Angular Distribution of 1.368 MeV Gamma-Rays from Inelastic Scattering of 14.1 MeV Neutrons on ^{24}Mg

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Abstract

In the frame of TANGRA-project at JINR-FLNP (Dubna) we measured the gamma-rays resulting from the inelastic scattering of 14.1 MeV neutrons on magnesium. As a source of neutrons we used ING-27 portable neutron generator of VNIIA (Moscow) where the neutrons are produced in a d-t fusion-fission nuclear reaction, ^{3}H(d,n)^{4}He. The α-particles were registered by a 64-pixel Si charge particle detector embedded in ING-27 vacuum chamber.

The sample tested was a 10cm-thick plastic cube filled with MgO powder. The gamma-rays from the interaction of neutrons with the sample we registered by a Romashka-type Fe-protected array, consisted of 22 hexagonal NaI(Tl) scintillator prisms. The analog signals form all the α- and γ-detectors were collected in list-mode, simultaneously, by a computerized 32-channel data acquisition system (DAQ) from JINR AFI-electronics, which was used, also, for digitizing and storing the waveforms on the computer hard-drive for further off-line analysis with CERN-ROOT modular scientific software toolkit.

Using the time-correlated associated particle method (TCAPM), also known as tagged neutron method (TNM), the influence of the background radiation on the collected gamma-ray spectra was drastic reduced.

We obtained the angular distribution of 1.368 MeV gamma-rays from ^{24}Mg(n, n′γ)-reaction in the range from ~15^{O} to ~165^{O} with a good statistical accuracy.

Here we report the results from our first experiment in comparison with the available data from the other authors. Further experiments are foreseen.

Keywords: ING-27; 14 MeV tagged neutrons; tagged neutron method; inelastic neutron scattering; gamma-rays angular distribution; NaI(Tl) multi-detector system

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Introduction

Magnesium (Mg) is one of the most important elements together with C, N, O, B, Al, Si, from fundamental and application (practical) points of view. That is why it is an object of investigation in different branches of physics: geophysics, planetology, astrophysics, nuclear physics. Magnesium is a fundamental building block of the terrestrial planets, constituting ~15% of Earth's mass. Compared to the 'solar' composition of the primordial disk, it is well established that the Earth is depleted in Mg by ~20%, relative to more Cosmo chemically refractory elements as Al, consistent with increasing terrestrial depletions of elements with higher volatility [1]. The atomic weights and isotopic compositions for magnesium are shown in Table 1.

Table 1. Atomic weights and Isotopic compositions for Magnesium

Isotope	Relative (to ^{12}C) Atomic Mass	Isotopic Composition	Standard Atomic Weight
12 Mg 24	23.985041697(14)	0.7899(4)	[24.304, 24.307]
25	24.985836976(50)	0.1000(1)	
36	25.982592968(31)	0.1101(3)	

Accurate determination of the Magnesium isotopic composition of the Moon, rocky planets and achondrites is important for Mg isotope studies of surface processes on Earth, as well as, for using Mg-isotope data to understand evaporation and condensation effects in the solar nebula, the behavior of Mg-isotopes during magmatic differentiation processes in different planetary bodies, and to evaluate the extent of Mg isotopic heterogeneity in the solar system. High-precision Mg-isotope measurements of terrestrial and extraterrestrial (asteroids, Lunar) material by different methods are used for determining the relative and absolute Mg-isotope compositions of the bulk samples from the oceanic mantle. Magnesium isotopes are also used as Tracer of Crustal materials in volcanic arc Magmas.

Magnesium is used in flashlight photography, flares and pyrotechnics, including incendiary bombs. It is one third lighter than aluminum, and in alloys is essential for airplane and missile construction. The metal improves the mechanical, fabrication, and welding characteristics of aluminum when used as an alloying agent. Magnesium is used in producing nodular graphite in cast iron, and is used as an additive to conventional propellants.

For modern nuclear science and applications there is need from more precise and detailed neutron-nuclear data [2–4]. In this field Magnesium and its substances play an important role.

Magnox is an alloy, mainly of Magnesium with small amounts of Aluminum and other metals, used in cladding unenriched uranium metal fuel with a non-oxidizing covering, to contain fission products in nuclear reactors. Magnox is short for Magnesium non-oxidizing. This material has the advantage of a low neutron capture cross-section, but has two major disadvantages: it limits the maximum temperature (to about 415^{o}C), and hence the thermal efficiency of the plant and it reacts with water, preventing long-term storage of spent-fuel under water in spent-fuel pools. The Magnox alloy Al80 has a composition of 0.8% Aluminum and 0.004% Beryllium.

MgO is prized as a refractory material, i.e. a solid that is physically and chemically stable at high temperatures. It is while used in in dry process plants (as one of the components in Portland cement), in medicine (for relief of heartburn and dyspepsia, as an antacid, magnesium supplement, and as a short-term laxative), in nutrition as a food additive (known as E530), animal feed, in agriculture as a commercial plant fertilizer, in radio-electronics as an insulator in heat-resistant electrical cable and a protective coating in plasma displays, etc. It is also used as a reducing agent in the production of pure uranium and other metals from their salts. In nuclear industry MgO is packed around transuranic waste at the waste isolation plants, to control the solubility of radionuclides.

Mg presents as ingredient of the core in the conceptual design of European Facility for Industrial Transmutation (EFIT) of U-free waste, Pu and minor actinides (MA). It can be a pure-lead cooled reactor, working at thermal power of about several MW power, aiming at high-performance and flattening of the radial power distributions in fuel elements with different MgO matrix content and suitable pin diameter, provided considerable burning of Pu and MA.

High-quality nuclear data are required for reliable design calculations of fusion and Generation IV neutron-nuclear reactors as well as analyses related to their safety, licensing, waste management, and decommissioning issues. The Generation IV Roadmap selected the sodium fast reactor (SFR) concept as one of the six technologies for further development under Generation IV. The Mg-isotope ^{24}Mg is produced in SFR coolant, as sodium (Na) is activated by neutron capture (the activation product ^{24}Na is short-lived with 15 h half-life and decays in the stable ^{24}Mg that influence k_{eff} of the reactor.

The study of the inelastic scattering (INS) of fast neutrons is of considerable theoretical and practical importance. From theoretical point of view such studies provide information about the level structure of stable nuclei. Information concerning inelastic scattering cross sections (CS) of neutrons can be obtained also by registering the gamma-ray spectra. This method is widely used, because it gives the possibility not only of establishing a scheme for nuclear energy levels, but also of determining the value of the excitation cross-sections of the individual levels. The use of pure isotopic targets (scatterers) permits unambiguously to interpret the experimental results.

The scheme of *n*-scattering on an A-nucleus via forming and decay of a compound nucleus system (CN) is shown in Fig. 1. Because the probability for emission of gamma-ray of multipolarity *l* is proportional to its energy as $\sim E^{2l}$, the probability for CN-decay directly to the ground state (GS) is $\sim 10^3$ times higher than the preliminary emission of gamma-ray, Fig.1(a). That is why it is assumed that the inelastic scattering follows the scheme of Fig.1(b), and that the loss of energy of the neutron, measured in the coordinate system in which the center-of-mass (CM) is at rest, is equal to the excitation energy of the residual nucleus. The practical value of these studies is due to the importance of the inelastically scattered neutrons in the operation of the fast-neutron reactors and the new reactor concepts. Knowledge of the Neutron Inelastic Cross-Section and spectra of the inelastically scattered neutrons and gamma-rays is essential to the provision of a sound theory of the fast reactors.

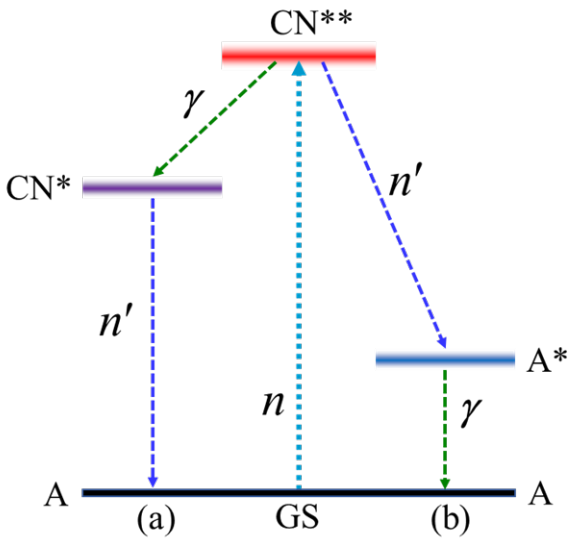


Fig.1. The scheme of n-scattering. A–scattering nucleus, CN–compound nucleus (A+n).

Most gamma rays, produced by fast neutrons, are made by inelastic-scattering reactions, e.g., ^{12}C(n,n′γ)^{12}C, ^{14}N(n,n′γ)^{14}N, ^{16}O(n,n′γ)^{16}O, ^{24}Mg(n,n′γ)^{24}Mg,with the gamma-ray emitted from an excited level of the target nucleus.

The γ-production cross-sections from neutron inelastic scattering on ^{24}Mg were measured for neutron energies up to 18 MeV at GELINA (Geel Linear Accelerator) [6]. They used GAINS (Gamma Array for Inelastic Neutron Scattering) spectrometer with seven large-volume high-purity germanium (HPGe) detectors placed at 110° and 150° with respect to the beam direction. Their results for $^{24}Mg(n,n'\gamma)^{24}Mg$ reaction is shown in Fig. 2.

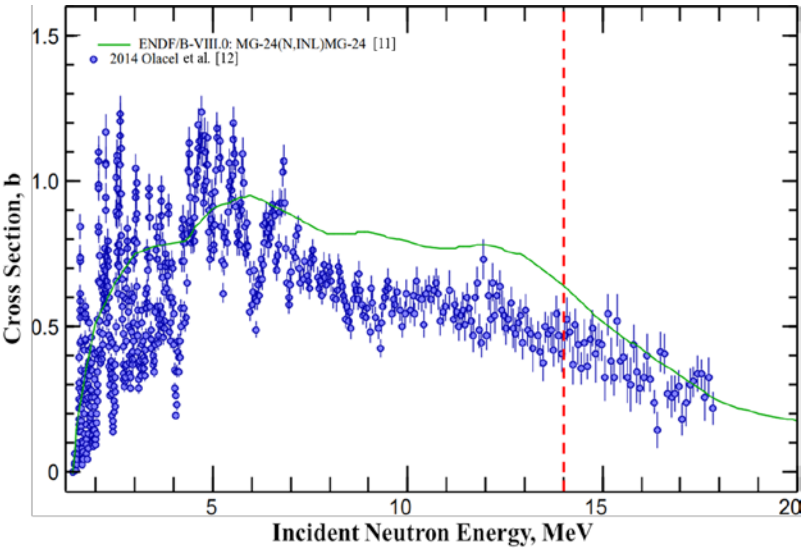


Fig. 2. Total inelastic cross-section for the $^{24}Mg(n,n'\gamma)^{24}Mg$ reaction. The line displays the evaluated values from ENDF/B-VIII.0 [5]. The full-circles with error-bars represent the result of the experiment by Olacel et al. [6].

The measurement of angular distributions (differential cross-sections) of gamma-rays, produced in the inelastic scattering of neutrons with nuclei, is one of the important experimental means of studying the nuclear level schemes. A systematic study over nuclei of different elements can lead to an insight into the nuclear reaction mechanisms. A comparison of the experimental excitation functions and angular distributions with the Hauser-Feshbach and Satchler formalisms, checks the validity of the statistical assumption in the compound nucleus formation. In this direction, the study of nucleon interactions with light nuclei is of great interest from early 60s till now.

In nuclear spectroscopy, the analysis of angular distribution is an important tool to determine the spins of states and the γ-ray intensity. Angle-differential (n,n') nuclear data is notoriously difficult to measure due to the difficulties involved in measuring the neutron energy and the absence of facilities supplying intense neutron beams of fast neutrons. An alternate approach to determine (n,n'γ) cross- sections involves measuring the prompt γ-rays emitted from the excited states populated via inelastic scattering, e.g. (n,n'). These data can be used to improve modelling for non-destructive assay of materials using active neutron interrogation. The 14-MeV neutron capture cross-section, as is well known, is quite small, and its contribution can be neglected. The reaction (n, 2n) has a threshold of 17 MeV, while the cross-sections of the (n, α) and (n, np) reactions have not been measured. The neutrons of different energies are used to test and validate materials suitable for harsh neutron environments, such as a fusion reactor, Fusion technology, Electronics and its application, Material science, Fundamental physics, Industrial applications, Metrology, Neutron radiation biology, therapy and pharmaceutics, Training and neutron science testing. Having 14-MeV kinetic energy, the incident neutron can excite the Mg-nucleus to higher excited state. After an incident neutron forms a compound nucleus, the excited Mg* decays to the ground state after some time by releasing a gamma-quantum of exactly the excitation energy.

Time-Correlated Associated Particle Method (TCAPM)

The TCAPM, also known and Associated Particle Technique (APT) or Imaging (API), as well as Tagged Neutron Method (TNM), is based on the advantage given by the kinematics of the binary (d-t)-fusion reaction, in which the reaction products, namely, neutron and alpha-particle are irradiated in opposite direction, in center-of-mass frame (CM) (Fig. 3).

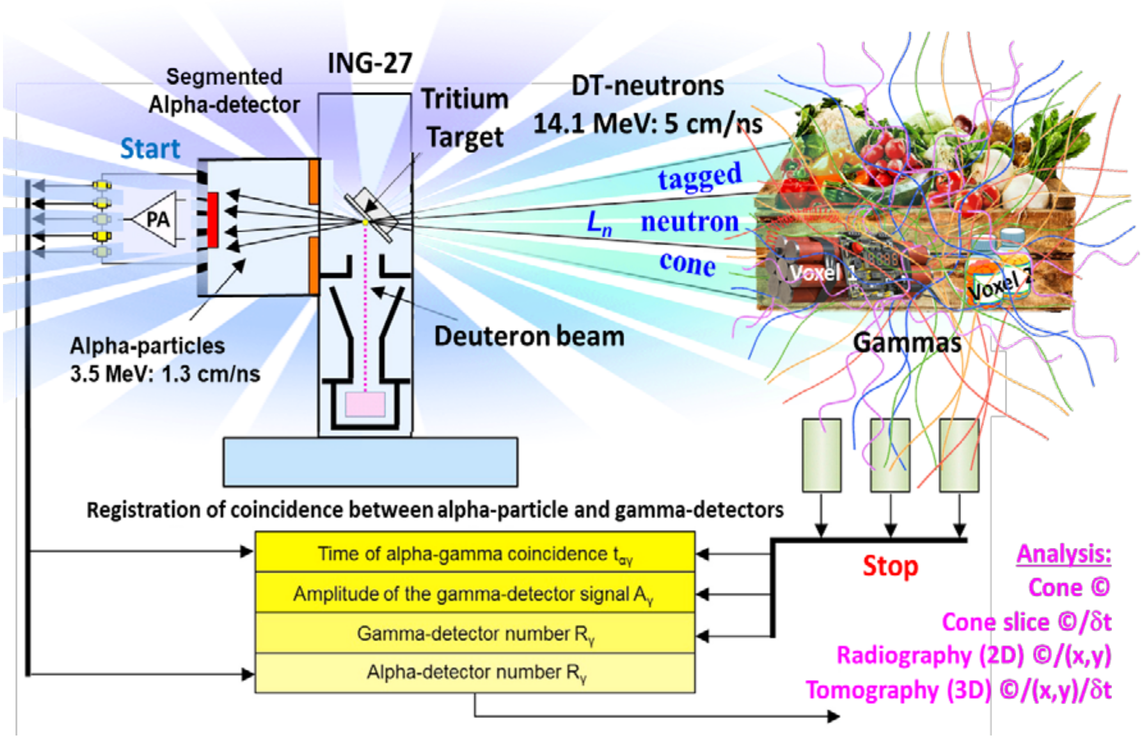


Fig. 3. TCAPM: The 14-MeV neutron is tagged in time and direction by detecting the associated α-particle, emitted in opposite direction, by a 64-pixel Si α-detector. Recording the coincided pulses from the α-particle and γ-ray detectors in different time-windows, one can investigate the content of any voxel of the target object [7].

The well-established associated-particle technique is distinguished by the source neutrons being tagged in time and direction by the particles, which are simultaneously emitted in the nuclear reaction generating the neutrons. Associated Particle Imaging (API) has been applied to bulk sample analysis due to the emergence of the associated-particle sealed-tube neutron generator (APSTNG), making use of the $^{3}H(d,n)^{4}He$ reaction. In the APSTNG, deuterons are accelerated to 100 keV, producing 14.1-MeV neutrons and 3.5 MeV alpha-particles, which are emitted in opposite directions, as illustrated in Fig. 3 [7]. Each alpha-particle, which is detected in the position-sensitive detector, tags the direction of the associated neutron. These neutrons then scatter inelastically on nuclei in the interrogated material, producing characteristic γ-rays in a similar fashion to the available fast-neutron techniques (FNA, PFNA and PFTNA). Knowledge of the direction and speed (5.2cm/ns) of the neutron and the speed of the γ-rays (30 cm/ns) allow the position of the scattering nuclide to be located in space. The main advantage of this approach is that the interrogating neutron beam does not need to be pulsed, allowing the use of cheaper sealed-tube neutron generators. However, these generators do have a finite lifetime and typically need to be replaced after ~800-900 hours, if operated to produce $\sim 10^7$ neutrons per second.

Experiment Setup Model Simulation

In the framework of TANGRA project [8], using GEANT4 simulation toolkit we modelled the geometry of the experimental setup and determined the timing and energy characteristics of gamma-rays from $^{24}Mg(n,n'\gamma)^{24}Mg$ for “Romashka” gamma-ray detector system. This multi-detector γ-ray detecting system consists of 22 hexagonal NaI(Tl) radiation detectors, situated around the target-sample (Fig. 4, left). This geometry allows measuring the angular distribution of characteristic gamma-rays (CGR) from the INS of 14-MeV neutrons on ^{24}Mg with a good angular resolution, while preserving an optimal efficiency of their registration. The expected time-resolution function of the system, as well as the timing- and energy-

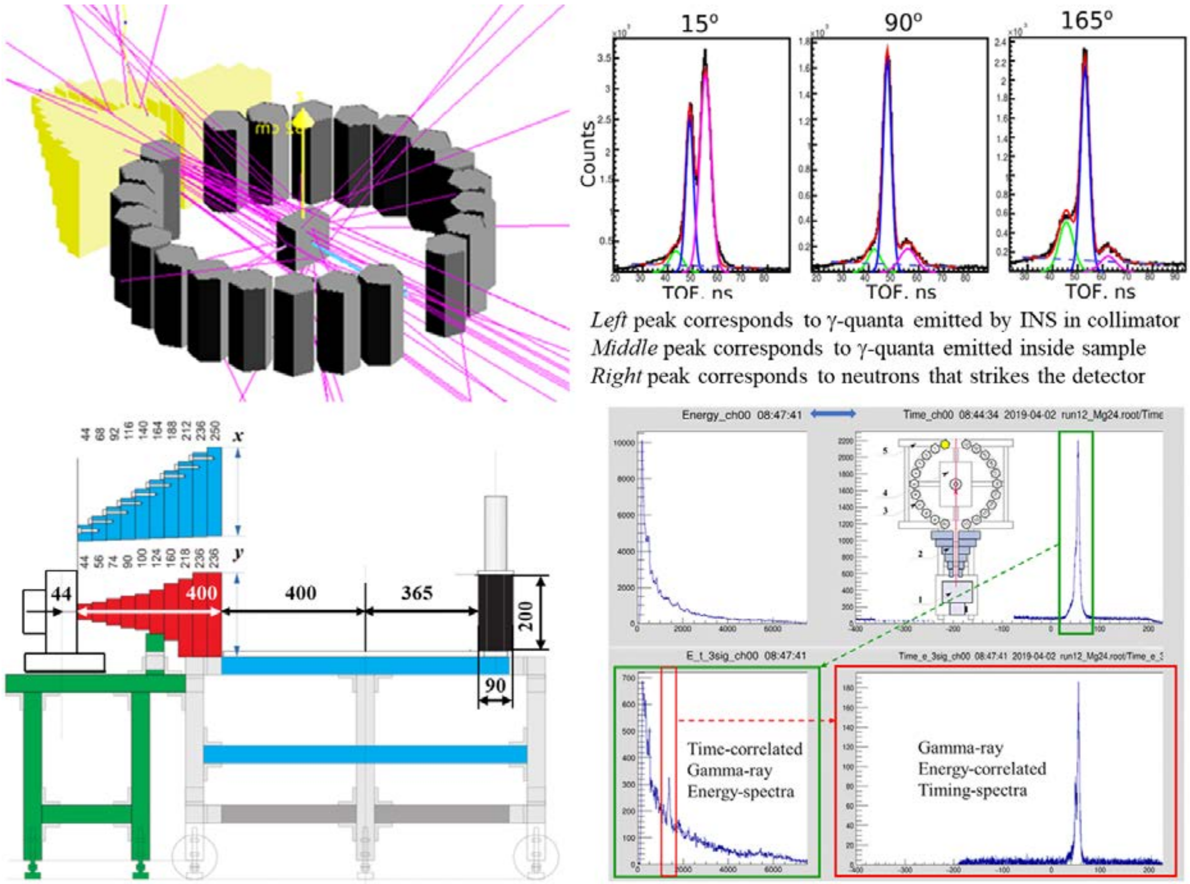


Fig. 4. GEANT4 simulation of TANGRA NaI(Tl) "Romashka" setup (left), the gamma-ray timing spectra (top right), the time- and energy- correlated timing- and energy- spectra (bottom right).

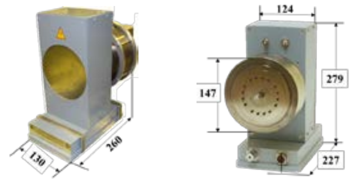
spectra at 3 angles (15^O, 90^O, 165^O) of registration of CGR, relative to the direction of the incident neutrons, are shown in Fig. 4, top-right. The contribution from the gamma-rays, originating from different parts of the model setup, is clearly seen and can be distinguish by using the time-correlated associated particle method and analyzing the data in time- and energy- windows (ToF-Energy gating).

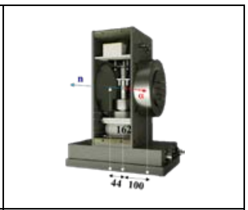
Experimental Setup

For investigating the energy spectra and angular distribution of gamma-rays from INS of 14-MeV neutrons on the nuclei of ^{24}Mg we designed, constructed and used 3 multi-detector, multi-purpose, multi-functional, mobile TANGRA system setups [9]. They consist of ING-27 portable generator of 'tagged' neutrons with energies of ~14.1 MeV, with or without an iron shield-collimator, 2D fast-neutron beam profilometer [10], arrays of neutron-gamma detectors in geometry of daisy-flower ("Romashka", "Romasha", HPGe), and a 32-channel computerized system for data acquisition and analysis (DAQ).

The Portable Neutron Generator ING-27 is a D-T Neutron Generator, manufactured by VNIIA (Moscow, Russia) that utilizes $^{3}H(d, n)^{4}He$ reaction to produce 14-MeV neutrons and has a pixelated charge-particle detector, embedded in its sealed-tube vacuum chamber. The main characteristics of ING-27 are listed in Table 1. The beam of deuterons is accelerated up to ~120 keV (in Lab-frame) and bombards a tritiated Ti-target (TiT) in the generator assembly. The generator has a rated 14-MeV neutron output of up to 10^{8} n/s in 4π. The main advantages of a D-T neutron generator with built-in position-sensitive detector of accompanying α-particles over an isotopic sources like ^{252}Cf, ^{210}Po-, ^{241}Am-, $^{238,239}Pu$-Be are: 1) neutrons with higher energies, produced in D-T fusion reaction, having higher cross-sections of inelastic scattering on nuclei of light chemical elements; 2) position sensitivity, which provides information about which area of space is actually being investigated, helping to extract events coming from small objects, "hidden" inside a large volume of "parasitic" material; 3) neutron generator can be switched off, making it safe during transportation and storage; 4) the activation of the investigated objects and the generator's constructive materials is negligible.

Table 1. Main characteristics of ING-27





Characteristic	Value
TiT-to-front distance	44.0 ± 1.4 mm
TiT-to-α-detector distance	100 ± 2 mm
Power supply voltage	200 ± 5 V
Max Power Supply Current	300 ± 30 mV
Consumed Power	< 40 W
Continuous Mode, n-energy	14-MeV neutrons
Initial Intensity	> 5.0 x 10^{7} n/s/4π
Final Intensity	> 2.5 x 10^{7} n/s/4π
Double-side Si α-particles detector	
Number of pixels	64 (8x8 strips)
Pixel area	6x6 mm^{2}
Distance between strips	0.5 mm
Voltage bias	–250V DC
Dark current	< 5 μA
n-tube life-time	> 800 h
ING-27 <Duty time>	> 18 months
Weight: ING-27	7.5 ± 0.5 kg
Power and Operation Unit	2.7 ± 0.3 kg

The TANGRA NaI(Tl) setup, consisted of ING-27 and "Romashka" gamma-ray spectrometer, built according to GEANT4 simulation studies, is shown in Fig. 5, where some important information on the DAQ and main counting and spectrometric characteristics of the experimental system is given, also. The analogue signals from the α-particle and γ-ray detectors are fed to a 32-channels computerised data-acquisition (DAQ) system, where after digitizing the waveform are saved in list-mode (consequently one-by-one) by ADCM-software. List-mode files contain energy (ADC number) of each event detected along with a time-stamp when the event happened. Offline, the saved waveforms are analysed with ROMANA software, by which are determined the time-of-registration and the amplitude of each digitized signal, and the timing and amplitude (energy) spectra histograms are constructed. The procedure is depicted in Fig. 4, bottom right.

The gamma-ray efficiency of every NaI(Tl) detector (gamma-ray full-energy peak) was determined at various gamma-ray energies, using standard point-like gamma-ray sources ^{137}Cs (661.8 keV), ^{60}Co (1173 keV, 1332 keV) and a $^{238}PuBe$ neutron-gamma source (the shape of its gamma-ray energy distribution is dominated by the 4.44-MeV gamma-ray, associated with the decay of the first excited 2^{+}-state of ^{12}C ($\alpha + {}^{9}Be \rightarrow n + {}^{12}C^{*}$) with a 4.44-MeV gamma-quantum). The results from the measurements were in very good agreement with those obtained by GEANT4 software.

Two Mg-contain samples of different type and shape were used: a plastic box (10x10x10cm) filled with high-purity MgO and an Al-box (6x6x14cm) filled with fine metallic Mg-chips. The sizes of the samples were optimized by GEANT4 simulations to minimize the fast neutron attenuation and gamma-ray absorption.

In the measurements only one tagged neutron beam (one α-pixel detector) was used to avoid the correction of the angular distributions of the gammas, caused by INS of neutrons from the nearby tagged neutron beams that touched the samples at average angles $\sim 4^o$, relative to the used one. A photo of TANGRA "Romashka" setup, together with some important characteristics (and details) of its basic components, are shown in Fig. 5.

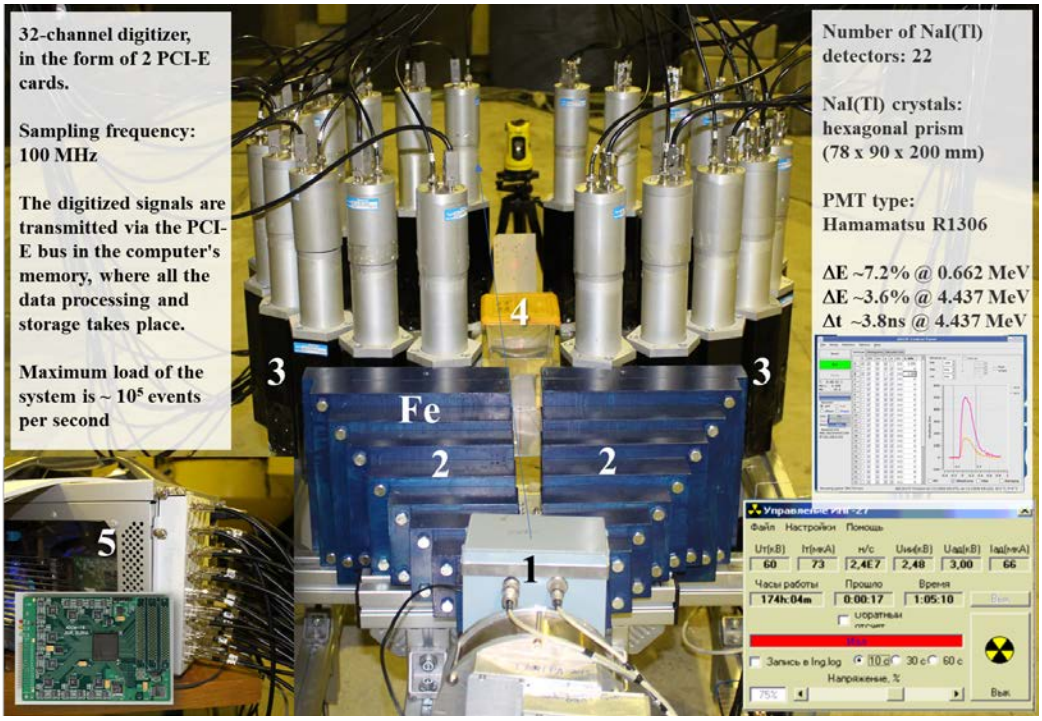


Fig. 5. Experimental setup: 1 – ING-27, 2 – 40cm-thick Fe shielding-collimator, 3 – NaI(Tl) probes, 4 – target, 5 – computerized AFI Electronics ADCM DAQ.

Experimental Results Analysis and Interpretation

A typical gamma-ray energy spectrum, measured with this setup, is shown in Fig. 6. This energy spectrum is of the gamma-rays from a time-interval of 6 ns (T-window {54-60} ns, Fig. 4, top right) and corresponds mainly to the interactions of neutrons with the nuclei of the sample, because for this time-interval the 14-MeV neutrons, covering a distance of ~30cm, can inelastically scatter mainly on the nuclei of Al support. The contribution of random coincided pulses (uncorrelated background) can be estimated from a time-interval of the same length taken outside the true-coincidence window. The correlated radiation background can be reduced by taking narrower true-coincidence time-windows or can be subtracted from the energy spectrum by approximating it with a spline function (dashed line in Fig. 6). Because of the moderate energy resolution of NaI(Tl) not many gamma-lines can be resolved. Particularly it can be said for gamma-line at ~3866 keV from $3^+ \rightarrow 2^+$ transition in $^{24}Mg^*$, as well as, for the gamma-lines from $^{16}O(n,n'\gamma)$-reaction above 5 MeV, where the efficiency of registration of gamma-rays with these energies is also smaller.

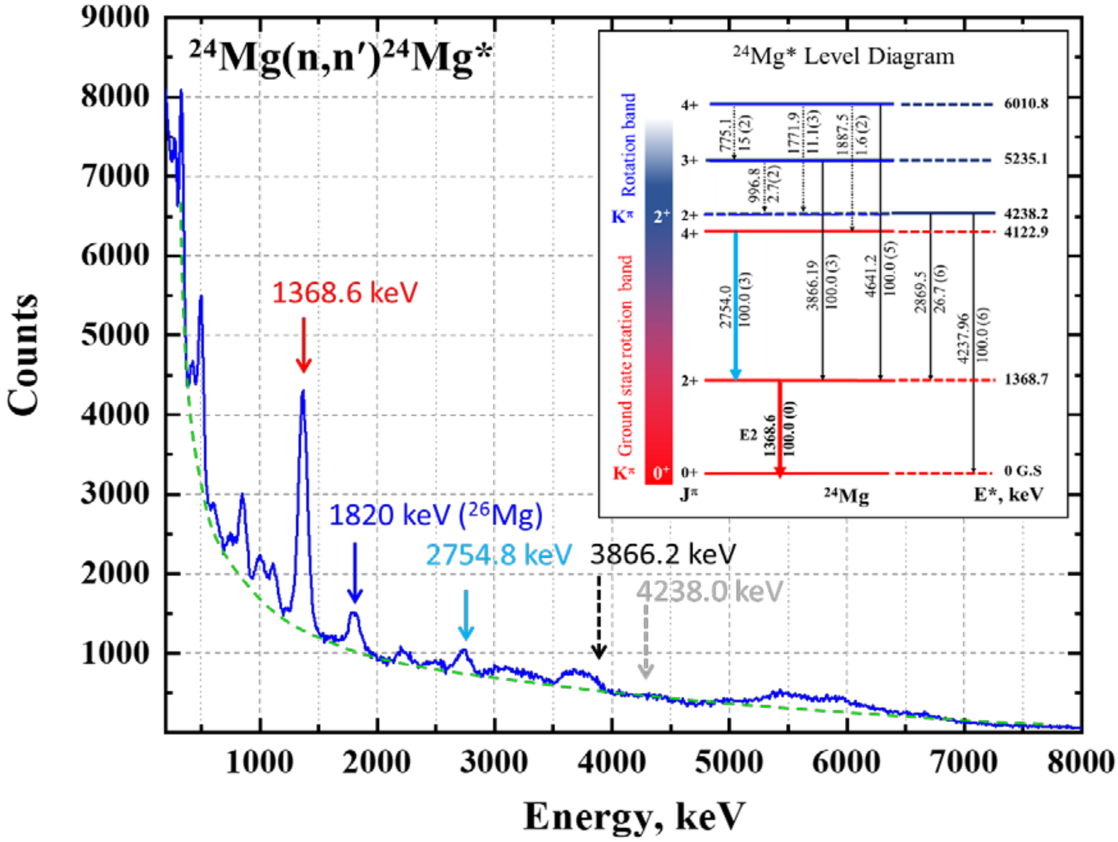


Fig. 6. Gamma-ray energy spectrum, measured with "Romashka" NaI(Tl) system and the decay scheme of ^{24}Mg*, exited by INS of 14.1-MeV neutrons

The weaker peaks at ~ (1014, 2211, 3004) keV are from ^{27}Al(n,n′γ)-reaction, those at ~ (847, 1038, 1238) keV are from INS-reactions in the Fe shielding-collimator: ^{56}Fe(n,n′γ)-reaction. The strongest line produced by inelastic reactions on ^{24}Mg is at ~1369 keV, resulting from transitions from the first excited state to the ground state: $2^{+}\rightarrow 0$, the small peak at ~2755 keV can be from transition $4^{+}\rightarrow 2^{+}$. After subtracting the background contribution, the peak at ~1369 keV was approximated by a Gauss function and its parameters (the peak energy, area and standard deviation) were determined by least-square fit procedure. It was done for the energy spectra from all 22 NaI(Tl) gamma-spectrometers. The full-energy peak area values were corrected for different intrinsic and geometrical efficiencies of the gamma-detectors. The corresponding values in the intervals [15^{o}, 135^{o}] and [-15^{o}, -135^{o}] (the angles are related to the tagged neutron beam axis) with a step of 15^{o} were averaged and the mean values were used to plot the angular distributions of gamma-rays from INS-reaction on some light elements [11-12]. The results for Mg were normalized to the A-value at 90^{o} in order to compare them with the data from other authors [13–19], which is shown in Fig. 7. It is seen that our experimentally determined anisotropy (A) of irradiation of gamma-rays with energy of ~1369 keV from first 2+ state of ^{24}Mg* nucleus, in the interval of angles between ~45^{o} and ~135^{O}, and in the limits of the shown experimental uncertainties, are in reasonable agreement with the data of the cited authors for ^{24}Mg(n,n′γ)-reaction for neutrons with energies between ~2.6 MeV and ~14.7 MeV (the INS-reaction threshold energy E_n^{thr}=1.4 MeV, Tab. 2). Below ~45^{O} and above ~135^{O} a decreasing of the anisotropy is reviled. The A-values at 15^{o} (±4^{o}) and 165^{o} (±4^{o}), measured for the first time, keep this tendency.

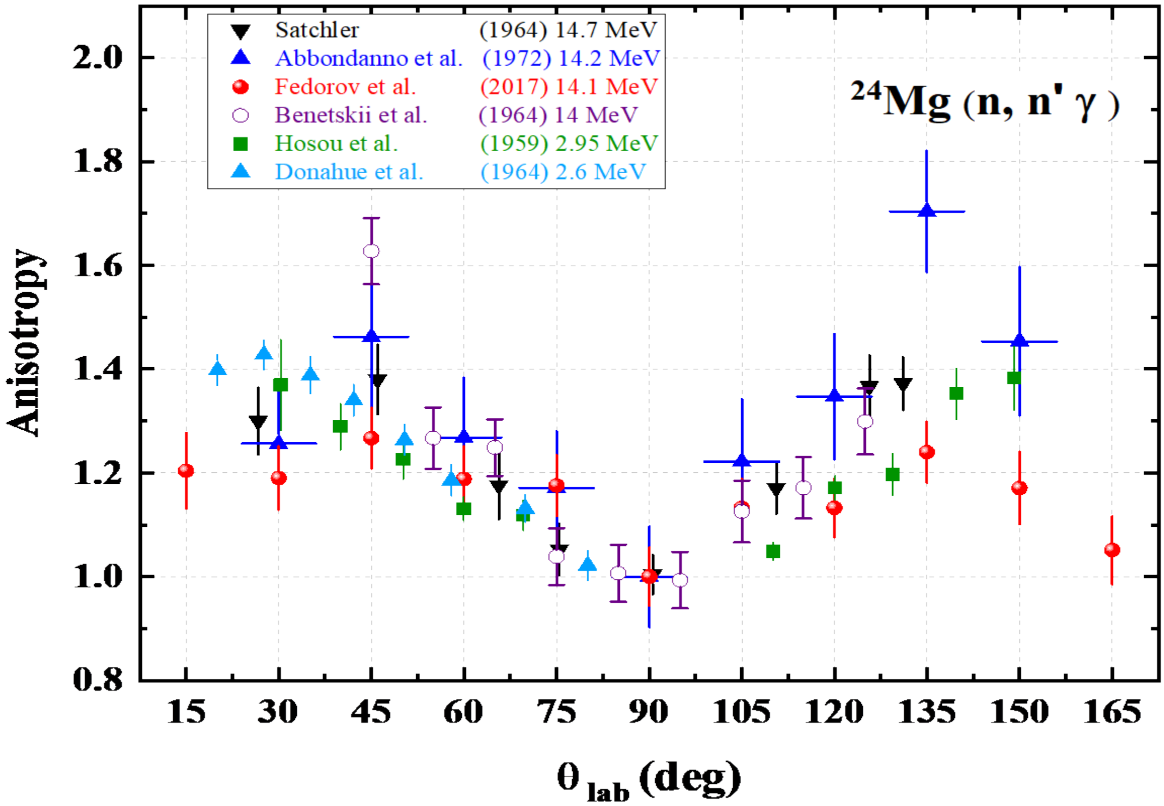


Fig. 7. Comparison of the anisotropy of irradiation of γ-rays during INS-reactions of 14.1-MeV neutrons with ^{24}Mg (2+, 1368.67 keV level), obtained in different experiments.

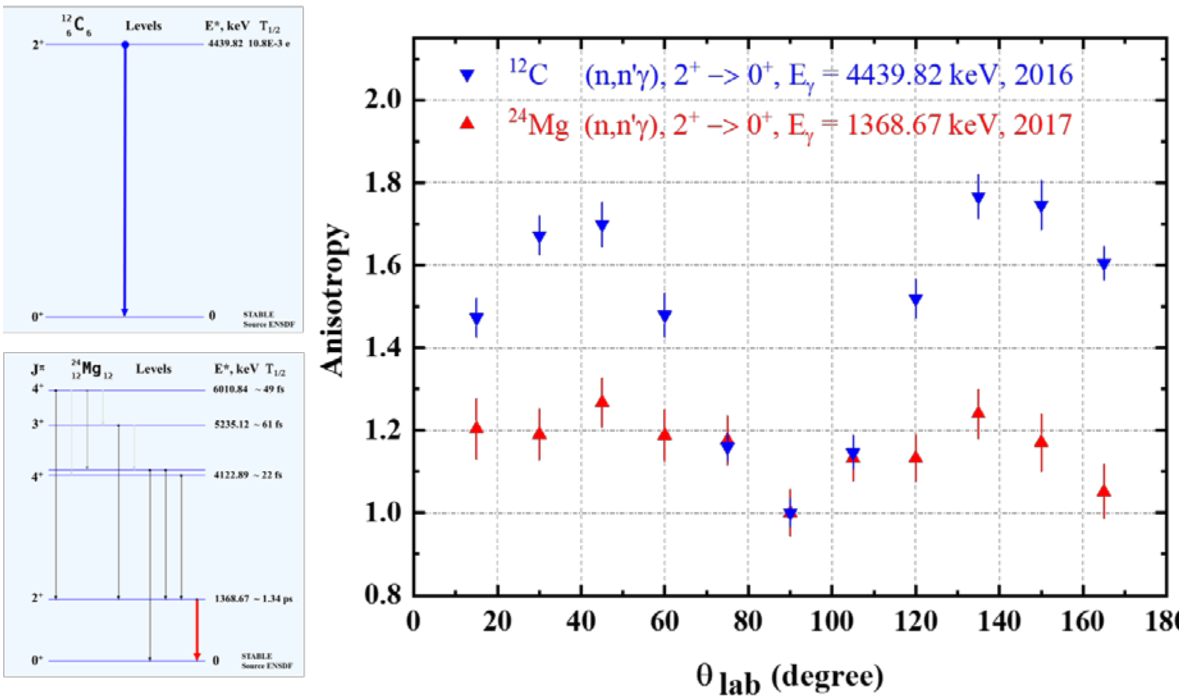


Fig. 8. Anisotropy of irradiation of γ-rays during INS-reactions of 14.1-MeV neutrons with ^{12}C (2+, 4439.82 keV level) and ^{24}Mg (2+, 1368.67 keV level)

Table 2. Main characteristics of the 1st excited state of the nucleus formed by INS-reaction.

Reaction	E_n^{thr}, MeV	σ_{γ}, mb	$J^{\pi}\to 0$	$T_{1/2}$	E_{γ}, keV	I_{γ}, %	M_{γ}
^{12}C (n,n′γ)	4.8	450	$2^{+}\to 0$	10.8 meV	4438.94	100	E2
^{16}O (n,n′γ)	6.6	265	$3^{-}\to 0$	18.4 ps	6128.63	100	E3
^{24}Mg (n,n′γ)	1.4	600	$2^{+}\to 0$	1.33 ps	1368.63	100	E2
^{27}Al (n,n′γ)	4.8	220	$7/2^{+}\to 5/2^{+}$	26.6 fs	2212.01	100	M1+E2

In (Fig. 8, left) are shown the gamma-decay scheme of exited nucleus $^{12}C^*$ (the only one level) and $^{24}Mg^*$ (only levels build on the base rotation band with $K^{\pi}=0^{+}$ are shown).

In (Fig. 8, right) we show the anisotropy coefficient as function of the angle of irradiation of the gamma-rays during the decay of 1368.67 keV 2+ level of $^{24}Mg^*$ to the 0-level (ground state, g.s.) in comparison with the A-values for 4.439.82 keV 2+ level of $^{12}C^*$, obtained by us with the same experimental setup [11]. It is well known that the angular distribution of the first γ-ray from the decaying cascade is less isotropic than that of the following γ-rays because each successive gamma-emission causes a spread in the direction of the CN-spin. The feeding of low-laying levels from higher lying also attenuates the angular distribution, as can be seen in Fig. 8 for the anisotropy of the first γ-ray from 2^{+} excited states of $^{12}C^*$ and $^{24}Mg^*$ in ^{12}C(n,n′γ) and ^{24}Mg(n,n′γ) reactions.

Conclusions and Outlook

Using ING-27 portable generator of 14-MeV "tagged" neutrons, 22 NaI(Tl) gamma-ray spectrometer "Romashka" and time-correlated associated particle method (TCAPM), we measured the angular distribution of gamma-rays from the first exited state 2+ of ^{24}Mg formed by inelastic scattering (INS) of 14.1 MeV neutrons on the nuclei of this isotope, ^{24}Mg(n,n′γ)-reaction. Our results agree with the data from the literature in the range of their experimental uncertainties. The anisotropy values at ~15^{o} and ~165^{o} are measured for the first time. Meanwhile, we measured the timing- and energy- spectra of gamma-rays from this reaction by a HPGe gamma-ray spectrometer, in order to determine the angle-integrated gamma-ray production cross-sections for each observable transition. A comparison of recorded gamma-ray energy spectra is shown in Fig. 9. Recently, by means of the new constructed 18 BGO array "Romasha" we have measured the angular distributions of gamma-rays from 6 exited states of ^{24}Mg in the angular range from 14^{O} to 136^{O} (step of 14^{O}) with a good accuracy and precision.

The angular distributions for discrete reactions are conventionally given in the Center-of-Mass (CM) frame, while the energy-angular distributions for continuum reactions are conventionally given in the Laboratory (Lab) frame. However, the energy-angular distributions are often given in the CM frame in ENDF. The high-order Legendre polynomials are commonly used to describe the anisotropy of angular distributions.
Because the gamma-ray angular distributions are symmetric about 90^{O} they can be expressed as a series of even order Legendre polynomials (0, 2, and 4) and their coefficient a_o, a_2 and a_4 can be determined. The coefficients of the Legendre polynomials are obtained by a least-squares fit of the measured angular-distribution data. Angle-integrated gamma-ray production cross-sections are obtained by integrating the angular distribution over the full 4π-solid angle. Using the orthonormal condition of the Legendre polynomials, the integrated cross-section becomes $\sigma_{tot} = 4\pi a_o$. The results from the last experiments will be published elsewhere [20].

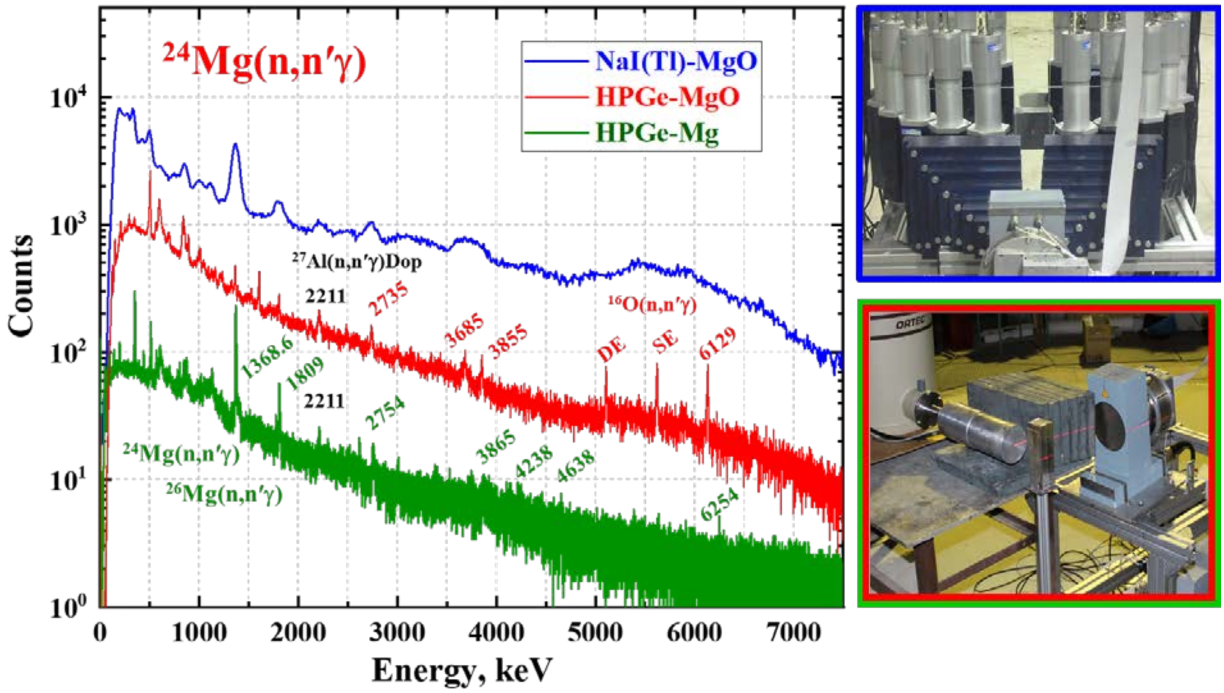


Fig. 9. The energy spectra of γ-rays from INS-reaction of 14.1-MeV tagged neutrons on ^{24}Mg (2+, 1368.67 keV) by "Romashka" (MgO, top), HPGe (MgO, middle) and HPGe (Mg, bottom)

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