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Peculiarities of the modern neutron spectrometry

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Abstract. Neutron spectrometry provides many branches of science and technology with the necessary data. Usually the main part of the data is supplied by powerful neutron time-of-flight spectrometers. Nevertheless there are many other very effective but simpler and cheaper neutron spectroscopy methods on accelerators, suitable for solution of plenty of scientific and applied problems (for example, in astrophysics and radioactive waste transmutation). The methods of slowing-down spectrometry in lead and graphite, generating of neutron spectra, characteristic for nucleosynthesis in the stars, and neutron spectrometry by means of primary γ-transition shift are discussed in the report.

Keywords. Neutron spectrometry; slowing-down spectrometry; nucleosynthesis; Maxwellian neutron spectra.

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> *"One can hardly find another field, the study of which gives so much for expanding the physical horizon, as the neutron physics."*
>
> Prof. F L Shapiro

1. Introduction

Neutron spectrometry is a powerful method of the investigation of atomic nuclei and condensed matter. These investigations supply the necessary data for a very wide spectrum of scientific and technological applications, from the fundamental problems of the structure of matter and the nucleosynthesis in the Universe up to atomic power technologies and the structure of condensed matter. The situation is illustrated in table 1.

The broad variety of neutron spectrometry methods is well-known. The most frequently applied method is the time-of-flight (TOF) method for pulsed neutron sources. To have a good intensity of neutrons on the sample for a long flight path, powerful neutron sources must be used. The examples of many-purpose high intensive neutron spectrometers are:

- ELECTRON LINACS — ORELA (ORNL, USA), GELINA (IRMM, Belgium), IBR-30 (a complex of LINAC and a plutonium buster as a multiplicator of neutrons, JINR, Russia),
- PROTON ACCELERATORS (spallation sources) — LANSCE (LANL, USA), ISIS (RAL, UK), PS-TOF (CERN, Switzerland).

Table 1. Neutron spectroscopy.

Particle physics	Nuclear physics		Condensed matter (CM) physics
Charge of the neutron	Neutron resonances as compound states		CM structure
Dipole moment of the neutron	Nuclear structure and dynamics		CM dynamics
Ultra cold neutrons, $T_{1/2}$ of the neutron	x-Decay of individual states $\mathbf{x} = \gamma, \alpha, \mathbf{n}, \mathbf{p}$, fission,	Nuclear power technologies	
Parity violation	An informative two-dimensional picture (λ_i, f_k)	Nucleosynthesis s-process r-process	

By the way, the combination of an electron accelerator and a subcritical active zone (IBR-30) in Dubna could be named as a prototype of the future safety accelerator-driven subcritical reactor. This facility may be used for the study of the subcritical stability of the accelerator — reactor system.

The investigation of the decay of individual neutron resonances λ_i to different final states f_k of a daughter nuclide gives a very informative two-dimensional picture of the many-channel decay of compound states.

The traditional way of using experimental data:

- Measurements of partial cross sections $\sigma_i(n, x)$, ...$\rightarrow$
- Determination of partial widths Γ_{ni}, Γ_{xi}, ... $\rightarrow$
- Calculation of averaged widths $\langle \Gamma_n^0 \rangle$, $\langle \Gamma_x \rangle$, D...$\rightarrow$
- Testing of nuclear models, usage of the resonance data in applications.

But these high-intensity neutron spectrometers are very expensive and complicated in operation. In many particular cases one may use more effective, simpler and cheaper methods. The measurements of average cross sections of stable and radioactive nuclei, irradiated by neutrons, whose spectra are specific for the neutron fluxes in the stars or in the active zone of a transmutation reactor, will be useful and sufficient as the first step of investigation of the nucleosynthesis in astrophysics and of the problems of transmutation of the radioactive waste. In this case the way of analysis may be shorter:

- Measurement of average cross sections $\langle \sigma(n, x) \rangle$...$\rightarrow$
- Determination of the average parameters $\langle \Gamma_n^0 \rangle$, $\langle \Gamma_x \rangle$, S_0, S_1, $\langle \Gamma_\gamma \rangle$ ...$\rightarrow$
- Testing of nuclear models and applications.

As an example, in figure 1 the analysis of the average cross section of natural indium sample is presented: $\langle \sigma(n, \gamma) \rangle \rightarrow S_0, S_1, S_\gamma$. This analysis was done 40 years ago, but the value $S_0 = (0.24 \pm 0.01) \times 10^{-4}$ [1] coincides very well with the last data $S_0 = (0.26 \pm 0.03) \times 10^{-4}$ from the neutron widths of individual resonances [2].

So, other methods besides TOF spectrometry may be used effectively.

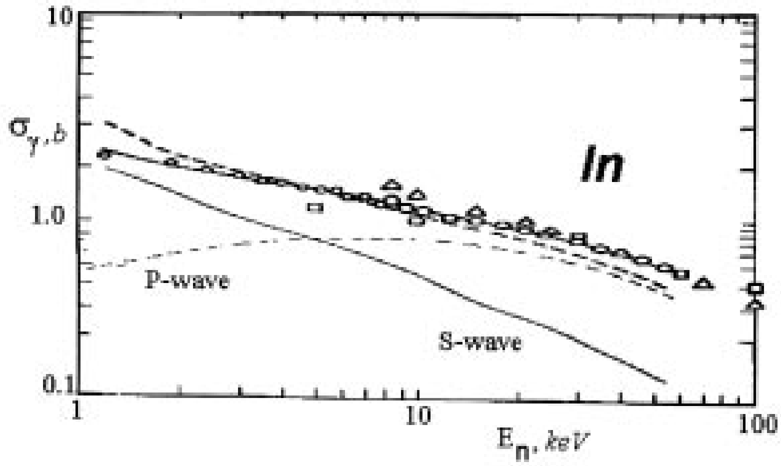

Figure 1. Analysis of the s-wave and p-wave contributions to the average capture neutron cross section of natural In, E_n in keV.

2. Slowing down neutron spectrometry

The methods of slowing down neutron spectroscopy (SDNS) on lead and graphite moderators are useful. A short burst of fast neutrons (time duration 0.1–1 microsecond) is injected into a block of moderator. Usually it is a 1–2 meter cube. The first Pb-SDNS in Lebedev Institute (Moscow, USSR) used the T(d,n)He reaction as a neutron source [3]. At the first step of moderation the inelastic collisions of neutrons take place (in lead — till 0.5 MeV). At a lower energy the moderation is due to elastic collisions, in this case the grouping of neutron velocities in a comparatively narrow interval velocities around a mean value also takes place. The average energy of neutrons (in keV) is simply connected with the time of moderation (in microseconds):

$$E_n = 183/(t+0.3)^2.$$

The energy resolution of this method is about 30% at a neutron energy from 1 eV up to 1 keV and worse at higher energies. This spectrometer worked effectively for neutron energies from 1 eV to 30 keV. It demonstrated the broad capacities of this method for measurements of cross sections in different kinds of neutron reactions [4]. As I know, the Pb-SDNS was created in Trombay [5] but I do not know its fate.

Compared to the TOF method, the lead SDNS gives a 10^3–10^4-fold increase of the neutron flux on the sample for the same intensity of neutron sources. The method is effective for measurements of average cross sections in the keV neutron energy region. Second generation of Pb-SDNS (USA, Japan) used more powerful neutron sources based on electron LINACs and demonstrated the possibility to measure fission cross sections on microgram samples of rare trans-actinides.

2.1 *The third generation of the lead SDNS*

Forty years after the first SDNS, the third generation of SDNS demonstrated its capacity to obtain neutron data, including the capture cross sections of high accuracy for the milligram radioactive samples (see figure 2) [6]. Carlo Rubbia proposed ARC-method (adiabatic resonance crossing) for the effective radioactive waste transmutation. Monte-Carlo simulation of the slowing-down process from the 3.5 GeV neutron energy to 1 eV gave a possibility to make corrections for distortion of neutron flux by the sample. It has significantly increased the accuracy of the cross sections measurement. Take into account that the lead SDNS is very convenient for the investigation of radioactive samples, as the samples are placed inside a big lead prism (figure 2).

2.2 *Graphite SNDS*

It would be interesting to use the specific capacities of the graphite SDNS. In comparison to the lead moderator, the usage of the graphite SDNS will decrease the gamma-background by an order of magnitude and will increase the time- and volume-density of the neutron flux inside the moderator [4]. The last property is very important for investigations in the area of nonlinear neutron spectroscopy, where one nucleus may capture two or more neutrons. This phenomenon is characteristic for the r-process at supernovae explosion, for example. The PS-TOF-facility implemented now in CERN [7] is interesting from this point of view. High time-density of a neutron impulse ($\sim\ 2 \times 10^{16}$ neutrons during a

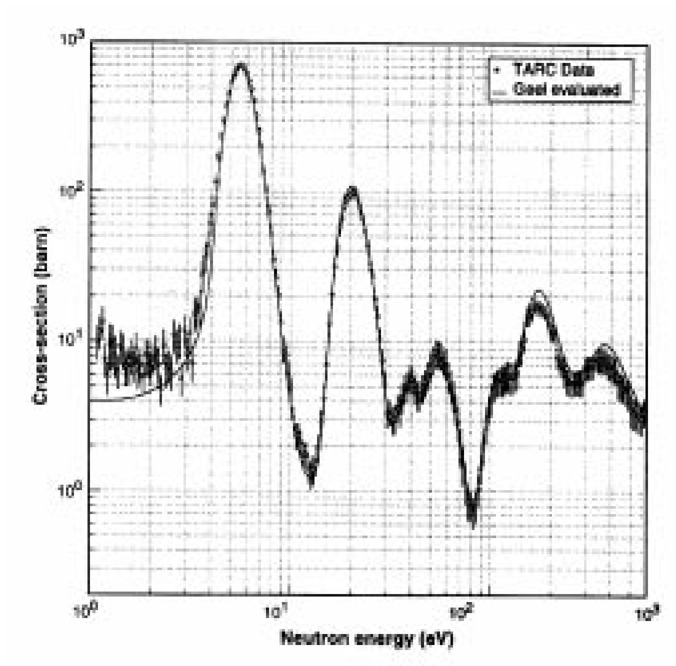

Figure 2. $\sigma(n,\gamma)$ for $^{99}\mathrm{Tc}$. Neutron energy interval $E_n \sim 1$ eV–1 keV.

12 nanosecond pulse) gives better possibilities for investigations in the area of nonlinear neutron spectroscopy. This extremely high neutron density may be important not only for modeling of the nucleosynthesis at supernova explosions, but also for the burning of radioactive wastes in powerful reactors.

3. Neutron spectroscopy specific for astrophysics (nucleosynthesis in the stars)

Practically, the nucleosynthesis by means of consequent capture of neutrons takes place in the stars for the nuclei heavier than Fe (and partly for many lighter nuclei). Roughly, neutron spectra in the stars are having a Maxwellian form with the temperature about 30 keV. According to this, the product of the capture cross section at 30 keV by the abundance of this isotope is close to constant for some intervals of atomic mass. For real modeling of the processes in the star we must know the cross sections of different neutron reactions (see figure 3).

Two sources of neutrons in the stars are proposed now:

- the main neutron source in massive stars: ^{22}Na(α, n) ^{25}Mg — $kT = 30$ keV,
- the source for lighter stars with mass $M < 3M_{\odot}$ ($M_{\odot}$ is the mass of the sun): $^{13}C(\alpha, n)^{16}O$ — $kT \sim 10$ keV.

For testing of different astrophysics scenarios one needs to know the capture cross sections averaged over Maxwellian spectra for kT between 10 and 30 keV for all stable (s-process) and radioactive (r-process) isotopes. There are nice reviews on these processes [8] and [9]. The data of TOF and SDNS about individual resonances may be used for the calculation of

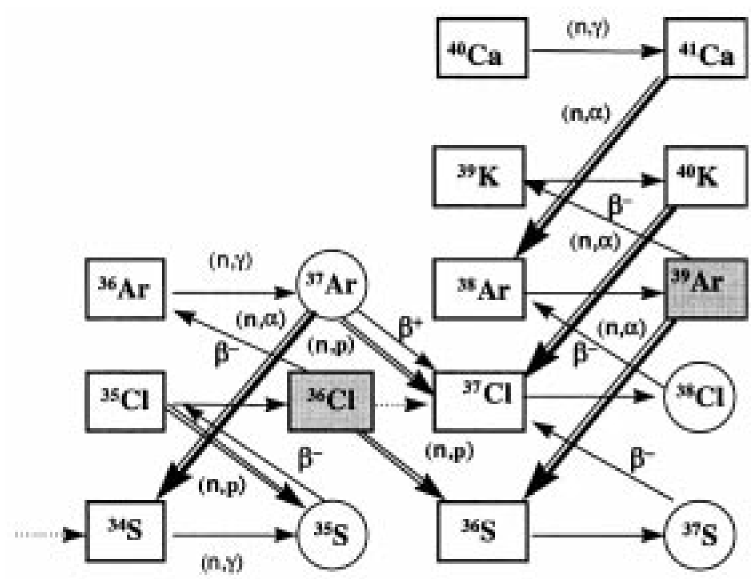

Figure 3. Chart of the nuclides for sulfur-calcium region.

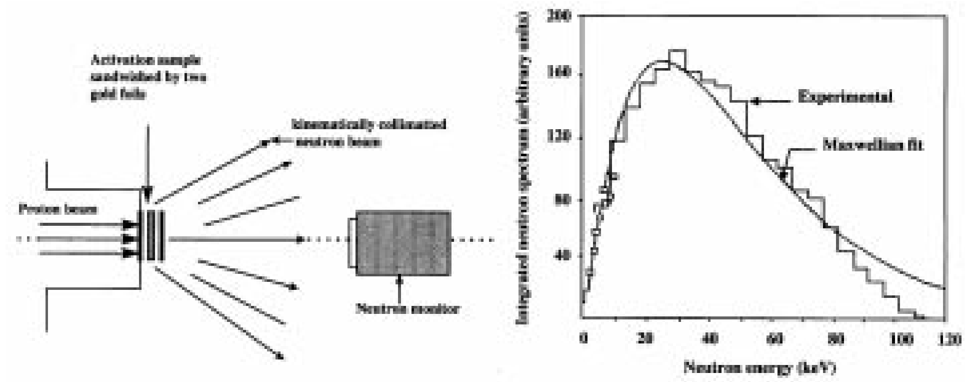

Figure 4. Experimental set-up (left) and Maxwellian neutron spectrum from Li(p,n) reaction on Van de Graaf at $E_p = 1884 + 30$ KeV (right).

averaged cross sections (specific 'resonance integrals' for Maxwellian spectra), but there are some problems (unknown inter-resonance cross sections, rare and radioactive isotopes and so on). It would be useful to consider the possibilities for measurements of the 'resonance integrals' by using the neutron sources with required (Maxwellian) form of neutron spectra. For $kT = 30$ keV the Li(p,n) reaction at $E_p = 1884 + 30$ keV may be used [10] (see figure 4).

4. The graphite prism $(a, b \gg c)$

A moderator of specific form or a combination of moderators and absorbers may be used for generation of a special form of the neutron spectrum. Kazarnovsky and others [11] proposed a special form of graphite and lead moderators to generate intensive Maxwellian neutron spectra corresponding to the stellar temperatures at kT from $kT = 10$ to 30 keV.

Results of the mathematical modeling [11] are presented in table 2 for the prism with $c = 5$ cm and the distance between Li-target and sample $r = 7$ cm (see figure 5).

Unfortunately, the experimental testing of these results of calculation did not done up to now.

Table 2. Maxwellian neutron spectra parameters for graphite prism.

kT, keV	$E_p - E_{\rm thr}$, keV	$\Phi, 10^6 n/({\rm cm}^2{\rm s})$
10	10	0.2
12.5	15	1.3
15	30	5,8

Φ is the neutron flux on the sample at the proton current of 30 μA.

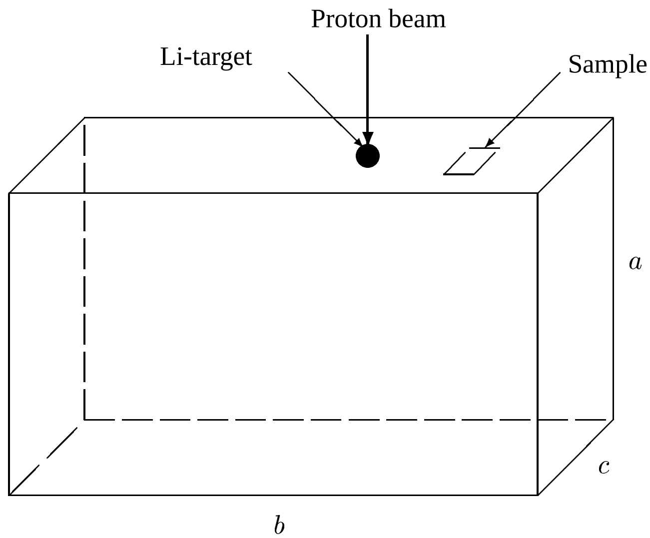

Figure 5. Positioning of the Li-target and the sample on a graphite prism for generating Maxwellian neutron spectra with $kT = 10-15$ keV.

5. Neutron spectrometry by means of the primary γ-transition shift

New possibilities for the measurements of the partial capture cross section and for extracting the radiative strength functions for E1 and M1 multipolarities of γ-transition appears in the method of neutron spectrometry by means of the shift of primary γ-transitions, because of its higher efficiency (luminosity) comparing to the TOF method. This method was implemented for neutrons from the ^{7}Li(p, n) reaction on a Van de Graaff proton accelerator [12].

The energy of a primary γ-quantum $E_{\gamma i}$ to the ith state of the final nucleus is very simply connected with the captured neutron energy:

$$E_{\gamma i} = E^{0}_{\gamma i} + [A/(A+1)]E_n.$$

Here $E^{0}_{\gamma i}$ is the energy of a primary γ-quantum after thermal neutron capture. The registered γ-quanta counts depend on the partial cross section $\sigma(E_n)$ and on the neutron flux for the investigated interval $f_n(E_n)$:

$$N_{\gamma}(E_{\gamma}) = k \int \sigma(E_n) f_n(E_n) \mathrm{d}E_n.$$

- If $f_n(E_n)$ is known, the value of $N_{\gamma}(E_{\gamma})$ allows us to determine the cross section $\sigma(E_n)$.
- If $\sigma(E_n)$ is known, the value of $N_{\gamma}(E_n)$ allows us to determine the neutron flux $f_n(E_n)$.

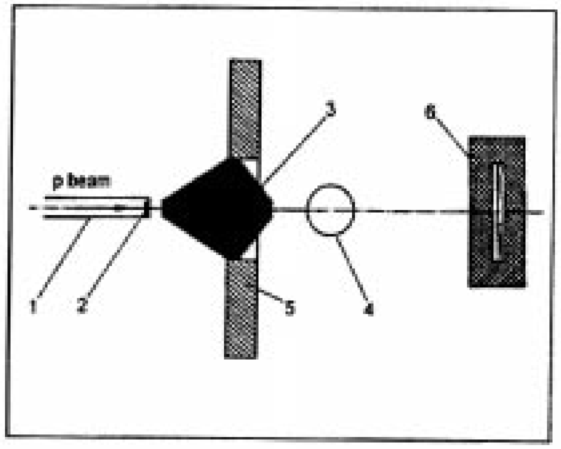

Figure 6. Geometry of the experimental setup for neutron spectrometry by means of the shift of primary γ-transitions. 1 – ion guide, 2 – Li-target, 3 – Pb shadow shielding, 4 – Ge-detector, 5 – sample, 6 – neutron monitor.

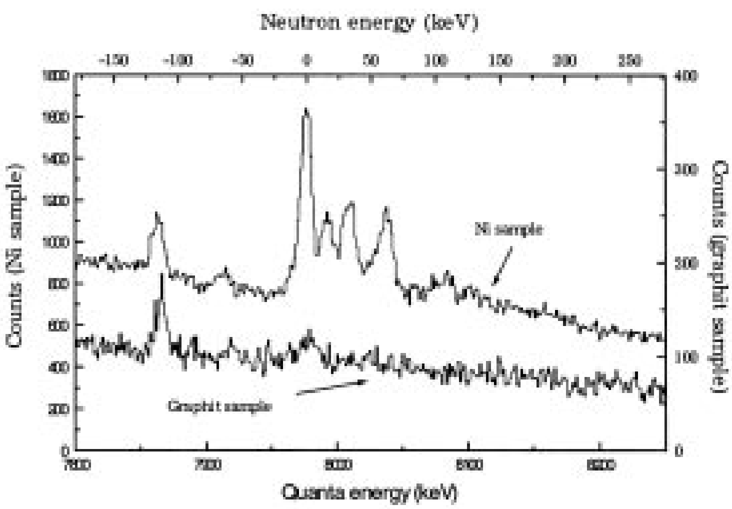

Figure 7. Experimental γ-ray spectra with Ni (effect) and graphite samples (background). Lower scale — for γ-quanta energy, upper scale — for energy of neutrons.

Because of the compact geometry (see figure 6), the profit of the utilization of neutrons comparing to the TOF methods is better:

—for Van de Gaaff ~ 100 times,

—for LINACs (100 m) $\sim 10^6$ times.

In figure 7 the experimental γ-ray spectra for a Ni-sample (upper curve) and for a graphite scatter (lower curve) are presented. The main sources of the background are the Compton electrons and γ-quanta from more energetic γ-transitions. The peculiarities

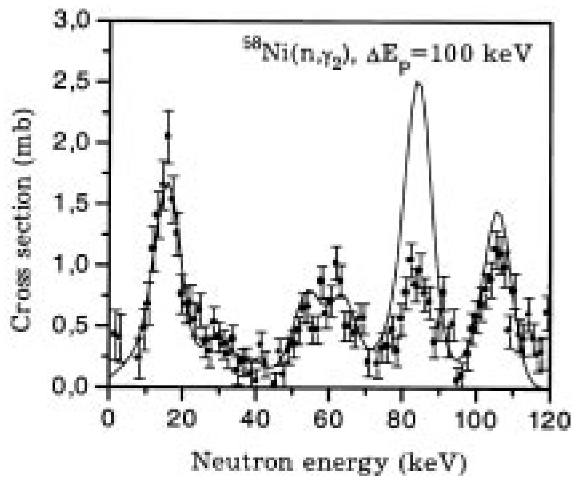

Figure 8. The partial capture cross section for the γ-transition to the second excited state of ^{59}Ni. The solid curve is the cross section corrected for the self- shielding in a thick sample.

of the method are the constant neutron energy resolution ($\sim$ 8 keV because of Ge(Li) detector for $E_\gamma \sim 9$ MeV) and the absence of neutron background.

On figure 8 the partial capture cross section for the primary γ-transitions to the second excited state of daughter nucleus ^{59}Ni is presented. This might be the first measurement of this kind. It seems, the development of this method in the future may reveal the possibility to analyse the spectra of stationary (non-pulsed) neutron fluxes in the 10–200 keV neutron energy interval, which is inaccessible now.

6. Conclusion

The analysis of a broad set of required neutron data indicates the necessity of developing the neutron spectrometry, including the creation of new methods for the specific problems of science and engineering. The availability of a number of rather simple and cheap methods in neutron spectrometry, useful in important scientific and applied problems has been demonstrated. Take into account, that these methods can compete with the modern TOF methods based on powerful electron and proton accelerators.

Acknowledgement

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