MEASUREMENT OF (n, xnγ) REACTION CROSS-SECTIONS ON NATURAL LEAD USING IN-BEAM GAMMA-RAY SPECTROSCOPY

by

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New concepts in nuclear reactor technology require precise neutron reaction data in the intermediate and high energy range. At present, experimental and evaluated nuclear data, particularly for (n, xn) reactions, are very scarce. Moreover, real discrepancies exist between different databases.
The lack of experimental data is essentially due to the difficulty of measuring (n, xn) reactions. No universal method applicable to all isotopes exists. One of the possible methods is the in-beam γ-ray spectroscopy and neutron time of flight technique on white neutron beams. In this way one actually directly measures (n, xnγ) reaction cross-sections. These serve as a starting point in the subsequent derivation of (n , xn) reaction cross-sections using nuclear models. This method was applied with a natural lead sample at the GELINA white neutron beam facility in Geel, Belgium.

Key words: (n, xn) reactions, cross-section, γ-ray spectroscopy

INTRODUCTION

In the last ten years, with increasing world energy demands, there has been a renewed interest in nuclear energy production. However, existing nuclear technologies present several serious drawbacks that hinder its further development. The classical uranium cycle can ensure an energy supply for only a limited time. The disposal of radioactive waste has still to find satisfactory solutions, especially in terms of environmental and social acceptability. Improved safety is desirable as well.

Solutions were sought in several directions, including Fast Breeder, Molten Salt, and Hybrid (accelerator-driven) reactors. Accelerator-driven Systems (ADS) have attracted much scientific attention in the last decade [1]. Management of radioactive waste is defined as one of the priorities in nuclear research under the Fifth and Sixth Framework Programs of the European Community. At present, there are three European collaborations dedicated to producing fundamental nuclear data of importance for ADS systems and waste transmutation technologies. These are MUSE (Multiplication de Source Externe), HINDAS (High and Intermediate Energy Nuclear Data for ADS), and nTOF (neutron Time Of Flight) [2]. The present work has been done in the frame of the nTOF collaboration.

An ADS is a hybrid system that consists of a particle accelerator as an adjunct to a subcritical nuclear reactor [3, 4]. In a sub-critical reactor, the number of neutrons originating from fission is not sufficient to overcome the losses (due to leaks and

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the absorption of neutrons). Therefore, a chain reaction cannot be self-sustained and in order for the reaction to proceed, one needs to continuously supply neutrons from an external source. In an ADS, these external neutrons are created by spallation, when a medium energy proton beam reacts with a heavy target (usually lead). The supply of neutrons is proportional to the proton beam intensity which can be modified precisely and with a very short time constant. The proton beam plays the role of the control bars in a reactor, the difference being that it is proactive rather than reactive: if it fails, the reaction stops and it can never lead to overheating.

As for the commercial energy production, besides the point of safety, ADS have an additional advantage over critical reactors: the use of thorium as a nuclear fuel. Interest in using thorium (^{232}Th) as a nuclear fuel exists for years, since it is three times as abundant in the earth's crust as uranium. Also, all of the mined thorium is potentially useable in a reactor, compared to the 0.7% of natural uranium, meaning that some 40 times the amount of energy per unit mass might be available. A thorium reactor would work by having thorium-232 capture a neutron to become thorium-233, which decays to uranium-233, which fissions.

Finally, the overall dynamics of nuclear reactions with the high external neutron flux is such that the ADS can be successfully used for waste transmutation.

The successful development of a hybrid reactor and even the design of a demonstrator require knowledge of a wide range of nuclear data. The data bases are relatively well filled below 20 MeV and nuclei involved in the uranium cycle, but for those involved in the thorium one and for high neutron energy, the situation is not satisfactory. The experimental data are very scarce and if they exist, very imprecise. Concerning the evaluated data, real discrepancies exist between the different databases.

The (n, xn) reactions have little importance in critical reactors where the flux of neutrons above 1 MeV is very low. In ADS, where there is a high flux of neutrons produced by spallation, these reactions are very important. They intervene in the flow of neutrons and thus modify the criticality. Moreover, they modify the spectrum since they, in addition, convert fast neutrons ($E_n > 5$ MeV) into slow ones ($E_n < 1$ MeV).

Elements targeted for (n, xn) cross-section measurements include actinides (such as ^{233}U and ^{239,241}Pu, targeted by nTOF, or ^{238}U targeted by HINDAS), shielding materials (such as ^{56}Fe targeted by HINDAS), and spallation target materials (Pb and Bi). Lead is an important component of the shielding for neutron radiation as well. Large amounts of data already exist for lead to restrict the parameter space for nuclear model calculations. Also, there is very good spectroscopic information on discrete levels and γ-branching ratios for all lead isotopes reached by (n, xn) reactions up to $x = 9$. This information is important for a correct interpretation of the measured γ-production cross-sections.

One method to study neutron-induced reactions is to use high-resolution in-beam γ-ray spectroscopy with either a pulsed "white" neutron source or a quasimonoenergetic neutron source. In this way one actually directly measures (n, xnγ) reaction cross-sections. These serve as a starting point in the subsequent derivation of (n , xn) reaction cross-sections using nuclear models. With a white beam, one can measure neutron cross sections over the whole incident neutron energy range in a single experiment. In this case, neutron energy has to be determined by the time of flight method [5, 6].

In general, neutron induced reactions leave the residual nuclei in highly excited states, which subsequently decay via γ-cascades to their ground states in typically three to four steps. The initial intensity distribution over a very large number of highly excited levels is collected in the first few excited levels, which then decay to the ground state. Such transitions between low-lying levels are identified by their characteristic energies in the γ-emission spectrum. In this way, the production cross-sections for several transitions in a number of residual nuclei can be measured simultaneously over a wide incident neutron energy range in a single experiment.

Since the residual nuclei are mostly formed with relatively large angular momenta, direct transitions to the 0+ ground states of even-even nuclei are strongly inhibited. In even-even nuclei, often more then 90% of the γ-cascades proceed to the ground state via 2+ levels [5]. Thus for even-even residual nuclei, we get nearly the total production cross-section by counting the first 2+ to the ground state γ-ray transitions. The partial cross-sections not included in this measurement result from those γ-rays in the cascade that bypass the first 2+ excited state, and those reactions that leave the residual nuclei in the ground state. Their contribution can be calculated using nuclear models.

This technique can also be used when the final nucleus is not even-even. In this case, several partial production cross-sections are obtained by counting given γ-ray transitions, and the total production cross-section must be deduced through nuclear model calculations. The partial production cross-sections are of interest because they indicate the population of individual states including isomeric ones. They are therefore of interest for comparison with the result of nuclear model calculations.

The present article describes a measurement of neutron reactions with natural lead. The prompt γ-ray spectroscopy method was used at the GELINA (Geel Electron Linear Accelerator) white

neutron beam at Institute for Reference Measurements and Materials (IRRM), Geel, Belgium. Next sections describe the experiment, give the procedures used in deriving γ-production cross-sections from the raw data and the calculation of the measured cross-section and describe the basic features of nuclear reaction calculation. In the last section, the experimental and theoretical results are presented, compared and discussed.

EXPERIMENTAL SETUP

The measurements were performed at IRMM on the GELINA white neutron beam facility.

The beam

GELINA is a linear electron accelerator that produces a pulsed electron beam whose energy spectrum extends from 70 to 140 MeV. The beam frequency is 800 Hz. The electron pulse duration at the impact point is about 1 ns, thanks to the magnetic compression system of the facility [7]. At the moment of the impact, the system generates a logical t_0 pulse that can be used as the time reference for the creation of the neutron pulse. This signal is wired to all control rooms and experimental areas for the sake of time of flight measurement.

The neutrons are produced in a uranium target [8] bombarded by these electrons. The target is constantly rotating in order to avoid overheating. Gamma rays created by electron bremsstrahlung provoke (γ, n) and (γ, f) photonuclear reactions through which neutrons are emitted. Neutron energy spectrum at the GELINA facility reaches its maximum in the interval of 1 to 2 MeV. At 14 MeV, neutron fluency is reduced by a factor of ~150.

The neutrons, then, pass through collimators and penetrate several beamlines extending radially outside the target area. Experimental rooms are installed along the beamlines at various distances, according to the application of each one.

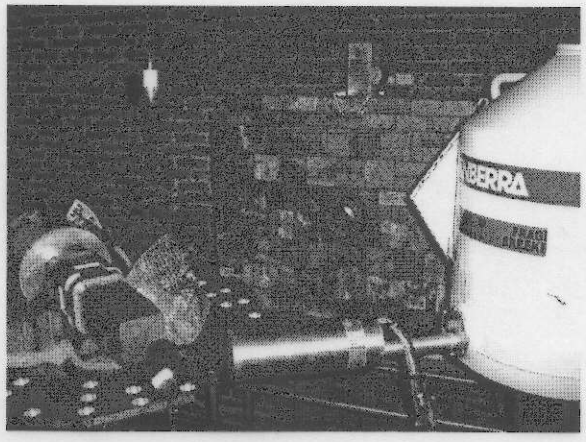

Figure 1. Sample and the detectors. The CLOVER detector is seen in the left

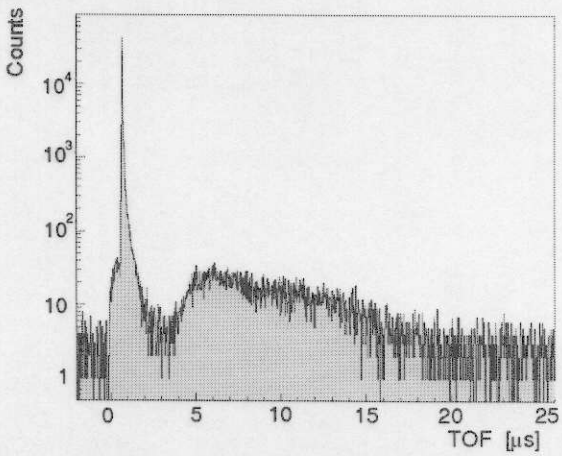

Figure 2. Typical γ detection time statistic collected over several hundred thousand beam pulses. The γ-flash peak is clearly visible at 0.662 μs. The bump between 4 and 18 μs belongs to the neutron-induced γ-rays

The sample and the detectors

The experimental area used in this experiment was in the beamline number 3 at 200 m from the neutron source. The natural 6 mm thick lead sample was placed at 198.551 m, inside the room. The diameter of the sample was 6 cm. The HPGe CLOVER detector was placed at 12 cm from the sample, at 135° with regard to the beam (see fig. 1).

CLOVER is an HPGe-based detector developed by Canberra EURISYS. It contains four closely packed HPGe crystals mounted in a common cryostat in order to improve the detection efficiency. The resulting efficiency is more than a simple sum of four independent crystal efficiencies. In the case where the full γ-ray energy is deposed in more than one crystal, it can be restored by adding it back from parts.

The γ-flash

At every beam pulse, bremsstrahlung γ-rays also travel through the beamline at the speed of light and arrive at the experimental areas before the neutrons. They diffuse at the target and interact with the detector. This γ-flash appears always at a fixed time after t_0 (fig. 2). Bearing in mind that the cables transmit the t_0 signal with a delay, the γ-flash is used to perform the absolute t_0 calibration for the TOF measurement.

However, γ-flash causes also some technical difficulties. As the fastest neutrons arrive only several microseconds later (2.5 μs for 20 MeV neu-

trons), the pulses induced by the fastest neutrons often ride on the tails of γ-flash pulses. It is very difficult to resolve such pileups using analog electronics without a heavy deterioration of the energy resolution. A solution had to be sought using digital methods.

Digital spectroscopy methods

Digital spectroscopy is a common name for techniques where the detector preamplifier signal is sampled at very high rates, of the order of tens or hundreds of millions samples per second, and the data so obtained treated numerically. The goals of this treatment are essentially the same as with the analog methods:

(a) to extract the quantities of interest, such as the pulse heights and forms, as well as the interaction time,

(b) to suppress non-essential information, or "noise",

(c) to reduce the data to a manageable level, and

(d) to represent the results in an intelligible manner.

The basic concept of digital methods has many common points with analog methods. However, digital methods offer some important advantages over the analog ones. First, the fidelity of samples can be maintained indefinitely, and their offline treatment is always possible. Digital filters are easy to design and offer much flexibility. Finally, if the system is saturated, its recovery time depends on the preamplifier, rather then of the slow pulse shaping circuit [9].

In the present work, because of the presence of the γ-flash, it was critical to ensure fast counting, *i. e.*, the possibility of precise measurement of pulses close to each other in time, without a significant loss of energy resolution. Digital filtering allows producing pulse shapes with flat tops and finite lengths, ensuring the best compromise between the conflicting demands of good energy resolution and high instantaneous counting rates.

One of the factors that put the most severe limitations to any nuclear spectroscopy system based on high-volume Ge detectors is the so-called ballistic deficit effect. Briefly, it is a combined consequence of the variation of the pulse rise time in Ge detectors, and the exponential decay of its preamplifier signal. An elegant solution to this problem is the mathematical elimination of the exponential decay in the digitally sampled preamplifier signal [10, 11]. A trapezoidal shaping method based on this idea was implemented in the software that was used for digital data treatment in this work.

Digital data acquisition

Signals from the four CLOVER segments were digitally sampled using analogue to digital converter (ADC) modules developed at Institut de Recherches Subatomiques (IReS), Strasbourg. Each of the modules contains two fast ADC circuits that are capable of sampling the signals at a rate of 65 MHz. Two such modules were sufficient to sample the four CLOVER outputs. The sampled data was stored on four hard disks of 120 GB each, in order to be treated later. Some basic data treatment was, however, immediately done for acquisition monitoring purposes.

The time of flight interval chosen for the measurement extended from 1 to 26 μs after the t_0. This corresponds to neutron energies down to 0.3 MeV. In this interval only one γ-ray was detected each 40 beam pulses. In order to reduce the average data transfer rate and the memory usage, the acquisition was triggered only when detector pulses were present in this interval. The two ADC modules were equipped with logical circuits that generated logical "selection" signals when interesting γ-rays are detected. This selection circuit is represented in the fig. 3. In the upper branch, the logical t_0 signal, supplied by the accelerator, was shaped and delayed using a gate/delay (G/D) element in order to create the logical gate corresponding to the chosen time of flight interval. In the lower branch of the circuit, two discriminator elements were used to signal the presence of pulses in the series of samples and logical OR (OU) was performed between their signals. Coincidences of the signals from the upper and the lower branches were detected using a logical AND (ET) element. The selection signal so obtained was then reshaped to duration of 25 μs using a G/D element for its use in the next stage. This signal correctly tells when γ-rays have been detected inside the chosen time of flight interval, but it is created with a variable delay with respect to the t_0. In order to preserve the time information with respect to the t_0 in the series of

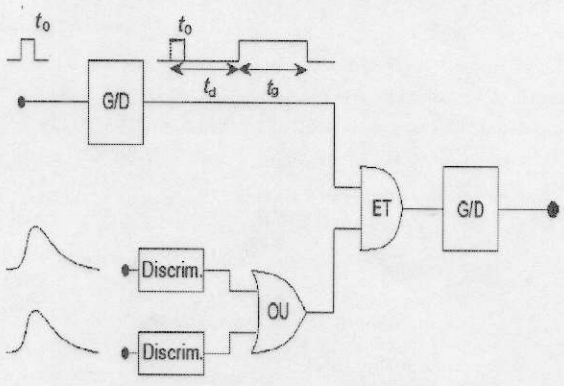

Figure 3. Logical scheme for the selection circuit

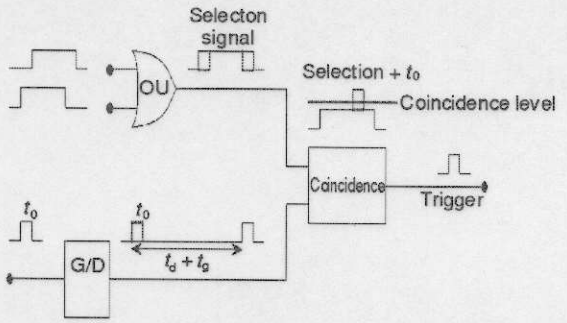

Figure 4. Acquisition triggering circuit

samples, it was necessary to always trigger the acquisition with a fixed delay after the t_0. This purpose was achieved using the "triggering" circuit schematically shown in the fig. 4. It unites selection signals from both ADC modules and creates a triggering signal with a fixed delay with respect to the t_0. In its upper branch, logical OR (OU) was applied between the selection signals from the two modules. In its lower branch, the t_0 was delayed by 26 μs using a G/D element. The acquisition was, then, triggered by the coincidence between the signals in the two branches of this circuit. At every trigger event, 60 μs of signal were stored, including 2.5 μs before and 57,5 μs after t_0.

Digital data treatment

The acquired data were treated offline, using a PC with digital signal treatment software developed by the authors.

The principal information to be extracted from the samples were the pulse heights (indicating γ-ray energy) and their detection times (indicating incident neutron energy). The pulse heights were extracted using the trapezoidal shaping technique [10, 11], while the detection times were precisely determined using the digital triggering method presented by C. L. Mihailescu in his doctoral thesis [12].

Since the γ-pulses induced by the fastest neutrons are very close in time to the γ-flash, one has to use the trapezoidal technique with very short shaping times. However, short shaping times sacrifice the energy resolution. Some compromise trapezoid parameters had to be found in order to reach as high neutron energies as possible.

The parameters to adjust were the durations of the trapezoid rising edge and flat top. The total length of a shaped pulse is made up of 2 times the rising edge and one flat top. Two consecutive pulses can be separated if the time distance between them is at least one trapezoid length. Full separation of shaped pulses is necessary when one needs to determine the baseline for each one of them (fig. 5a). However, if the input signal baseline is sufficiently stable, one can assume a constant baseline in the shaped array. Then the shaped pulses need not be completely separate. It is sufficient to ensure that one pulse does not interfere with the flat top of the other (fig. 5b). In the case of CLOVER detectors, it was possible to work that way. This allowed approaching the γ-flash closer in time, and reaching higher neutron energies. In spite of the rapidly decaying neutron flux at higher energies and the low statistics of the present run, it was possible to deduce the cross-sections up to 14 MeV of neutron energy. The trapezoid parameters were 2 μs rise time, and 1 μs flat top, which was close to the maximum allowed by the requirement to measure 14 MeV neutrons. Figure 5c represents a case from which pulse heights cannot be extracted.

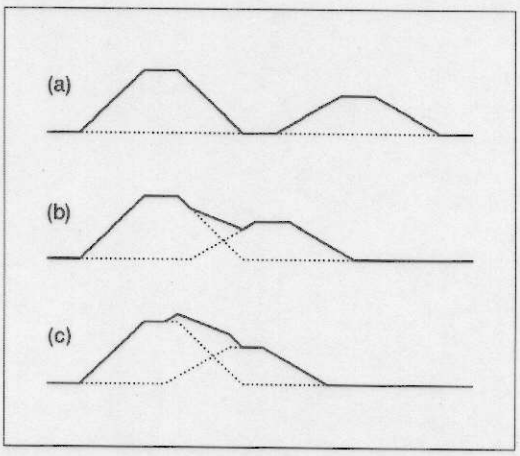

Figure 5. Separation of trapezoidal pulses. (a) pulses are well separated and both baselines can be estimated, (b) pulses are separated enough for an accurate measurement of both flat top heights, and (c) pulses interfere with each other's flat top

DATA REDUCTION

The neutron energy interval from 0.31 to 14 MeV was divided into 14 bins, with one bin from 0.31 to 1.0 MeV and 13 equal 1 MeV bins from 1 to 14 MeV. The data collected during 30 hours run time was used to form the γ-ray spectra corresponding to these neutron energy bins, according to the measured neutron time of flight (fig. 6).

Unfortunately, the data from only three of the four CLOVER segments could be used, because one of the acquisition channels presented gain variations due to a bad electronic contact. The data from the three valid channels were calibrated according to the positions of ^{206}Pb and ^{208}Pb ground transition lines and summed up in one spectrum for each of the 14 neutron energy bins.

Each of the studied γ-energy peaks was fitted using a sum of a Gaussian distribution function and

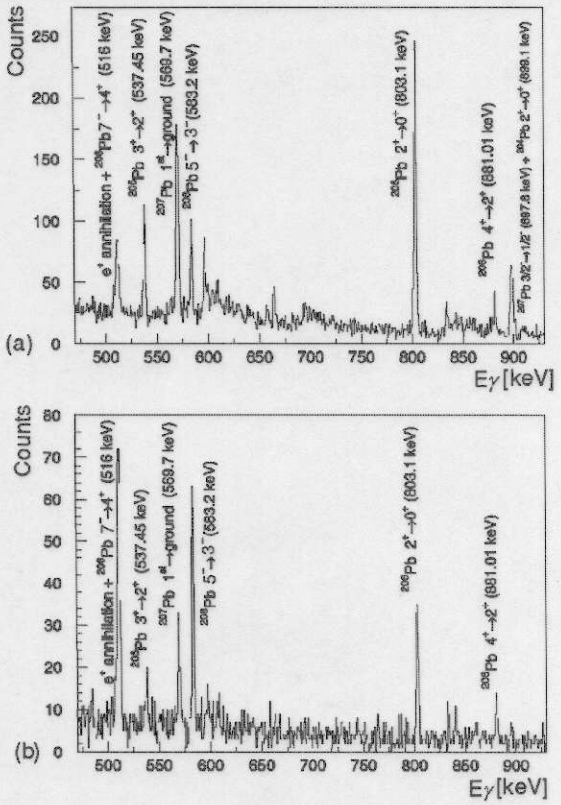

Figure 6. Prompt γ-spectra from neutron interactions with ^{nat}Pb in two neutron energy bins: (a) 3-4 MeV; (b) 8-9 MeV

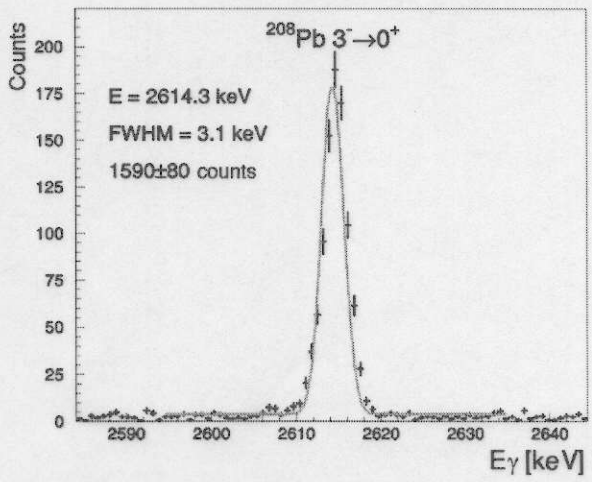

Figure 7. 803.1 keV peak fitted using PAW

a first order polynomial to account for the background. The fitting was done using the PAW (Physics Analysis Workstation) package developed at CERN [13] (fig. 7). The number of counts so obtained was normalized using the fission-chamber neutron flux measurement results for each of the 14 neutron energy bins. The absolute overall normalization was performed comparing these results to code predictions.

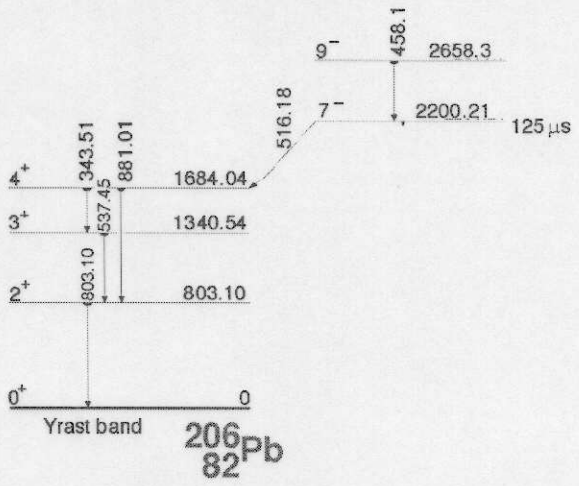

Figure 8a. Level scheme for ^{206}Pb showing the isomeric 7⁻ state at 2200 keV and its 516 keV transition to the 4⁺ state

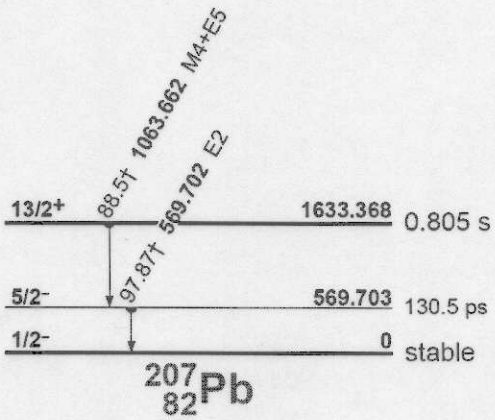

Figure 8b. Level scheme for ^{207}Pb showing the isomeric 13/2⁺ state at 1633 keV and its 1064 keV transition to the first excited state

RESULTS - DISCUSSION

In the analysis of the transitions one has to consider isomeric states involved in the cascade. When a cascade passes through an isomeric state, the transitions that follow after it in the cascade do not take place promptly. Such delayed transitions are not properly correlated with the neutron energy because the measured time of flight includes the decay delay. According to the level schemes for ^{206,207}Pb (figs. 8a, 8b) [14], when there is more than one isomeric state, all of the known higher lying isomeric states decay to the lowest-energy isomer. Thus the γ-decay cross-section for the lowest energy isomer equals the sum of the population cross section of all isomers. In the case where the lifetime of the lowest-energy isomer is long compared to the

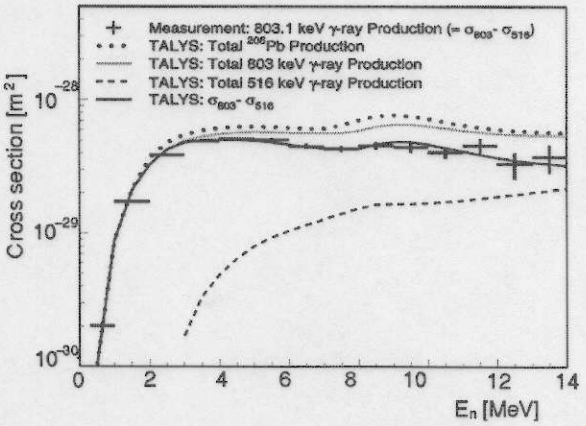

Figure 9. The cross-section for 803.1 keV prompt γ-ray production in natural lead in function of neutron energy. The crosses represent experimental points normalized to TALYS predictions. The lines represent TALYS predictions. The dotted line represents the total cross-section for the production of ^{206}Pb via the (n, xn) reactions. The gray line represents the cross-section for the ^{206}Pb fundamental transition at 803.1 keV. The dashed line represents the cross-section for the isomeric transition at 516.2 keV, and the solid line represents the difference of the fundamental and isomeric transition cross-section

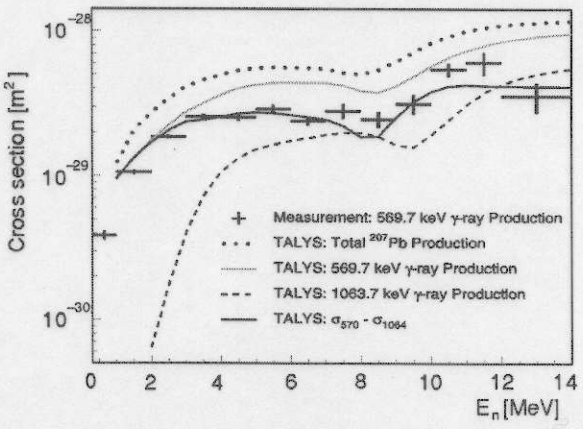

Figure 10. The cross-section for 569.7 keV prompt γ-ray production in natural lead in function of neutron energy. The crosses represent experimental points normalized to TALYS predictions. The lines represent TALYS predictions in the same way as in fig. 9

neutron time of flight, the measured prompt γ-yield represents approximately the difference of the relevant transition yield and its delayed part. The greatest part of the delayed transitions occur between the beam pulses, while the acquisition is gated off. However, a smaller part of these γ-rays get detected at moments corresponding to the time of flight of neutrons of lower energies. This introduces a slight overestimate of the number of counts for these transitions. This can be corrected by following the number of detected isomeric state decays in the same neutron energy bin. With the statistic acquired in this experiment, these isomeric decay peaks were invisible in the γ-ray spectra for all neutron energy intervals, which lead us to conclude that this correction is statistically still insignificant.

When calculating the derived cross-sections, correction procedures have to be applied to ensure that the derived cross-sections relate to the total emission of γ-rays.

The investigated transitions are listed in tab. 1. Observed ground transition yields of both ^{206}Pb and ^{207}Pb are affected by the presence of isomers. The excitation function for ^{208}Pb ground transition is not affected by any isomeric state.

All results were compared to the predictions of the TALYS code (see the subsection dedicated to the TALYS code). The effect of the isomeric states was taken into account by calculating the differences of ground and isomeric transition cross-sections.

Figures 9 and 10 represent the ground transition production cross-sections for ^{206}Pb and ^{207}Pb. The ground transition of ^{206}Pb at 803.1 keV is fed by both ^{206}Pb(n, n') and ^{207}Pb(n, 2n) reactions. The ground transition of ^{207}Pb is fed by both ^{207}Pb(n, n') and ^{208}Pb(n, 2n) reactions. The measurement of both of these excitation functions by the neutron time of flight method is affected by the presence of

Table 1. List of transitions investigated

Transition investigated	Possible feeding reactions	Energy [keV]	Isomers in residual nucleus			Energy characteristic for isomer decay [keV]	Measured γ-production cross section
			J_π	E [keV]	$t_{1/2}$		
^{206}Pb $2^+ \rightarrow 0^+$	^{206}Pb(n, n'γ)^{206}Pb ^{207}Pb(n, 2nγ)^{206}Pb	803.1	12^+ 7⁻	4027.0 2200.2	197 ns 125 μs	516.2	σ(803,1)-σ(516.2)
^{207}Pb $(5/2)^- \rightarrow (1/2)^-$	^{207}Pb(n, γ)^{207}Pb ^{207}Pb(n, n'γ)^{207}Pb ^{208}Pb(n, 2nγ)^{207}Pb	569.7	$13/2^+$	1633.4	0.805 s	1063.7	σ(569,7)-σ(1063.7)
^{208}Pb $3^- \rightarrow 0^+$	^{207}Pb(n, γ)^{208}Pb ^{208}Pb(n, n'γ)^{208}Pb	2614.6		none			σ(2614)

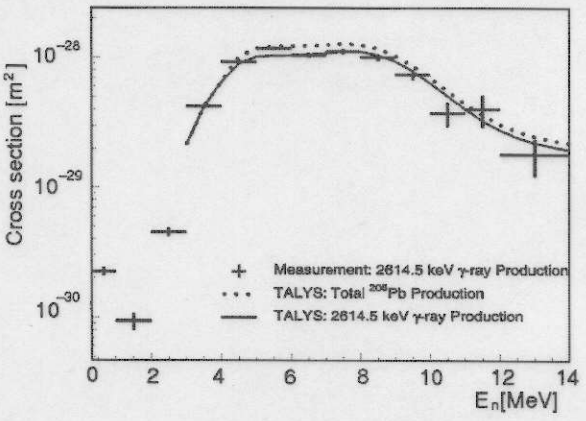

Figure 11. The cross-section for 2614.5 keV prompt γ-ray production in natural lead in function of neutron energy. The crosses represent experimental points normalized to TALYS predictions. The dotted line represents the total cross-section for the production of ^{208}Pb via (n, n') and capture reactions. The solid line represents the cross-section for the ^{208}Pb fundamental transition at 2614.5 keV

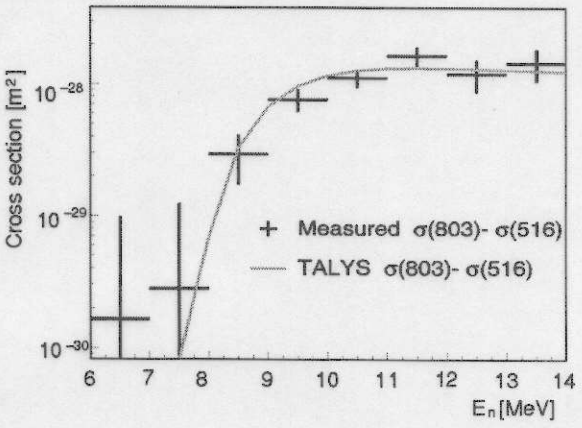

Figure 12. The cross-section for 803.1 keV prompt γ-ray production via the ^{207}Pb (n, 2n) reaction in function of neutron energy. The crosses represent the values derived from the experimental results. The gray line represents TALYS prediction

the isomers. They were, therefore, compared to the difference of TALYS predictions for the ground transition and the isomeric transition cross-sections.

Figure 11 represents the ground transition excitation function for ^{208}Pb. It is fed by the neutron capture on ^{207}Pb and the ^{208}Pb(n, n') reaction. It is not affected by any isomeric state.

The ^{206}Pb and ^{207}Pb excitation curves contain contributions from (n, n'γ) reactions on the same isotope, as well as (n, 2nγ) reactions on the isotope with one more neutron. The contributions from (n, 2nγ) reactions can be disentangled by subtracting (n, n'γ) contributions, as predicted by the code, from the total excitation curve. This was done for the ^{207}Pb(n, 2nγ) reaction, and the result, compared with the relevant code prediction, is shown in fig. 12.

The TALYS code

TALYS is a nuclear reaction calculation code developed by Arjan Koning [15]. It is conceived for analysis and prediction of nuclear reactions in the energy range extending from 1 keV to 200 MeV. The incident particles covered are neutrons, protons, deuterons, tritons, hellions, alphas and photons. At the output, detailed data for all open channels are produced. Many nuclear models are implemented into it, and the code is capable of predicting reactions in the regions that are not covered by the existing experimental database.

The code is organized as a chain of nuclear models, where every model is used at a separate stage in the calculation of cross-sections for the possible output channels. At the first stage, the probabilities of the elastic scattering and the direct component of the inelastic scattering are calculated using the optical model. The optical model also furnishes the reaction cross-section and the transmission coefficients used in the pre-equilibrium and the compound nucleus models. The exciton and Multi-Step Direct/Multi-Step Compound models are used to calculate the preequilibrium reactions. The statistical model used to describe the compound nucleus is an advanced implementation of the Hauser-Feshbach theory. Compound elastic and inelastic scattering are calculated, as well as fission.

CONCLUSION

The feasibility of (n, xn) cross-section measurement by the prompt γ-method has been demonstrated at the GELINA facility up to 14 MeV of neutron energy. Measurements of (n, n'γ) reaction relative cross-sections were performed on ^{206}Pb, ^{207}Pb, and ^{208}Pb, up to the threshold for (n, 2n) reactions. The results were found to be in good agreement with calculations based on existing data. It was possible to estimate the ^{207}Pb(n, 2nγ) reaction cross-section, comparing the measurements with the known data for the ^{206}Pb(n, n'γ) reaction. Absolute measurements of ^{207}Pb(n, 2n) reaction cross-section independent of code predictions are in view for the beginning of 2004, on a pure ^{207}Pb sample and with more beam time. In this way, a significant improvement in statistics is expected, which will allow reaching 20 MeV of neutron energy and a better precision in cross-section values.

REFERENCES

[1] ***, Nuclear Energy Agency – Organization for Economic Cooperation and Development, Comparative Study, Accelerator Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles, Nuclear Energy Agency, 2002

[2] ***, Nuclear Fission and Radiation Protection Projects Selected for Funding 1999-2002, EURATOM, European Commission – Community Research, 1998

[3] Carminati, F., Klapisch, R., Revol, J. P., Roche, Ch., Rubio, J. A., Rubbia, C., An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Beam Accelerator, CERN/AT/93/47 (ET), November 1, 1993

[4] Rubbia, C., Rubio, J. A., Buono, S., Carminati, F., Fietier, N., Galvez, J., Geles, C., Kadi, Y., Klapisch, R., Mandrillon, P. Revol, J. P., Roche, Ch., Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier, CERN/AT/95-44 (ET), 1995

[5] Vonach, H., Pavlik, A., Chadwick, M. B., Haight, R. C., Nelson, R. O., Wender, S. A., Young, P. G., ^{207,208}Pb(n, xnγ) Reactions for Neutron Energies from 3 to 200 MeV, *Phys. Rev., C50* (1952), 4, pp. 1952-1963

[6] Bernstein, L. A., Becker, J. M., Younes, W., Archer, D. E., Hauschild, K., Johns, G. D., Nelson, R. O., Wilburn, W. S., Drake, D. M., Probing Reactions Dynamics with the ^{196}Pt(n, xnγ) Reactions for x ≤ 15, *Phys. Rev., C57* (1998), R2799

[7] Tronc, D., Salome, J. M., Böckhoff, K. H., A New Pulse Compression System for Intense Relativistic Electron Beams, *Nuclear Data for Science and Technology, 228* (1985), pp. 217-227

[8] Salomé, J.-M., Cools, R., Neutron Producing Targets at GELINA, *Nucl, Inst, and Meth,. 179* (1981), pp. 13-20

[9] Warburton, W. K., Momayezi, M., Hubbard-Nelson, B., Skulski, W., Digital Pulse Processing: New Possibilities in Nuclear Spectroscopy, presented at the Conference on Industrial Radiation and Radioisotope Measurement Applications (IRMMA-99), October 3-7, Raleigh, NC, 1999

[10] Jordanov, V. T., Knoll, G. F., Digital Synthesis of Pulse Shapes in Real Time for High Resolution Radiation Spectroscopy, *Nucl. Inst. and Meth., A345* (1994), pp. 337-345

[11] Lukić, S., Baumann, P., Rudolf, G., Analysis of Various Detector Signals Digitized by a 12-Bit Flash ADC, *Proceedings*, 11th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, September 2-6, Pruhonice near Prague, Czech Republic, 2002

[12] Mihailescu, C. L., Principles and Methods for γ-Ray Tracking with Large Volume Germanium Detectors, Ph. D. thesis, Bonn, 2000

[13] ***, Physics Analysis Workstation, CERN Program Library Long Writeup Q121, CERN Geneva, Switzerland

[14] Firestone, R. B., Table of Isotopes, CD-ROM, 8th edition, Wiley – Interscience, 1996

[15] Koning, A. J., Upgrading JEFF-3 with TALYS – Low and Intermediate Energy Data, Speech given at JEFF Meeting, April 24-26, Aix-en-Provence, France

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МЕРЕЊЕ ЕФИКАСНИХ ПРЕСЕКА (n, xnγ) РЕАКЦИЈА НА ПРИРОДНОМ ОЛОВУ МЕТОДОМ ПРОМПТНЕ ГАМА СПЕКТРОСКОПИЈЕ

Нови концепти технологије нуклеарних реактора захтевају прецизне податке о неутронским реакцијама на средњим и високим енергијама. Савремени експериментални подаци у овој области енергија недовољни су, посебно за реакције (n, xn). Поред тога, између различитих база података постоје значајна неслагања.

Недостатак експерименталних података везаних за реакције (n, xn) првенствено је повезан са тешкоћама мерења оваквог типа реакција. Не постоји универзални метод применљив на све постојеће изотопе. Један од могућих метода је употреба γ-спектроскопије и технике мерења времена прелета неутрона. На овај начин директно се мере ефикасни пресеци реакције (n, xnγ). Они даље служе за одређивање ефикасних пресека реакција (n, xn). Овај метод примењен је на узорку природног олова озраченом белим снопом неутрона у Институту за референтна мерења и материјале у Гелу, Белгија.