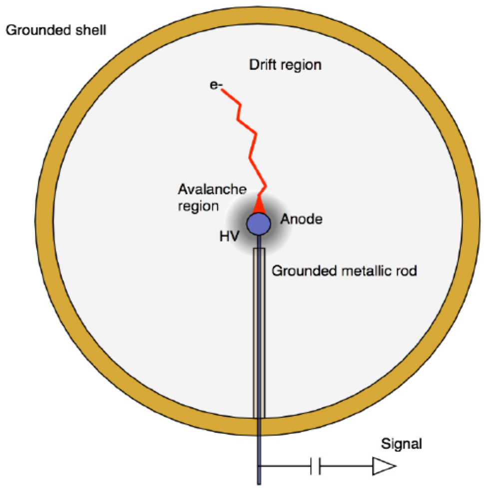


Fig. 1. The Spherical Proportional Counter situated in Aristotle University of Thessaloniki with its electronic components (left) and its detection principle (right).

HIGH-ENERGY NEUTRON DETECTION

The matter at hand is to optimize the SPC, in order to detect the highly energetic flux of solar neutrons propagating through the atmosphere. The proposed method is implemented through the neutron–induced fission of Bismuth or the ^{209}Bi(n,f) process. This specific process is utilized due to its higher energetic threshold, leading to the conclusion that ^{209}Bi may be the most suitable candidate regarding solar neutron detection in the energy range of 100 MeV to 10 GeV, (that being the estimated upper limit regarding the solar cosmic ray flux). Moreover, as a threshold reaction it will lead to simultaneous background cutoff regarding atmospheric neutrons of lower energies, thus enhancing the detector's capabilities.

Simulation with INCL++/ABLA07

Main purpose of the simulations is to check whether available neutron induced fission data for ^{209}Bi can be reproduced with satisfactory accuracy using the same set of model parameters. Thus, recent experimental data from Tarrio et al. [3] and the n_TOF [4] collaboration in the energy range of 50 MeV – 1 GeV will be reproduced by a recent C++ version of the Liège Intranuclear Cascade Model, INCL++ coupled with a Fortran version of ABLA07. INCL++ [5], is a time-like intranuclear cascade model while ABLA07 [6], is a statistical code that calculates the de-excitation of a nucleus by particle evaporation, fission, or multifragmentation.The characteristics of the 209 Bi(n,f) process are thoroughly examined, thus serving as a basis for calculations of the expected reactions regarding highly energetic neutrons with the 209 Bi spherical shell of the Spherical Proportional Counter. It is worth noting that for the energy interval of 100 MeV – 1 GeV Monte Carlo simulations have been performed by S. Lo Meo et. al [7] and at the upper limit of 2 GeV, by I. Duran et al. [8] both with the INCL++/ABLA07 model. Results seem to be in accordance with the experimental data from the n_TOF facility in the energy range of 100 MeV – 1 GeV. Improvements are made in the ABLA07 model, in order to acquire the best fits possible. With modest changes in the two fission parameters that are basic in the decay models: the height of the fission barrier of the fragments, ΔB_f , increased by +0.1, and the asymptotic level density parameter, a_f, multiplied by a factor (k=1.007). With the adaptation of the adjustable parameters discussed in [8], the simulation implemented in this study is performed for the extended 100 MeV – 10 GeV energy range.

In this work, beside the extended calculations regarding the incident neutron energies, numerous changes have been implemented, concerning the source code of the INCL++/ABLA07 model. The reason is to comprehend the fission characteristics in depth, by adding calculations for the mass (A) and atomic number distribution (Z) of the fragments together with the expected fragment's kinetic energy at scission point as expected in [9]. Those changes, along with the cross section calculation, will enable a more complete picture regarding the detection of fission fragments by the Bi(n,f) process in the sensitive volume of the SPC.

Total cross section results

Having analyzed a total of 30 incident neutron energies ranging from 100 MeV to 10 GeV, the exported results concerning the cross section simulation with the INCL++/ABLA07 model are shown in Figure 2. It is stressed out, that the model parameters adapted in the aforementioned simulations are in par with I. Duran et. al, in the energy interval of 100 MeV up to 2 GeV and seem to be in accordance with the uncertainties regarding the IAEA recommended values. The resulting plot seems to effectively reproduce the experimental cross section data from the n_TOF collaboration, thus validating the INCL++/ABLA07 model's efficiency. In addition to the extracted information regarding the mass (A) and atomic number distribution (Z) together with the kinetic energy per fragment, a clearer picture regarding the ^{209}Bi(n,f) process is attained and consequently leads to a more precise optimization of the SPC, as examined in the following section.

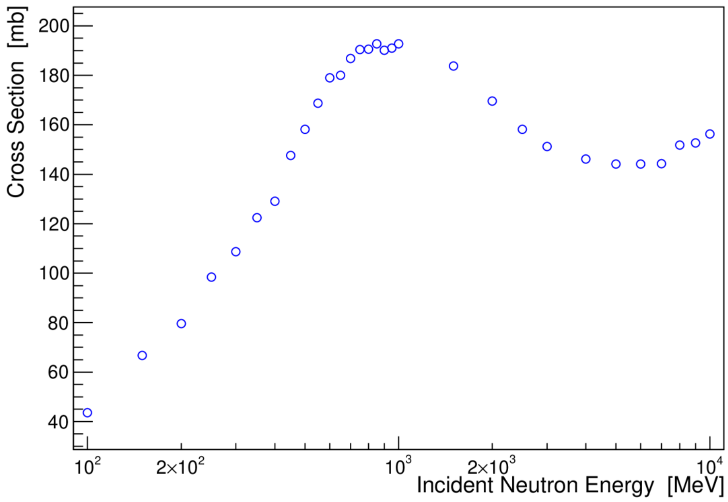


Fig. 2. Total cross section results for the ^{209}Bi(n,f) reaction using the INCL++/ABLA07 model.

SPC OPTIMIZATION WITH BISMUTH FOIL

Following the simulation of the ^{209}Bi(n,f) process with the INCL++/ABLA07 model, calculations with SRIM [10], concerning the fragment's range in ^{209}Bi are essential, as the thickness of the spherical foil relies heavily upon the projected range of fission fragments inside the sensitive volume of the detector.

From the cross section simulation, together with the average fragment mass & atomic number distribution, the average fragment's kinetic energy and the utilization of SRIM, the optimized ratio of fragments detected over total reactions in the ^{209}Bi shell, will be a valuable asset in the detection of highly energetic neutrons cascading through the atmosphere.

In the present work, the six most probable fission fragments are selected together with a wide range of fragment' kinetic energies ranging from the lower of about 40 MeV to the most probable kinetic energy interval that spans from 68–75 MeV. In that way, a lower limit regarding the fragment's projected range will be obtained, from which the optimal shell thickness will be evaluated. The summarized picture of the fission fragment range in ^{209}Bi with SRIM, is presented in figure 3.

In the following section, calculations regarding the expected fission processes in the ^{209}Bi shell of the detector are performed with various detector sizes, ranging from r = 0.65 m, which is the detector utilized in the Aristotle University of Thessaloniki, to theoretical calculations for detectors with r = 2.5, 5 and 10 m radii. Following the SRIM calculations from the previous section, the optimized shell thickness would be approximately 5 μm. This particular value is selected, in order to preserve a decent ratio concerning the expected reactions in the detector over the total reactions taking place in the ^{209}Bi shell, due to the fragments' limited range in ^{209}Bi, which is close to 9 – 10 μm, for the average kinetic energies and 6.5 – 7 μm for the lower-end kinetic energies.

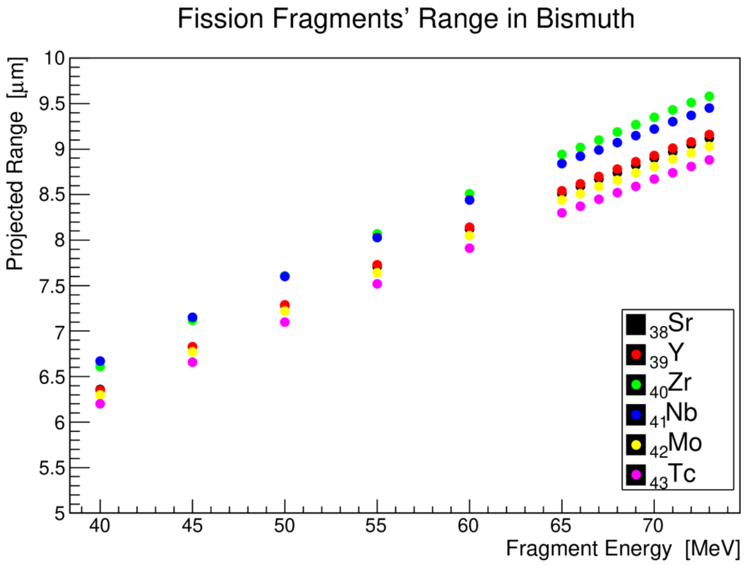


Fig. 3. Projected range of fission fragments in Bismuth.

Expected reactions for atmospheric depths of 700 & 1000 g/cm²

Calculations regarding the expected reactions per unit of fluence in various detector sizes are extended, in order to account for the neutron attenuation in various atmospheric depths. That being said, the results of the expected fission reactions in ^{209}Bi are multiplied with the attenuation factors utilized for the solar neutron propagation in the Earth's atmosphere. The aforementioned factors are imported from the calculations of S. Shibata [11], specifically for the aforementioned atmospheric depths.

EXPERIMENTAL DATA FROM A CALIFORNIUM SOURCE

The aim is to validate the detector's efficiency in fission fragment detection. The SPC utilized in this study has 1.3 *m* diameter, while the spherical electrode used has 1 *mm* diameter. The Ar + CH_4 mixture has been selected as the preferred gas in a 98:2 ratio (Ar : CH_4), while the optimal gas pressure results in 200 *mbar*. High voltage applied to the central electrode (+490V), while the cathode remains grounded. The same experimental conditions are employed, but this time a Mylar window of 2 *μm* thickness is situated in front of the Californium source, attenuating the emitted particle flux. The aim of this experiment is to study the deviation in the energy loss of α–particles and fission fragments through the Mylar absorber. In that way, the ^{252}Cf + Mylar analyzed data can serve as a basis, regarding the expected results of high energy neutron detection with the use of a spherical ^{209}Bi shell.

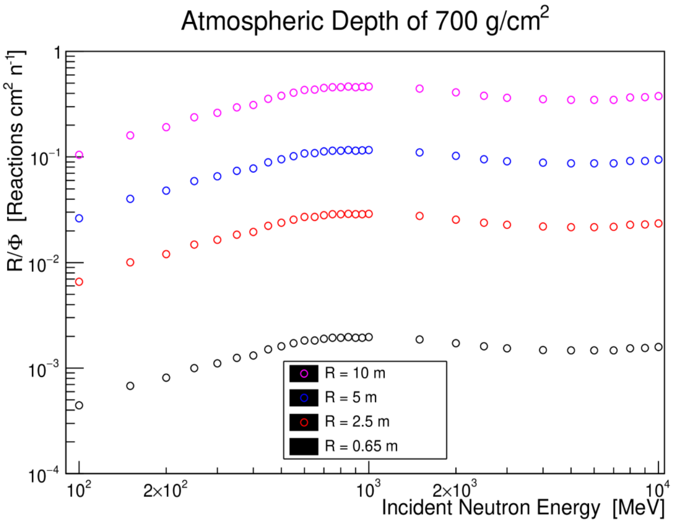


Fig. 4. Expected reactions for the optimized SPC in the atmospheric depth of 700 g/cm^2

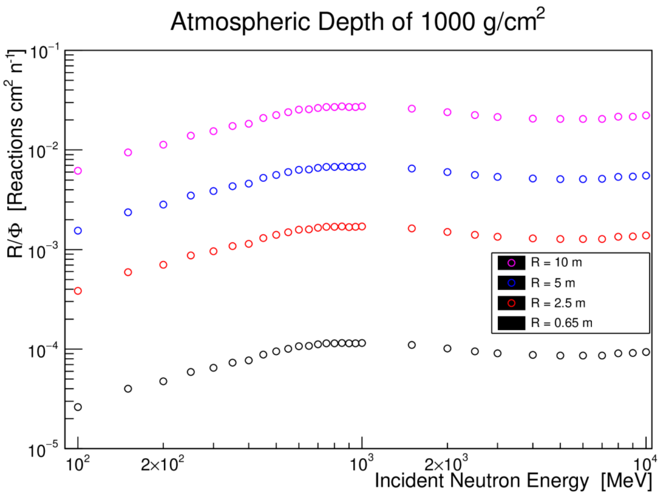


Fig. 5. Expected reactions for the optimized SPC in the atmospheric depth of 1000 g/cm^2

CONCLUSION

Recent experimental data from the n_TOF collaboration at CERN, regard the ^{209}Bi(n,f) process as a standard for the high–energy neutron detection, due to the larger cross section values at the energy range of 50 MeV – 1 GeV. Acting as a threshold reaction for neutrons with energies lower than 50 MeV, it can be the most suitable candidate for the detection of relativistic neutrons cascading through the atmosphere.

The simulation of the ^{209}Bi(n,f) process with the INCL++/ABLA07 model seem to be in accordance with the experimental data in the energy range of 100 MeV to 1 GeV, while the extended simulation of this study up to 10 GeV, reveals valuable insight regarding the physics of the Bi(n,f) process. With SRIM, the projected fission fragment range in ^{209}Bi was computed in order to determine the optimum spherical shell thickness.

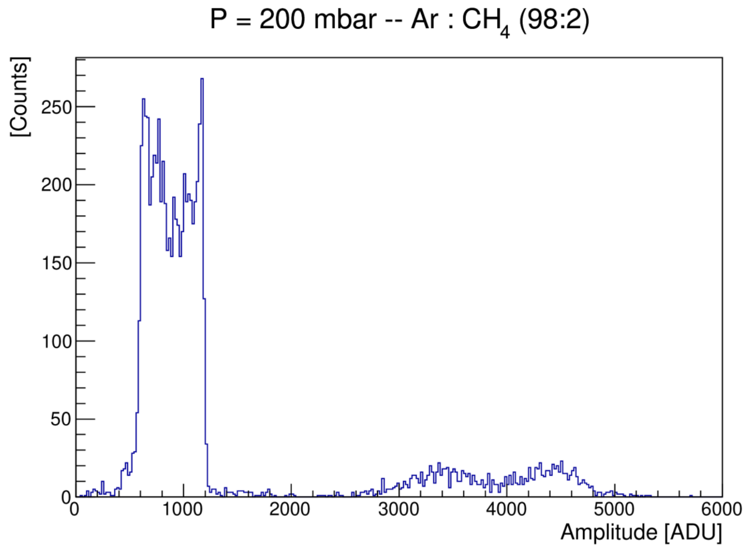


Fig. 6. Amplitude histogram (in ADU) regarding the ^{252}Cf spontaneous fission spectra. The distribution in the left represents the α–particles at 6.1 MeV with background at lower ADUs. Fission fragments are evident in 3 – 5K ADU.

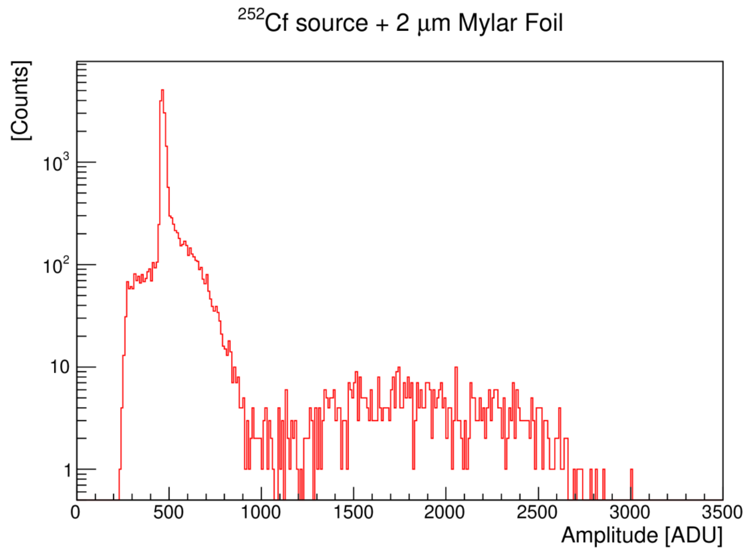


Fig. 7. Pulse amplitude histogram (in ADU) regarding the ^{252}Cf + Mylar spontaneous fission spectra.

Following the results for the optimized detector, calculations were performed in order to deduce the expected reactions for various atmospheric depths and detector radii. Thus, an integrated proposal would include an array of SPCs (covering a larger effective area) complimented with a spherical shell of Bi to be situated inside the sensitive volume of the detector, leading to the detection of energetic solar neutrons that cascade in the atmosphere, through the fission fragments of Bi(n,f) process, that plays the role of a threshold reaction. These detectors are expected to be placed at higher altitudes, and operate in low gas pressures for background reduction, as the fragments' projected range, results only in several μm.

Experimental results from the analysis of the ^{252}Cf + Mylar run with the SPC, demonstrate the expected shifting of the pulse amplitude spectra at lower ADUs as a consequence of the energy degradation of both α–particles and fission fragments, passing through the Mylar foil.

Moreover, a deformation in the fission fragment mass distribution is evident, due to aforementioned effects, that shift the expected distribution to decreased ADUs.. Specifically for fission fragments, the mass distribution is deformed and shifted to lower ADUs (average of 2000 ADUs) in the ^{252}Cf + Mylar run, while different results are obtained from the ^{252}Cf run (3300 and 4500 ADU), yet well discriminated from the α–particle signal.

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