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EXPERIMENTAL CONDITIONS FOR CROSS SECTION MEASUREMENTS FOR ANALYTICAL PURPOSES

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Abstract

The aim of this work was to study the experimental conditions affecting nuclear reaction differential cross section measurements in Atomki. The accuracies of the beam current measurement and the accelerator energy calibration were tested, the energy efficiency of the HPGe detector and the solid angle of the particle detector were determined. A low background environment for deuteron induced gamma-ray emission analysis was made.

I. Introduction

Particle induced gamma-ray emission (PIGE) is an analytical technique which uses prompt gamma radiation from nuclear reactions produced by an energetic ion beam (1-10 MeV) bombarding the sample. This technique has been used since the 1960s for analytical purposes in materials sciences, geology, biology, environmental and cultural heritage studies. One of the advantages of PIGE in comparison to other ion beam analysis (IBA) techniques is its high sensitivity in the low Z number region. However, the main disadvantage of PIGE in comparison to particle induced X-ray emission (PIXE) and Rutherford backscattering spectrometry (RBS) is that the reaction cross sections necessary to determine the elemental composition cannot be given in a simple way. The use of standards and compilations of thick target gamma-yields served to overcome this problem. (See e.g. [1-4]). Nevertheless, for the quantitative analysis without standards, reliable and precise differential cross section data are needed. Recently the International Atomic Energy Agency (IAEA) started a coordinated research program to produce a comprehensive compilation — including new measurements — especially dedicated to the IBA community [5]. The IBA Laboratory of Atomki joined this coordinated research program with measurements providing fundamental cross section data, among other things for deuteron induced gamma ray emission analysis. This work is a continuation of our cross section measurements started a few years ago [6]. The novelty of the present program is the simultaneous measurement of gamma-rays and particles from reactions.

The intensity of a nuclear reaction is expressed in terms of the cross section which is the probability of occurrence of a given reaction. If we record the yield of resultant particles emerging into a small solid angle dΩ at a given angle φ, we define a differential cross section which gives the angular distribution of the events; it is expressed in barns/steradian or in cm^2/steradian.[7]

Physical parameters influencing the experimentally determined differential nuclear reaction cross sections are the energy definition of the accelerator, beam current, efficiency of the gamma detector, solid angle of the particle detector, stopping power of the sample, number of target nuclei.

The aim of this paper is to report on the proper experimental conditions for PIGE differential cross section measurements in the case of a deuteron beam.

II. Experimental conditions

The measurements were carried out on the J30° beam line of the 5 MV Van de Graaff accelerator of Atomki. The available ions for analysis are H^+, D^+, and $^4He^+$. The assortment of ions and their energy range (0.6-3.8 MeV) makes it possible to apply most of the ion beam analytical techniques: PIXE, PIGE, RBS, scanning transmission ion microscopy (STIM), elastic recoil detection analysis (ERDA) etc.

The experimental setups consists of a target chamber with a long Faraday cup, as well as HPGe, SSD and long counter detectors to detect gamma rays, particles and neutrons, respectively. The setup arrangement is shown in Fig. 1.

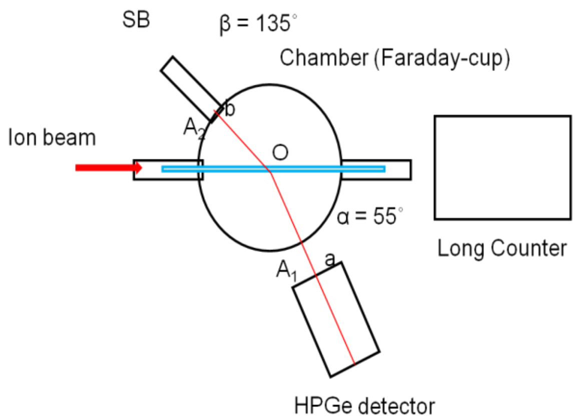

Fig. 1.: The schematic view of the experimental arrangement

We carried out the beam current measurement with an Ortec 439 Digital Current Integrator. The stability of this device was below 1 %, obtained from the test measurements.

For the detection of γ-rays, a Canberra Model GR4025-7600SL coaxial type HPGe detector (59.5 mm diameter, 170 cm^3 volume) was applied at 55° angle relative to the incident beam direction with a distance of 9.5 cm from the samples.

Particles from Rutherford backscattering were detected by an ORTEC surface barrier (SB) detector with 50 keV energy resolution. We used a 3 mm diameter red-copper collimator before the SB for the elimination of high intensity backscattered particles. The long counter, which we used for the neutron threshold determination, was borrowed from the Institute of Experimental Physics, University of Debrecen. This home-made device was built by M. Buczkó and Gy. Csikai, includes a BF_3 cylindrical proportional counter. The bonamid cylinder around it was 32.5 cm in diameter, 33 cm long.

III. Experimental results

III.1 The energy calibration of the accelerator

In the energy calibration of particle accelerators, the recommendations of J. B. Marion (1966) [8] are accepted by most of the laboratories. For proton beams, he suggested several gamma-ray resonances and neutron threshold energies measured with absolute methods. Contrarily, in the case of deuteron beams he cited only one work on the absolute determination of the $\mathbf{O^{16}(d,n)F^{17}}$ threshold energy. [9]

We used two different methods for the accelerator calibration. The aim of this work was to control the data and to determine the possible discrepancies from an early calibration of the VdG-5 accelerator [10]. We performed the calibration of the accelerator for protons with the $\mathbf{^{27}Al(p,\gamma)^{28}Si}$ reaction at the 991.81±0.04 keV resonance and the $\mathbf{^{7}Li(p,n)^{7}Be}$ reaction at the 1880.6±0.07 keV neutron threshold. After this, we made and attempt to use the $\mathbf{^{16}O(d,n)^{17}F}$ reaction at the 1829.2±0.6 keV neutron threshold.

Measuring the gamma-yield of the $\mathbf{^{27}Al(p,\gamma)^{28}Si}$ reaction at the 992 keV resonance is a widespread method for accelerator calibration. We used a 750 nm thick aluminium foil as target and we carried out the measurement starting at 1000 keV by 1 keV steps until 987 keV. The yield of 1778.9 keV γ-ray depend on the beam energy is shown in Fig. 2. The intersections of the fitting line and the inflexion point of the scale function are indicated in the diagram.

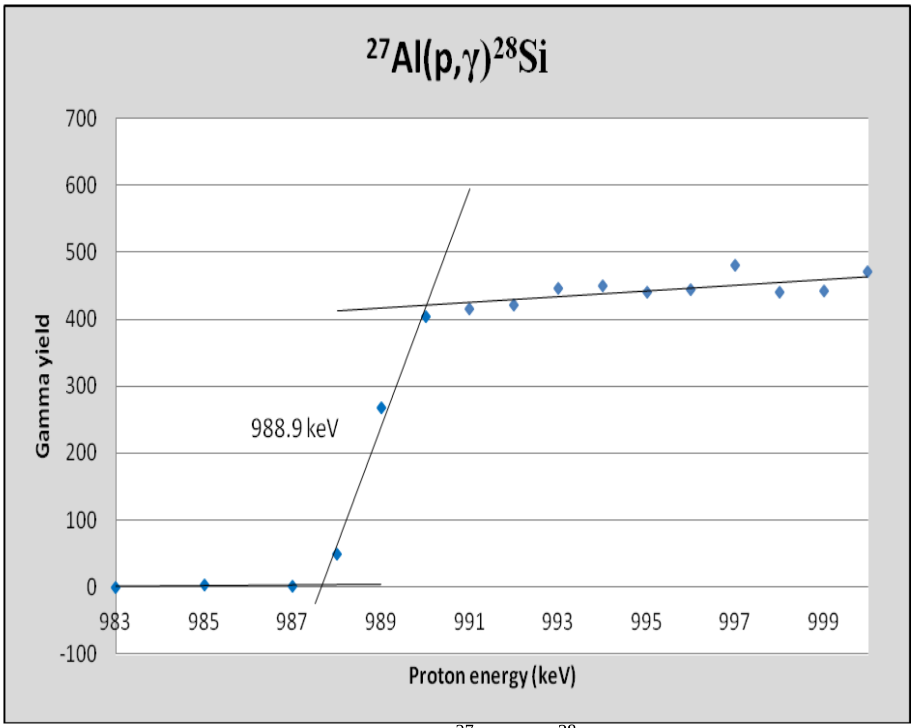

Fig. 2. Results of the $^{27}Al(p,\gamma)^{28}Si$ reaction

We got 988.9 keV as the inflexion point. The repetition of the calibration procedure 3 months later gave the value of 991.0 keV. This means that the present calibration was averagely 1.9 keV below the earlier calibration. The energy spread between the intensity ¼ and ¾ [11] was 1.2 keV and 1.1 keV, respectively. The discrepancy between the new and the old calibration could be caused by the changes in the slit settings (positions and widths) of the analysing magnet.

We used LiF evaporated on Ta back of 135 μg/cm^2 thickness for the ^{7}**Li(p,n)**^{7}**Be** neutron threshold calibration and carried out the measurement with 1 keV steps from 1890 keV until the threshold. We used the $X^{2/3}$ function of neutron yields for fitting the data and determining the intersection [12]. The neutron yield depending on the beam energy, including the fitting line and the cross point is shown in Fig. 3.

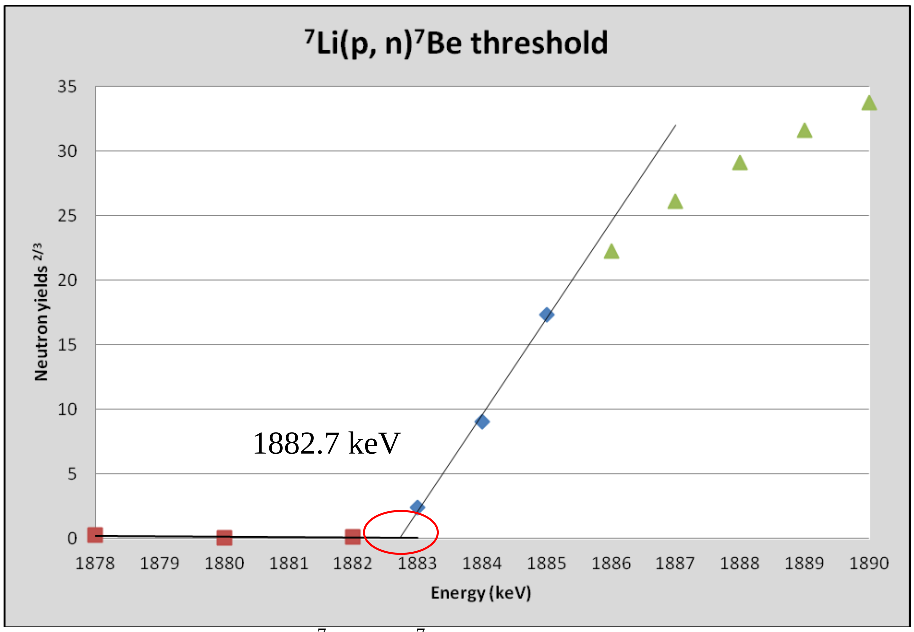

Fig. 3. Results of the ^{7}Li(p, n)^{7}Be reaction and fitting curve of data

From the fitting line extrapolation we got 1882.7 keV for the neutron energy threshold. This value is 2.1 keV above of the value given by the previous calibration.

After the accelerator calibration with proton, we carried out the **^{16}O(d,n)^{17}F** neutron threshold measurements. For this, we used SiO_2 of 1 mm thickness as a thick target and made 10 and 5 keV steps below the threshold energy. In the obtained neutron yield – deuteron energy function no step was observable. It means that the high background of the neutrons from d+d reactions cover up the small neutron yield around the threshold energy. This problem can be solved by using counter ratio techniques with two neutron detectors [13].

III.2.Determination of the energy efficiency curve of the gamma detector

The full energy peak (FEP) efficiency is one of the most important characteristics of γ-ray detectors. The knowledge of this factor is essential for the quantitative PIGE analysis. We followed the procedure described by Elekes et. al [14] with the difference that we used **^{27}Al(p,γ)^{28}Si** resonance at 992 keV instead of the resonance at 767 keV. For the detector calibration we used several radioactive sources, ^{133}Ba, ^{56}Co, ^{60}Co, ^{137}Cs, ^{152}Eu and one gamma resonance at 992 keV of the **^{27}Al(p,γ)^{28}Si** reaction as known γ decays of radioactive capture reactions have to be used in addition to those from radioactive sources in order to construct efficiency curves in nuclear reaction studies [15].
The results of the measured HPGe detector absolute efficiency data are shown in Fig. 4.

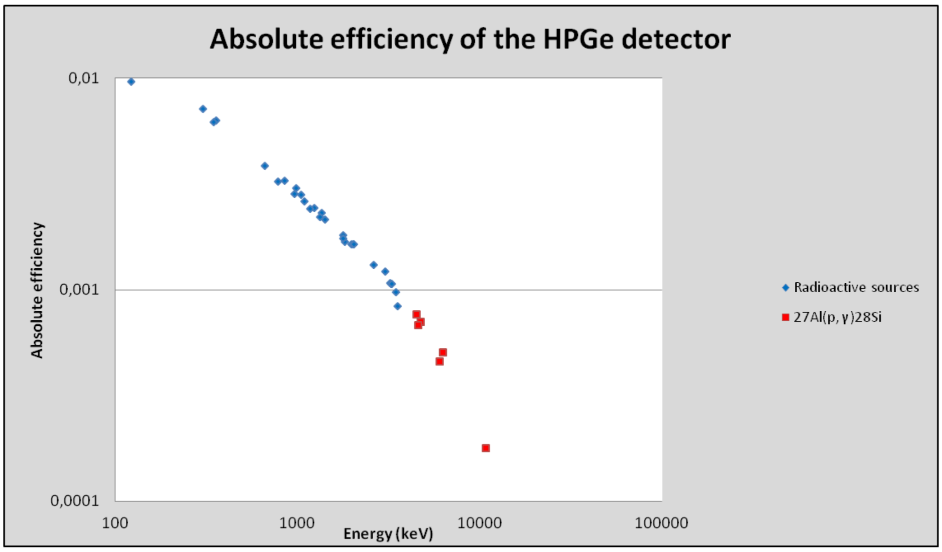

Fig. 4.: The measured absolute efficiency data for the HPGe detector.

To summarize, we had 35 data point, 29 from radioactive sources and 6 from the **^{27}Al(p, γ)^{28}Si** resonance. The previous fitting of the data gave an appropriate accordance in the lower energy region (by 3500 keV) but we need more data in the high energy region (3500-11000 keV) for a precise data fitting. Another measurement is planned using one of the **^{23}Na(p,γ)^{24}**Mg resonances on 1416.9±0.1 keV.

III.3. Determination of the solid angle of particle detector

We used three different methods for the solid angle determination. We calculated the solid angle based on the geometry. We performed measurements using a Th(B+C) radioactive source and calculated the solid angle based on the particle spectra. This source gives high intensity alpha particles at 3 energies. The first two groups with 6050.8 and 6090.1 keV energy have a 0.3485 branching ratio. The third group of alpha particles at 8784.9 keV has a 0.6406 branching ratio [16]. The third method based on Rutherford backscattering. We used Ag layers evaporated on silica substrate with different Ag layer thicknesses (50, 100, 150 and 200 nm).
We measured the AgSi standards at 2000 keV proton energy and based on the RBS spectra we plotted the Ag yield- Ag thickness function. After the determination of the gradient of the line, we calculated the solid angle using the following equation from the quantitative form:

$$\Omega = a / (N_T * d\sigma/d\Omega)$$

where a is the gradient of the fitting line, N_T is the number of Ag atoms /cm^2 , $d\sigma/d\Omega$ is the differential scattering cross section.

Methods	Geometry	RBS	Th(B+C)
Solid angle (sr)	0.00465	0.00581	0.00577

Table 1.: Results of solid angle calculation from three differential methods

The result of the calculated solid angle from the three methods is shown in Table 1. The difference between the values from RBS and Th (B+C) source measurements is below 1%. The lower value from geometry could be explained by the collimator application.

III.4.Gamma background conditions in the case of deuteron induced gamma radiation

In the measurement background, several kind of disturbing peaks appear. These peaks are produced mostly by neutron induced nuclear reactions on the beam collimator, material of the setup and reactions in HPGe detectors and less intensively by the laboratory background. The obtained background spectrum with a 2000 keV deuteron beam is shown in Fig. 5.a.

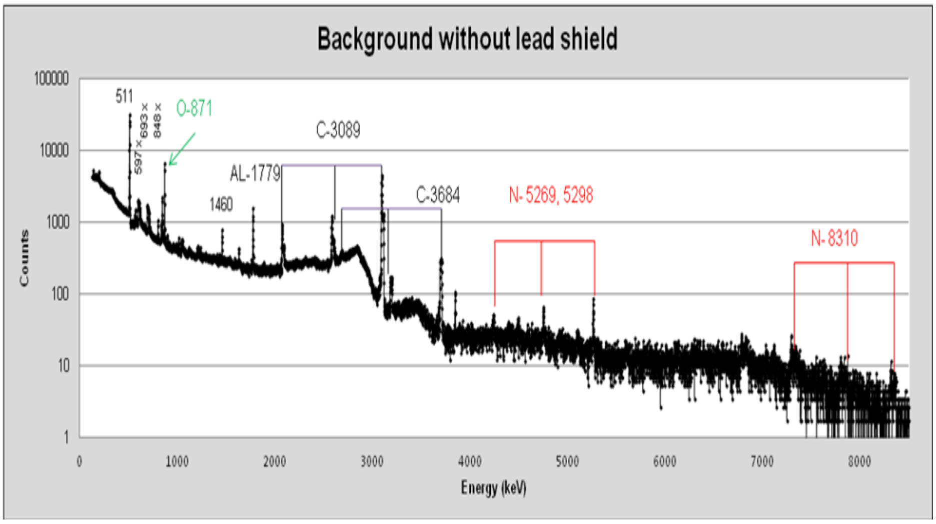

Fig. 5a.: Background without lead shield of the experimental arrangement measured with deuteron beam

For the accurate gamma detection, it was necessary to decrease the disturbing effects. With this aim, we rearranged the adjustment, set farther the end of the Faraday-cup with a tube and we used for the elimination of these sources a 5 cm thick lead shield around the detector, as well as lead bricks around the collimators, also on the end of the Faraday-cup. With these changeovers we could decrease every disturbing effect. We could eliminate the biggest part of the carbon, nitrogen and oxygen peaks. The full count rate decreased with one order of magnitude in the measurement background.

See below (fig. 5.b) the final experimental background.

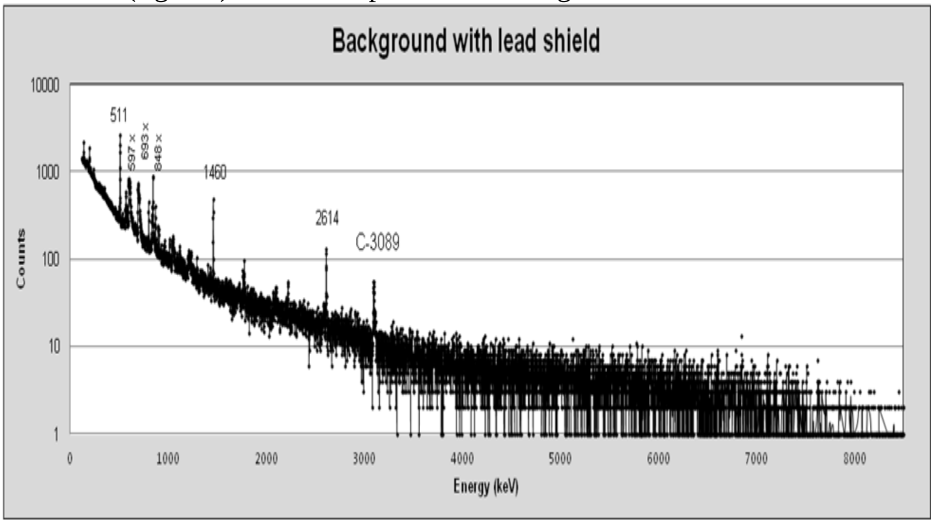

Fig. 5b.: Background with lead shield of the experimental arrangement measured with deuteron beam

IV. Summary

Due to the work presented, acceptable conditions were achieved for differential cross section measurements in deuteron induced gamma radiation. The first measurement will be performed with the reactions **$^{14}N(d,p)^{15}N$** and **$^{28}Si(d,p)^{29}Si$** using Si_3N_4 target foils.

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