REPORT 98-07
OKTOBER 1998

**A Monte-Carlo Code for Neutron Efficiency
Calculations for Large Volume Gd-Loaded
Liquid Scintillation Detectors**

A. Trzciński, B. Zwiegliński, U. Lynen, J. Pochodzalla

SCAN-9909035

CERN LIBRARIES, GENEVA

Gesellschaft für Schwerionenforschung mbH
Planckstraße 1 • D-64291 Darmstadt • Germany
Postfach 11 05 52 • D-64220 Darmstadt • Germany

A MONTE-CARLO CODE FOR NEUTRON EFFICIENCY CALCULATIONS FOR LARGE VOLUME Gd-LOADED LIQUID SCINTILLATION DETECTORS

A. Trzciński^a, B. Zwiegliński^{a, *},
U. Lynen^b, J. Pochodzalla^c

^a*Soltan Institute for Nuclear Studies, 00-681 Warsaw, Hoża 69, Poland*

^b*Gesellschaft für Schwerionenforschung, D-64220 Darmstadt 11, Germany*

^c*Max-Planck Institut für Kernphysik, D-69029 Heidelberg, Germany*

October 7, 1998

Abstract

This paper reports on a Monte-Carlo program, MSX, developed to evaluate the performance of large-volume, Gd-loaded liquid scintillation detectors used in neutron multiplicity measurements. The results of simulations are presented for the detector intended to count neutrons emitted by the excited target residue in coincidence with the charged products of the projectile fragmentation following relativistic heavy-ion collisions. The latter products could be detected with the ALADIN magnetic spectrometer at GSI-Darmstadt.

*Corresponding author. E-mail: bzuw@fuw.edu.pl

1 Introduction

Large volume, gadolinium-loaded, organic liquid scintillation detectors have found a widespread application in neutron multiplicity measurements, so that the name neutron-multiplicity meters (NMMs) for these devices acquires increasing popularity. Invented at Los Alamos [1], their early applications were in measurements of multiple neutron emission cross sections in proton [2], neutron [3, 4, 5, 6] and γ -ray [7, 8] induced reactions and in measurements of neutron multiplicities accompanying spontaneous [9, 10] and neutron-induced [11, 12] fission. The large multiplicity of about 10 neutrons expected in the spontaneous fission of superheavy elements prompted to search for their occurrence in nature [13] with the aid of an NMM.

The HMI-Berlin group [14, 15] was a pioneer in the application of NMMs in the heavy-ion (HI) domain. They demonstrated that the degree of violence of the interaction, respectively the impact parameter involved in a collision, can be quantified with the aid of the measured neutron multiplicity. The method relies on the basic property of hot, heavy nuclei to de-excite by evaporation of neutrons, each neutron carrying off some 10 to 20 MeV of excitation energy, approximately equally divided between binding and kinetic energies.

Having proved its merits at low energies (10-20 MeV/u) NMMs were soon after implemented at intermediate energy (20-100 MeV/u) heavy ion facilities. Reference [16] gives an excellent review of the progress achieved, using the measured neutron multiplicity as a diagnostic tool in the domain of hot nuclei created in intermediate energy HI collisions. Table 1 presents the main characteristics of these NMMs. Vacuum chambers have been accommodated inside the scintillator vessel housing the target and charged particle detecting systems of increasing size and complexity proportional to the HI energy. This, together with the increasing elongation along the beam direction, to account for the longer mean path of higher energy neutrons emitted at forward angles, resulted in a significant increase of the overall volume of the NMMs. Another feature of the newest generation of NMMs, worth to be stressed, is a segmentation of the vessel, permitting to roughly classify the neutron emission angles into several angular ranges. The range of measured multiplic-

Table 1: Neutron multiplicity meters (NMMs) in the intermediate energy (20-100 MeV/u) HI domain.

#	Laboratory	Vol. (l)	Tank configuration	Scintillator	Gd(%)	Ref.
1	HMI-Berlin	500	Two half-spheres $\varnothing 1\text{m}$	NE-323	0.5	[17, 18]
2	HMI-Berlin	1500	Two half-spheres $\varnothing 1.4\text{m}$ interlaced by cylindrical section	NE-343	0.4	[19, 20]
3	NSRL-Univ. of Rochester	900	One cylinder $\varnothing 1.15\text{m}$, two truncated conical endcaps	BC-521	0.2	[21, 22]
4	GANIL-Caen (ORION)	3000	Four segments - two cylindrical ($\varnothing 1.6\text{m}$), two forward-most conical	NE-343	0.3	[23]
5	Texas A&M University	1700	Two half-spheres $\varnothing 1.5\text{m}$ interlaced by cylindrical section	Self-made	0.3	[24]
6	MSU NSCL (SUPER-BALL)	18000	Five conical segments defined by radials originating from target position	ND-309	0.2	[25, 26]

ities has also been significantly extended in comparison with the first experiments at HMI, performed with beam energies in the vicinity of the Coulomb barrier [14]. Neutron multiplicities exceeding 60 have been detected with ORION [16] in the de-excitation of the heaviest systems studied at GANIL. To increase the neutron lifetime in the scintillator and thus improve to some extent the double-pulse resolution at these high multiplicities the applied Gd concentration (see Table 1) has been reduced.

At relativistic energies the decay products can be attributed to three sources, which have distinctly different kinematic properties in the laboratory system. Therefore the techniques required for their detection are quite different. The projectile-like and intermediate-velocity sources give rise to relativistic neutrons. For their detection the calorimetric method is used in the LAND detector [27] at GSI. On the other hand, the NMM technique is well adapted for the neutrons from the target-like source, which is slowly moving in the lab.

The ALADIN Collaboration, investigating HI-induced reactions at several hundred A·MeV, is interested in the measurement of temperature and excitation energy of the target spectator [28] at the instant of multifragmentation - quantities defining the caloric curve [29]. For the determination of the excitation energy a measurement of the neutron multiplicity and their energies is important. Two different experimental set-ups are discussed to achieve this goal.

The first one utilizes a large NMM. In order to avoid interactions of highly energetic projectile fragments and forward emitted particles from the projectile-target interaction region in the vessel of the NMM and the scintillator material, a full 4π coverage cannot be achieved, leading to a reduced accuracy in the event-by-event determined neutron multiplicity. Moreover, constraints on the NMM geometry are imposed by the existing ALADIN instrumentation [30] (see Sect. 7.1).

The second set-up would be an array of 96 separate detectors (multidetector DEMON [31]), containing organic liquid scintillator NE-213 (unloaded), which allow to measure the associated neutron multiplicities and by time-of-flight also energies. The solid-angle coverage for the neutron multiplicity measurements is inferior to the first one, yet the energy measurement may turn this second one superior in the foreseen application to the excitation energy-temperature measurements for the thermalized target residue. It will allow to resolve the preequilibrium and equilibrium components in the spectra, which was not possible in the previous measurements [32] of the projectile-like fragment neutrons using the LAND detector. With both set-ups the impact parameter involved in the collision will be tagged with the aid of $Z \geq 2$ charged products of the projectile fragmentation, to be detected with the ALADIN forward spectrometer [30].

The program MSX, described in this paper, has been written with the intention of creating a tool, permitting to perform a comparative study of these two systems, aimed to select the more suitable from the point of view of the above application. A flexibility in allowing for different detector geometries and taking into account differences in the neutron detection processes involved were the program's prerequisites.

The results of our previous experiments provide orientation as to the range of

neutron energies and multiplicities to be dealt with in the simulations. The energy range $0 \leq E_n \leq 35$ MeV will cover most of the equilibrium neutrons. The neutron multiplicities from the projectile-like source seen in the joint ALADIN - LAND experiment [32] saturate at $M \approx 35$. This we loosely associate with liberation of the entire neutron excess of the ^{197}Au nucleus.

The paper presents the program (Sect. 6) and some results of the simulations for an NMM which fulfills the above two constraints (Sect. 7). The results pertaining to the second of the above two set-ups are left to a forthcoming publication.

The modified version of DENIS [33] is the sole program hitherto used [23, 24, 34] for these purposes. An application of the NMM method in relativistic HII domain asked for a program giving a more comprehensive description of the neutron detection process. The aim is extending NMM's applicability beyond the standard domain, in particular, by the way of including into simulations all detection stages (Sect. 2). Sect. 3 describes the nuclear data input used in MSX, with emphasis on capture γ -rays, which have not been adequately covered in the past. Sect. 4 contains the details of treatment of nuclear reactions, while Sect. 5 of light production and transport. Those features, which have been incorporated into MSX and are missing from the published version of DENIS [33], are summarized in the Conclusions (Sect. 8).

2 Principle of neutron detection and related program features

The detection process in an NMM proceeds in the following stages:

- (i) Neutron slowing down due to the neutron-propagating collisions with the hydrogen and carbon nuclei of the scintillator. We term neutron-propagating the elastic collisions with ^1H and ^{12}C and those inelastic collisions with ^{12}C which are accompanied by the emission of at least one neutron in the final state. Below the threshold energy, $E_n = 4.813$ MeV, for the inelastic scattering to the first excited 4.443 MeV state in ^{12}C , only the elastic scattering contributes to the neutron slowing-down. Ultimately, the neutron comes into thermal equilibrium with the medium and diffuses within the scintillator volume. The velocity distribution of the diffusing neutrons is

a (distorted) Maxwellian, with the most probable velocity determined by the ambient temperature. The dissipation of the neutron's total initial kinetic energy occurs on a nanosecond time scale giving rise to the initial prompt part of the scintillation signal.

An escape through the walls of the vessel or a nonelastic collision with ^{12}C , resulting in only the charged particle(s) in the final state, represent the processes terminating the neutron's history. In the latter two cases the neutron does not reach the thermal energies, consequently, its contribution is limited to the prompt peak only.

(ii) Radiative capture following one of the three alternatives: in ^1H with the emission of a single 2.224 MeV γ -ray, in ^{155}Gd (natural abundance 14.8%) or in ^{157}Gd (natural abundance 15.7%) accompanied by the emission of a cascade of γ -rays with the summed energies of 8.536 and 7.937 MeV, respectively.

(iii) Gamma-ray energy degradation due to consecutive Compton scatterings from the electrons of H and C atoms of the scintillator. Ultimately, the γ -ray energy is decreased to the level at which the photoelectric absorption in C or Gd terminates its history. Thereby nearly the entire energy (K -shell binding energy excluding) of the γ -ray cascade is converted into electron energy.

(iv) Electron energy loss by the excitation and ionisation of the medium molecules. Part of this energy loss (determined by the scintillation efficiency) is converted into visible light.

(v) Light transport to the photocathodes of photomultipliers (PMs) in optical contact with the liquid via multiple reflections on the diffusely reflecting coating of the interior of the tank.

The signal originating from the capture γ -rays follows the prompt pulse with a delay statistically distributed over a period of some 50 - 100 μs , the time scale being determined by the probability of capture, which terminates the diffusion process (see Sect. 7.4). The latter opens the gate of the recording electronics for this time interval and the multiplicity of neutrons emitted in a reaction is determined by counting one-by-one the light flashes caused by consecutive captures. Typical HI beam intensities in experiments using the ALADIN spectrometer are of the order of a few

thousand particles per second. Therefore, the rate of data accumulation in the joint mode of operation (see above, Sect. 1) will not be limited by the slow response of the NMM.

A dead-time of the order of $100\ \mu\text{s}$, however, disqualifies NMMs in applications requiring high counting rates, as for example, impact parameter tagging in particle interferometry. A monotonic dependence of the charge integrated in the prompt peak on the measured neutron multiplicity has been demonstrated in the recent experiment performed with ORION at GANIL [35, 36]. This calorimetric mode of operation opens up the way of application of NMMs in high counting rate experiments. It is desirable, therefore, to have a single program giving the possibility to correct both multiplicity and prompt peak charge for the neutron detection efficiency. Led by these considerations we have decided to incorporate the prompt peak charge into MSX simulations. Sect. 5.1 outlines the way contributions of different particle species to the prompt peak are weighted. An application to relativistic HI collisions using an event generator, which predicts in a realistic way the spectral composition of fragmentation products, will be demonstrated in a later publication, after a final segmentation of the GSI detector (see Sect. 7.1) is defined.

Another application domain of the program is the evaluation of distortions of the multiplicity spectra caused by various instrumental effects. One such effect is multiple neutron production in interactions with C nuclei. The $^{12}\text{C}(n,2n)^{11}\text{C}$ reaction is taken into account in the stage (i) by tracking both secondary neutrons created in the final state. The program can handle, as well, higher secondary multiplicities which may result from a partial or the complete disassembly of ^{12}C at these high neutron energies. The latter processes are not represented in the results of Sect. 7 because of insufficient knowledge of the relevant cross sections.

The second spurious effect is caused by finite resolving time of the recording electronics. Two (or more) consecutive capture pulses, following each other within the resolving time, will be recorded as a single pulse, leading to an underestimation of the measured multiplicity (Sect. 7.4). The minimum resolving time is defined by the spread of the light propagation times from the source to the PM photocathodes. Including the light transport, stage (v), into the simulations makes it possible to de-

termine this time in a realistic way (Sect. 7.6). Moreover, this feature enables to investigate the dependence of the detection efficiency on the electronic thresholds.

3 Nuclear data input for the MSX simulations

3.1 Reaction cross sections

We give preference to the evaluated cross section data files, available via intermediary of the international Nuclear Data Centers. This choice offers several advantages. First, they represent a quasi-totality of the available data, in which the individual cross section measurements are appropriately weighted. Second, they are periodically updated by including the results of experiments performed over the last few years. Third, they serve as a convenient reference basis for comparisons of the simulations yielded by different Monte-Carlo programs.

Table 2 lists the reactions taken into account in our calculations. Entries 1-21, pertaining to the reactions with ^1H and ^{12}C , are from the evaluated data file HC.E6 from the ENDF/B-VI library. The cross sections for the radiative capture reactions $^{155}\text{Gd}(n,\gamma)^{156}\text{Gd}$ and $^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$ (entries 22 and 23) are from the JENDL-3 fission product data file J3FPGD.E5 (ENDF/B-5 format). Both files have been received from the International Atomic Energy Agency (Vienna). The cross sections for the indicated reactions with ^{12}C (entries 3 - 21) are available from their respective thresholds up to 32 MeV in the lab. system. In contrast to the $^1\text{H}(n,n)^1\text{H}$ elastic cross section, which decreases monotonously throughout the 0-100 MeV range, the cross sections for the neutron elastic scattering and some reactions on ^{12}C display prominent resonance structures up to ≈ 10 MeV above their thresholds (see Fig. 1). The interactions with oxygen, because of its negligible content in comparison with H and C in the currently used scintillators (see Sect. 7.1), are neglected.

The maximum laboratory energy of 32 MeV covers most of the equilibrium neutrons, expected to be emitted from the highly excited target residue, following relativistic HI collisions (see Sect. 1). An extension up to 100 MeV would be highly desirable to reach into the preequilibrium component. The ongoing research programs in several cyclotron laboratories, propagated by the needs of dosimetry and

Figure 1: Total elastic $^{12}\text{C}(n,n)^{12}\text{C}$ and some of the total nonelastic cross sections on ^{12}C in the 0-32 MeV neutron energy range.

Figure 2: Differential cross sections for the inelastic scattering $^{12}\text{C}(n,n')^{12}\text{C}$ to the 4.443 MeV first excited state in ^{12}C at different neutron energies. Left panel: variation across the group of resonances around 8 MeV in Fig. 1. Right panel: variation with increasing energy above the resonance region.

Table 2: Cross sections used by MSX.

# ^a	Reaction	Q-value (MeV)	Threshold (MeV)	Energy range (MeV)	σ type	
					$d\sigma/d\Omega$	σ_{tot}
1*	$^1\text{H}(n,n)^1\text{H}$	0.0	0.0	0 - 100	+	+
2	$^1\text{H}(n,\gamma)^2\text{H}$	+2.224	0.0	0 - 100	-	+
3*	$^{12}\text{C}(n,n)^{12}\text{C}$	0.0	0.0	0 - 32	+	+
4	$^{12}\text{C}(n,\gamma)^{13}\text{C}$	+4.946	0.0	0 - 32	-	+
5*	$^{12}\text{C}(n,n')^{12}\text{C}^{*4.439}$	-4.439	4.813	5.2 - 32	+	+
6*	$^{12}\text{C}(n,n')^{12}\text{C}^{*7.653}$	-7.653	8.299	9.0 - 32	+	+
7*	$^{12}\text{C}(n,n')^{12}\text{C}^{*9.638}$	-9.638	10.453	11.0 - 32	+	+
8	$^{12}\text{C}(n,\alpha)^9\text{Be}$	-5.702	6.182	6.2 - 32	-	+
9	$^{12}\text{C}(n,p)^{12}\text{B}$	-12.587	13.653	14.6 - 32	-	+
10	$^{12}\text{C}(n,d)^{11}\text{B}$	-13.732	14.895	15.5 - 32	-	+
11*	$^{12}\text{C}(n,np)^{11}\text{B}$	-15.957	17.309	17.5 - 32	-	+
12*	$^{12}\text{C}(n,2n)^{11}\text{C}$	-18.722	20.311	20.6 - 32	-	+
13	$^{12}\text{C}(n,t)^{10}\text{B}$	-18.930	20.537	20.6 - 32	-	+
14	$^{12}\text{C}(n,p\alpha)^8\text{Li}$	-22.588	24.509	25 - 32	-	+
15	$^{12}\text{C}(n,pd)^{10}\text{Be}$	-24.961	27.087	28 - 32	-	+
16*	$^{12}\text{C}(n,nd)^{10}\text{B}$	-25.188	27.333	28.5 - 32	-	+
17	$^{12}\text{C}(n,pt)^9\text{Be}$	-25.516	27.69	29 - 32	-	+
18*	$^{12}\text{C}(n,2n\alpha)^7\text{Be}$	-26.267	28.505	30 - 32	-	+
19	$^{12}\text{C}(n,2p)^{11}\text{Be}$	-26.684	28.959	30 - 32	-	+
20*	$^{12}\text{C}(n,nt)^9\text{B}$	-27.366	29.7	30 - 32	-	+
21*	$^{12}\text{C}(n,2np)^{10}\text{B}$	-27.412	29.75	30.5 - 32	-	+
22	$^{155}\text{Gd}(n,\gamma)^{156}\text{Gd}$	+8.537	0.0	0 - 20	-	+
23	$^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$	+7.941	0.0	0 - 20	-	+

^a) Neutron-propagating reactions are marked with an asterisk

health-physics, guarantee that the gap in the ^{12}C evaluated data will be filled in the nearest future [37]. An inclusion of the extended energy range into input data will then be straightforward.

The knowledge of differential cross sections, desirable for all neutron-propagating reactions, is limited at present to only those five among them, which are marked with the plus sign in the sixth column of Table 2. The differential cross sections for $^1\text{H}(n,n)^1\text{H}$ are close to isotropy in the center of mass system in the entire energy range of interest. Fig. 2 illustrates the prominent features of the differential cross sections for the interaction with ^{12}C . First, the resonant structures, containing as a rule several resonances of the compound nucleus ^{13}C , cause a rapid variation of

Figure 3: Total radiative capture cross section in ^{157}Gd in the neutron energy range 10^{-2} - 10^3 eV. The thermal energy, 0.025 eV, is indicated with the dashed line. Arrow marks the position of the $J^\pi=2^-$ capturing resonance in the thermal region.

the angular distributions. This is demonstrated in the left panel of Fig. 2 for the inelastic scattering $^{12}\text{C}(n,n')^{12}\text{C}$ (4.443 MeV, 1-st excited state) by the rapid evolution of angular distributions from backward to forward peaking, as the neutron energy increases across the group of resonances centered at about $E_n=8$ MeV in Fig. 1. Second, there is an overall tendency towards forward peaking, when the neutron energy increases further, past the resonance region (see the right panel in Fig. 2). This reflects the increasing contribution of the non-resonant processes - the potential elastic scattering for $^{12}\text{C}(n,n)^{12}\text{C}$ and the direct inelastic scattering for $^{12}\text{C}(n,n')^{12}\text{C}$ (4.443 MeV). Both features are faithfully reproduced in the simulations.

The radiative capture processes set-in after the neutron has slowed-down into the Gd resonance region ($E_n \leq 300$ eV). We sample exactly the resonant structure of the cross sections (see Fig. 3) in the 1-300 eV range and their rise towards the thermal energy ($E_n=0.025$ eV) caused by the down-going wing of the $J^\pi=2^-$ capturing states at 0.0268 eV in ^{155}Gd and 0.0314 eV in ^{157}Gd , respectively. Noteworthy are the cross section values in excess of 10^5 barns in the thermal region, justifying loading the organic, liquid scintillators with gadolinium for use in NMM's.

Table 3 presents the relative contributions of different capture reactions to the

Table 3: Contributions of different capture reactions to the total capture rate ^{a)}

Reaction	Contribution (%)	
	$E_n \leq 1$ eV	$E_n > 1$ eV
$^1\text{H}(n,\gamma)^2\text{H}$	2.66	0.51
$^{12}\text{C}(n,\gamma)^{13}\text{C}$	0.01	-
$^{155}\text{Gd}(n,\gamma)^{156}\text{Gd}$	17.96	0.42
$^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$	78.27	0.17

^{a)} Based on the simulation for 10^5 neutrons

total capture rate in the two neutron energy ranges - below and above 1 eV. These results were obtained in a simulation for the scintillator BC-521 (Table 5) filling the space between two concentric spheres 30 and 140 cm in diameter, with the neutron source in the geometrical center. One may conclude that the contribution of ^{12}C can be completely neglected. Contributions from the epithermal region ($E_n \geq 1$ eV) are of the order of 1% of the capture events.

3.2 Capture γ -ray spectra

The employed capture γ -ray spectra combine experimental information with the results of Hauser-Feshbach statistical model calculations for the γ -ray cascades in ^{156}Gd and ^{158}Gd . The subroutines describing electromagnetic transitions from the code EMPIRE [38] were modified to perform these calculations. An s -wave capture, leading to $J^\pi=2^-$ of the capture state is assumed.

The levels of the final nuclei below the neutron binding energy B_n (see Fig. 4) are divided into two energy ranges - discrete and continuum. A complete information on the excitation energies, spins, parities and the branching ratios for the γ -ray transitions to the lower lying levels is available for the energy levels in the former energy range. We used Refs. [39, 40, 41] as a source of this information for ^{156}Gd and Refs. [42, 43] for ^{158}Gd . The above mentioned modifications permit to take into account the transitions from the capture state directly to the discrete states, which also belong to the category of transitions with the experimentally determined branching ratios. The branching ratios for them are taken from Ref. [44]. Above a certain energy, denoted E_{cut} in Fig. 4, this detailed information is partly or completely miss-

Figure 4: Classification of the γ -ray transitions following the thermal-neutron radiative capture in $^{155,157}\text{Gd}$. The branching ratios for the transitions of type 1 (capturing state $\rightarrow$ continuum), type 2 (continuum $\rightarrow$ continuum) and type 3 (continuum $\rightarrow$ discrete levels) are calculated with the Hauser-Feshbach statistical model as implemented in the code EMPIRE [38]. Those from the capturing state to the discrete states (left hand side) and between the discrete states are adopted from experiment (see the text for further details).

ing. Therefore a continuous distribution of energy levels according to the Gilbert-Cameron [45] level-density formula is assumed. The continuum is binned into discrete energy intervals of 40 keV width. The branching ratios for the transitions of type 1 in Fig. 4 (capture state $\rightarrow$ continuum), type 2 (continuum $\rightarrow$ continuum), and type 3 (continuum $\rightarrow$ discrete levels) are calculated with the energy-dependent γ -ray transmission coefficients, $T(XL)$, where XL denotes the γ -ray multipolarity. The multipolarities E1, E2 and M1 were taken into account. The $T(XL)$'s incorporate the single-particle (Weisskopf) and the giant-resonance (Brink-Axel model [47]) contributions. For the $^{156,158}\text{Gd}$ nuclei, whose giant E1-resonance is split because of permanent deformation, both components were taken into account.

The initial set of parameters entering the Gilbert-Cameron level-density formula and the transmission coefficients were taken from the systematics contained in Refs.

[45, 48]. This was followed by a series of calculations, in which some of the parameters were fine-tuned to describe in an optimum way the thermal-neutron γ -ray capture data for ^{157}Gd , including the inclusive spectrum [44] and the γ -ray multiplicity distribution [49]. The latter serves as an important global characteristics of the capture spectrum, since the ratio of neutron binding energy to the most probable multiplicity gives the average γ -ray energy interacting with the scintillator. A few words of comment are here in place regarding these data. In spite of the fact that literature abounds in the published work on thermal-neutron capture γ -ray spectra for $^{156,158}\text{Gd}$, to our knowledge only the relatively old work of Groshev et al [44], performed with his second generation magnetic Compton spectrometer, meets the requirements of the present application. Only this measurement provides the relative intensities of both the resolved γ -ray lines to the low-lying levels and to the unresolved continuum of the final nuclei. The latter exhaust nearly the entire transition strength. The prominent discrete line with $E_\gamma=6.746$ MeV in Fig. 5 represents, for example, only 1.9% of the total γ -ray transition probability from the capture state [44]. In the more recent works, e.g. Refs [39, 40, 41] for ^{156}Gd and Refs [42, 43] for ^{158}Gd , performed with Ge(Li) and/or crystal diffraction spectrometers, the information on transitions from the capture state to continuum is missing.

For ^{156}Gd we have assumed the same set of parameters in our calculations as for ^{158}Gd , since the continuous part of the $^{155}\text{Gd}(n,\gamma)^{156}\text{Gd}$ spectrum is nearly identical in shape to that of ^{157}Gd [44]. Moreover, the product of cross section and isotope abundance makes the latter contribution to the combined (n,γ) spectrum dominant (see Table 3 and Sect. 7.5).

Fig. 5 compares the experimental (solid line) and the calculated (dashed line) γ -ray spectra. For the sake of comparison the calculations have been corrected for the energy-dependent efficiency of the Compton spectrometer [46]. The discrete lines above $E_\gamma \approx 4.5$ MeV are due to the direct transitions indicated with the upper arrow in the left-hand part of Fig. 4. The transition to the 0^+ ground state is forbidden, the weak line with the maximum energy $E_\gamma=7.855$ MeV goes to the 2^+ , first excited state of ^{158}Gd . The group of discrete transitions at low energies $0.5 \leq E_\gamma \leq 1.5$ MeV is strongly suppressed in intensity, because of the rapidly decreasing detection effi-

Figure 5: Comparison of the experimental [44] and the efficiency-corrected [46] calculated thermal-neutron capture γ -ray spectra from ^{158}Gd .

ciency of the spectrometer with decreasing E_γ . They correspond to the transitions between the levels below E_{cut} in Fig. 4. Finally, the continuous distribution extending in E_γ from about 1 to 6 MeV, with the maximum around 2.5 MeV is due to the transitions of type 1, 2 and 3 in Fig. 4, involving the continuum of unresolved levels in ^{158}Gd .

A more complete quantitative characterization of the spectra is provided by the γ -ray multiplicity distribution (Fig. 6). The experimental data [49] have been roughly corrected for the finite threshold and the detection efficiency of the γ -ray multidetector used in that work. The predicted average multiplicity of 4.5 quanta reflects the importance of transitions via the states of continuum, mentioned above. A forbiddenness of the direct $2^- \rightarrow 0^+$ transition explains the vanishing contribution of multiplicity one into the spectrum of Fig. 6. Ref. [50] demonstrates a good agreement between the experimental and the efficiency-corrected statistical model predicted multiplicity spectra also for the s -wave resonances in the epithermal region.

Following the procedure described in this section we succeeded to incorporate into the Monte-Carlo simulations not only the average energy and multiplicity of the deexcitation γ -rays, but also fluctuations of these quantities around the mean values. An approach similar to ours is applied in [51] to the γ -ray spectra from neutron capture in ^{113}Cd , the nuclide occasionally also used for the purpose of scintil-

Figure 6: Comparison of the experimental [49] and calculated γ -ray multiplicity spectra for thermal-neutron radiative capture in ^{157}Gd .

lator loading.

4 Treatment of nuclear reactions

4.1 Kinematics

Relativistic N-body kinematics is employed throughout the program permitting to treat on equal footing the reactions with participation of the particles with non-zero rest mass occurring in the stage (i) of Sect. 2 and those in the stages (ii) and (iii) involving massless photons. This led to a considerable simplification of the program's structure (see Sect. 6). Moreover, energy conservation is rigorously observed, therefore the total energy deposited in the scintillator, heavy recoils including, is accounted for.

4.2 Angular distributions

Angular distributions in the center-of-mass system (the CM system) for the reactions 1, 3 and 5 - 7 in Table 2 were reconstructed with the aid of energy dependent Legendre coefficients $c_l(E_n)$:

$$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = \frac{\sigma_t(E_n)}{4\pi} \left[1 + \sum_{l=1}^{l_{max}(E_n)} c_l(E_n) P_l(\cos \theta_{CM}) \right], \quad (1)$$

where $\sigma_t(E_n)$ is the total cross section for the given reaction at the incident neutron energy E_n , θ_{CM} is the CM angle of emission of the reaction product, $P_l(\cos \theta_{CM})$ is

the Legendre polynomial of the order l ; $l_{max}(E_n)$ is the order of the last, non-zero coefficient in the decomposition (1).

For the remaining reactions in Table 2, for which the differential cross sections are not available, we assume isotropy in the CM system. This assumption is strictly justified close to the reaction thresholds and for the secondary neutrons emitted by the excited products of the primary interaction.

5 Light production and transport

5.1 Light production

In the prompt peak there are superimposed the contributions of charged particles and γ -rays produced in the primary HI interaction and those created in the stage (i) by each neutron sent into the detector volume. The parametrization of Birks [52] is used to calculate the light output for different particle species. It relates in a nonlinear way dN_{ph}/dx (the number of photons emitted per path length dx traversed by a particle) with the stopping power dE/dx of the scintillator:

$$\frac{dN_{ph}}{dx} = n_0 \frac{dE}{dx} \left[1 + kB \left(\frac{dE}{dx} \right) \right]^{-1}. \quad (2)$$

In (2) n_0 is the average number of photons per unit expended energy, an intrinsic property of the scintillator, and kB is a particle dependent parameter. The denominator in (2) reflects in a phenomenological way the quenching effect of the ionisation density on the primary fluorescence process. The response of organic scintillators to electrons is known to be a linear function of the deposited energy for electron energies above approximately 100 keV with an extrapolation which passes within a few keV of the origin [52, 53]. Thus, for electrons we assume $kB = 0$ in eq. (2). Table 4 lists the kB -values quoted in the literature [54, 55] for the scintillator NE-213, commonly used for fast neutron detection. In particular, because of its outstanding n- γ discrimination capability, NE-213 has been also applied in the multidetector DEMON [31]. There seems to occur a systematic tendency of the kB -parameters towards decreasing with the increasing particle ionization density. Since the response studies of BC-521, the Gd-loaded scintillator, which we intend to apply in the design of Sect. 7.1 have not yet been performed in comparable detail, we have assumed

Table 4: Compilation of kB parameters for the liquid scintillator NE-213.

Particle	Energy (MeV)	kB (mg/cm ² MeV)	Ref.
Proton	0.24 - 15	12.5	[54]
Proton	10 - 56	9.1	[55]
Deuteron	26 - 42	6.9	[55]
Triton	20 - 36	7.0	[55]
Alpha	30 - 46	5.1	[55]

$kB=10$ mg/(cm²MeV) for all particles of interest. We expect that with this conservative assumption the relative light yield for different particle species in the latter scintillator will also be reasonably reproduced.

The energy-loss subroutine DEDX from the program SPAR [56] was employed to calculate the stopping powers in (2). The right-hand side of Eq. (2), integrated between the initial particle energy and zero, defines the total light yield. Fig. 7 presents the results of integration for the indicated particle types with initial energies in the range 0-32 MeV. The absolute normalization, implied by (2), is avoided by expressing the ordinate in MeV_{ee}, the electron energy, which would produce the same light output as the particle in question. The quenching effect is manifested by the rapid decrease of light yield with increasing ionization density, which makes the contribution of heavy recoils to the prompt peak negligible in comparison with electrons and light reaction products.

Figure 7: Total light yield for the indicated types of particles as a function of the energy deposited in the scintillator.

5.2 Light transport and signal formation

In our model of light emission (see Sect. 7.6) each particle trajectory is divided into bins of a constant energy loss ΔE , set equal 200 keV in the calculations of Sect. 7.6. Eq. (2) is numerically integrated within the appropriate limits to yield the number of photons ΔN_{ph} , emitted isotropically into the full solid angle, by each of these elementary light sources. The photons are allowed to propagate along straight-line trajectories with the group velocity v_{gr} given by c the velocity of light in vacuum and n the refractive index of the medium:

$$v_{gr} = c/n. \quad (3)$$

Because of absorption, the probability to reach the distance x in a free flight is:

$$P(x) = \exp(-x/\lambda), \quad (4)$$

where λ is the attenuation length. Furthermore, we assume that the internal surface of the container is covered with diffusely reflecting paint. In the case of diffuse light reflection the angle of reflection is independent of the angle of incidence and the differential reflection probability is given by Lambert's law [57]:

$$\frac{dP_{rfl}}{d\Omega} = \frac{R_1}{\pi} \cos \theta, \quad (5)$$

where R_1 is the reflection coefficient ($R_1 \leq 1$) and θ is the polar angle relative to the normal to the reflecting surface. Dispersive effects are ignored.

Upon reaching the photocathode of a photomultiplier (PM) tube the photon ejects a photoelectron with the efficiency coefficient Q_e . This will be focused onto the first dynode with the efficiency f_e and amplified by the dynode chain, typified by the total gain G . The PM current $i(t)$, flowing into the anode, is determined by the product:

$$i(t) = e\nu(t)Q_e f_e G, \quad (6)$$

where $\nu(t)$ is the rate of photon hits at the photocathode, calculated by the program, and e the elementary charge. The corresponding voltage pulse at the anode RC circuit is:

$$V(t) = \frac{Re^{-t/\tau}}{\tau} \int_0^t \exp(s/\tau) i(s) ds. \quad (7)$$

The time constant $\tau=RC$ is chosen sufficiently large to collect with a minimum ballistic error the contributions from all photons independent of the point of their emission and the path-length traversed in the tank. Under this condition, the amplitude of $V(t)$, a measurable quantity, is proportional to the total number of photons transported to the photocathode.

6 Program description

The program MSX is written in extended FORTRAN, commonly used on many UNIX machines. High performance and simplicity are its outstanding features, therefore its application is recommendable also to other detector types based, similarly as NMMs, on a multistage detection principle. The program consists of several modules, with a part of them being intended to be modified according to the specific demands of the user. In particular, the definition of the detector geometry and properties of the source of neutrons (geometry and energy spectrum), as well as choice of the quantities for presentation in the form of histograms are in disposal of the user.

A simplified flow chart of the program is shown in Fig. 8. Its execution starts with the block marked 'Initialization', which contains all the necessary data areas. The arrays with cross sections, material constants and the accumulated spectra are dynamically created in the course of execution of this block. After completion of the initialization phase, the program executes the main DO loop, in which the subprograms emitting and tracking particles are called.

The module termed 'Generator of incident particles' is intended for user's definition. It defines the geometry of the source of incident particles and their energy spectrum. The quantities returned upon its call are coordinates of the emission point, direction of the momentum vector and energy of the neutron leaving the source.

The essential part of MSX is the tracking subroutine. It tracks all particles, which are currently in the detector volume. This subroutine is recursively called. An outcome of its call is a shift of the currently tracked particle to the consecutive interaction point and emission of the reaction products. The advantage of the recursive calling is in using the same subprogram to track the incident particle as well as the

Figure 8: Flow chart of the program MSX.

products of interactions originating in all the consecutive detection stages. This solution permits to track simultaneously a very large number of particles. Its significance is particularly emphasized when tracking light photons, since about 2000 of them are assumed to be emitted per 200 keV energy loss of an electron in the scintillator (see Sect. 7.6).

The neutron detection process in an NMM can be symbolically represented with the aid of a characteristic tree, whose elements are the consecutive calls of the tracking routine. A simplified tree, serving for illustrative purposes, is shown in Fig. 9. The neutron n_1 emitted from the source S suffered in 1 a propagating collision and emerged as n'_1 with a reduced energy. In 2 a $^{12}\text{C}(n,2n)^{11}\text{C}$ reaction occurred, resulting in the secondary neutrons n_2 and n_3 . The neutron n_2 is slowed-down to thermal energy in a collision in 3 with a proton and captured in 4 by a Gd nucleus. The capture is followed with the emission of γ_1 to the intermediate state Gd(1). In 5 Compton scattering of γ_1 occurred resulting in γ'_1 and e_1 . The energy loss ΔE of e_1 is a source in 6 of the light photons ϕ_1 , ϕ_2 and the electron e'_1 with a reduced energy. The history of ϕ_1 begins with a free-flight (*ff*) in 7, continues with a reflection (*rf*) on the wall in 8 and terminates in the free-flight 9 with an absorption (*a*) in the detector volume. The branch 10 – 13 similarly depicts the history of the photon ϕ_2 . After its termination, the history of e_1 is continued with the consecutive energy losses ΔE , giving rise to light emission, until its complete stopping in the medium. This will terminate the branch starting with e_1 in 5. Next, in succession, the branches beginning with γ'_1 , Gd(1) and n_3 will be grown. An absorption of the last light photon emitted in the branch n_3 will complete the entire detection tree started by n_1 . The action of the tracking routine then terminates, which provokes emission of the consecutive neutron from the source by the generator of incident particles.

Three user-defined subroutines are called from the tracking routine. The first one defines the geometry of the scintillator vessel. This subprogram verifies geometrical relations, defining each part of the detector. It is an INTEGER function, which returns the number of the detector volume, depending on the space coordinates of the currently tracked particle. The second subprogram is used only in the case of investigation of light transport. It calculates the normal vectors at each

Figure 9: A fragment of the simplified detection tree illustrating functioning of the program MSX. The numbered circles indicate the consecutive calls of the tracking subroutine TRK. The corresponding process is indicated near by. Double circle indicates the call terminated with a RETURN. See the text for further details.

point of the surface defining the detector sensitive volume. The third one governs data acquisition. It describes the types of the acquired data and the way histograms, containing spectra, are to be filled.

The standard output of the program and the content of histograms are printed-out after termination of tracking of the predetermined number of neutrons. The data areas are then reset and simulations may be stopped or restarted again with modified input assumptions.

7 Results of MSX simulations

This Section is devoted to the presentation of some representative results of our Monte-Carlo simulations. The results refer to a geometry of the scintillator vessel which fulfills the constraints imposed by the physics of relativistic HI collisions and the existing ALADIN instrumentation (Sect. 7.1).

7.1 NMM for the ALADIN facility at GSI

An NMM intended to count neutrons emitted by the target residue in coincidence with the charged products of the projectile fragmentation is schematically shown in Fig. 10. The escape cone with 25° half-angle enables undisturbed detection of intermediate mass fragments from the projectile-like source with the ALADIN spectrometer and of light charged particles ($Z=1,2$) from the intermediate-velocity source with the 92-element Si-CsI(Tl) CATANIA array [30]. These are used to tag the impact parameter of the collision. A removal of the scintillator and construction materials on their paths simultaneously eliminates the sources of light and background neutrons, which would inevitably be present, if a closed geometry, common to all intermediate-energy NMMs of Table 1, were used. A requirement that the distance from the beam spot on target to the plastic-wall detector at the ALADIN exit is the same in the joined mode as in the stand-alone mode of the ALADIN operation [30] forced us to abandon the exact left-right symmetry of the external wall of the container by truncating its right-hand section. Moreover, its right-most part is reduced in diameter to fit the diameter of the aluminum ring housing the CATANIA array. The first of these installation-related modifications led to some

Figure 10: Geometry of the scintillator container for the ALADIN facility at GSI. Broken lines indicate the walls of the vacuum chamber, shaded areas the viewing windows. Right-hand side: section with a plane containing the beam axis. Left-hand side: section with a plane perpendicular to the beam axis at the target position viewed opposite to the beam direction.

further reduction of the detection efficiency for the residual neutrons not originating from the target-like source.

An application of the PMs XP2040 with the $\varnothing 4''$ photocathode, or of similar type, is foreseen. The shaded areas in Fig. 10 indicate the positions of the viewing windows with 10 cm diameter. There are twelve of them in each container section. In the left-hand section they are positioned on the circumference of the three rings seen at $\theta=22.5^\circ$ (3), 45° (6) and 67.5° (3) from the center of the hemisphere. The right-hand section has them arranged on the two rings with the adjacent windows rotated by $\Delta\phi=30^\circ$ relative to each other. We intend to employ the BC-521 liquid scintillator of Bicron Corporation. Its main properties, as given by the producer, are summarized in Table 5. The assumed concentration of Gd (optional parameter) is 0.5% by weight.

The source of isotropically emitted neutrons is located at the beam spot on target. Their total number was different in the simulations of different observables discussed in Sect. 7.2 - 7.6 and varied between 10^5 and 10^6 .

The geometry of Fig. 10 does not allow for an easy access into the interior of the vacuum chamber to install, for example, a charged particle multidetector. There-

Table 5: Compilation of chemical and physical parameters for the liquid scintillator BC-521.

Chemical composition	Atomic densities (cm^{-3})	Physical parameters
Base 1,2,4 Trimethyl-Benzene Gd-content 0.5% weight	H $5.231 \cdot 10^{22}$ C $4.004 \cdot 10^{22}$ O $3.409 \cdot 10^{20}$ Gd $1.000 \cdot 10^{18}$ e^- $2.958 \cdot 10^{23}$	flashing-point 44°C density 0.89 g/cm^3 refractive index 1.50 decay time 3.6 ns light attenuation $\lambda \geq 4 \text{ m}$ light output 68% (relative to Anthrazene)

fore, we consider also a segmentation of the vessel into two sections by dividing it along the plane passing through the target perpendicular to the beam axis. Apart from the modifications of the right-hand section, the geometry will then follow closely that of the HMI-Berlin NMM #2 in Table 1. One of the advantages of segmentation was already mentioned in the Introduction. A decreased background counting rate seen by each of the container sections in comparison with that from the total volume is the further advantage.

7.2 Distribution of capture sites

The spatial distribution of radiative capture events in Gd is shown in Fig. 11 for the two neutron energies $E_n=1 \text{ MeV}$ (left panel) and $E_n=30 \text{ MeV}$ (right panel). Since $\text{Gd}(n,\gamma)$ reactions occur predominantly in the thermal region (see Sect. 3.1), Fig. 11 illustrates how the slowing-down length increases with increasing neutron energy. Short slowing-down lengths at low energies (left panel) result in a concentration of the capture sites in the vicinity of the vacuum chamber. Obviously, only few of these neutrons escape the detector. The loss is essentially determined by the solid angle of the entrance and exit channels. As energy and slowing-down length increase, capture sites approach the external walls (right panel) indicating that neutrons with increasing probability leak out of the active volume. This and the increasing inelasticity of the $n+^{12}\text{C}$ interaction lead to a rapid decrease of the detection efficiency of the NMM (see below).

Figure 11: Distribution of capture sites within the NMM of Sect. 7.1 for the neutrons with $E_n=1$ MeV (left panel) and $E_n=30$ MeV (right panel).

7.3 Neutron capture efficiency

The qualitative conclusions of the preceding Section are expressed quantitatively in Fig. 12, which presents the balance of the number of neutrons emitted from the target at different energies. The solid curve indicates the neutron capture efficiency - the fraction that has been captured in the reactions #2, 22 and 23 of Table 2 within the detector volume. In the energy range $0 \leq E_n \leq 6$ MeV the detection efficiency is rather constant, because the neutrons suffer exclusively the propagating collisions with ^1H and ^{12}C , which lead with high probability into the thermal region. Consequently, in this range the efficiency is determined mostly by the dead volume (5%) and to lesser extent ($\sim 3\%$) by the leakage through walls. The fall-off above $E_n \approx 6$ MeV is caused by the combination of two factors: the increasing slowing-down length (dashed curve) and the loss in non-propagating reactions #8, 9 and 10 (dash-dotted curve). The latter reflects a nonmonotonic dependence on energy of the cross sections of these reactions. In particular, the resonant structure centered at $E_n \approx 9$ MeV in $^{12}\text{C}(n,\alpha)^9\text{Be}$ results in a spike in the dash-dotted curve (marked with the arrow), consequently a dip in the solid curve. Above $E_n \approx 20$ MeV the rate of decrease of the capture efficiency is diminished by the increasing

Figure 12: Number of neutrons balance. Solid curve - captured, dashed - lost through walls, dash-dotted - lost in reactions. Arrows mark the position of the group of resonances in the $^{12}\text{C}(n,\alpha)^9\text{Be}$ reaction, centered at $E_n \approx 9$ MeV.

Figure 13: Normalized probability density of capture times for the neutrons with $E_n=30$ MeV.

contribution of the $^{12}\text{C}(n,2n)^{11}\text{C}$ reaction, which adds an extra slow neutron into the system.

7.4 Time distribution of capture events and counting losses

Fig. 13 presents the time distribution of capture events. The simulation was performed for neutrons with $E_n=30$ MeV. The predicted shape, including the position of the maximum at $\approx 5 \mu\text{s}$, is in agreement with the measurements [18] for the NMM #1 in Table 1. The quantity governing its location is the slow-neutron average lifetime, which depends primarily on the Gd concentration and to lesser extent on the system size. We have the former in common with Ref. [18] and differ in the latter.

A concentration of the instants of capture in vicinity of the maximum inevitably leads to counting losses due to finite time resolution $\Delta\tau$ of the recording system. In order to evaluate them we generate M -fold events by drawing M -wise from the probability distribution, corresponding to the one-neutron density of Fig. 13. The

Figure 14: (a) Distributions of lost counts due to dead-time $\Delta\tau = 50$ ns of the recording electronics for the three multiplicities of captured neutrons. (b) Average (left ordinate) and variance (right ordinate) of the loss distribution as a function of M .

number of lost counts in each event is then determined by checking the distance Δt between the current capture and its nearest neighbour and treating the latter as lost if $\Delta t \leq \Delta\tau$. Fig. 14 presents the counting losses due to an NMM event handler [58] with the assumed dead-time $\Delta\tau = 50$ ns as a function of M , the multiplicity of captured neutrons. At $M=10$ in about 80% of all events there are no counting losses [Fig. 14(a)]. With increasing M both the average loss and the width of the loss distribution increase rapidly [Fig. 14(b)], the former exceeds 10% at $M=50$.

7.5 Summed energy spectrum of Compton electrons

The γ -ray quanta emitted following the neutron capture (Sect. 3.2) propagate independently, suffering Compton scatterings with the electrons of ^1H and ^{12}C atoms of the scintillator. Fig. 15 shows the spectrum of summed energies deposited by the Compton electrons in the active volume. The three prominent peaks correspond to conversion into the electron energy and its deposition in the scintillator of the full binding energy of a neutron in ^{156}Gd , ^{158}Gd and ^2H , respectively. The underlying continuum is due to the events with partial deposition because of either γ -ray escape and/or electron expending only a fraction of its energy in the sensitive vol-

Figure 15: Spectrum of summed energies deposited by the Compton electrons in the scintillator.

ume. These latter two effects are also responsible for the differences of widths between the multiplicity one, ^2H peak and the Gd peaks, which result from the cooperative effect of, on the average, 4.5 quanta of comparable energy (see Sect. 3.2). The higher chance of an escape makes the latter two peaks more prone to broadening.

7.6 Light transport and signal formation

The simulation of light transport was performed at $E_n=1$ MeV with the parameters specifying the volume absorption of the scintillator, $\lambda=4$ m [eq.(4)], and the surface reflectivity, $R_1=0.96$ [eq.(5) in Sect. 5.2]. The effective quantum efficiency of the PM photocathode was reported equal, $Q_e=0.27$ *phe/inc. ph* and the photoelectron collection efficiency on the first dynode, $f_e=0.6\div 0.8$ by the PM manufacturer [59]. We assumed a smaller product, $Q_e \cdot f_e=0.1$ *phe/inc. ph*, than that resulting from these values. Instead of $n_0 \approx 10^4$ *ph/MeV* [eq.(2)], the reported [59, 60] average light yield per unit energy deposited in the scintillator, we propagate 10^3 *ph/MeV* and assume a 100% photoelectron conversion efficiency for each photon reaching the photocathode. This leaves the product, eq. (6), invariant, therefore, leads to the same current at the PM output.

Fig. 16 presents the results of the simulation performed with the above assumptions. The quantity calculated by the program is the total number of light photons reaching the photocathodes of all PMs looking at the scintillator. The quantity taken

Figure 16: Amplitude spectrum resulting from adding the output signals of the individual PMs (see Sect. 7.6 for further details) at $E_n=1$ MeV.

as the abscissa in Fig. 16 is the relative pulse height. The latter is linearly related to the former (see Sect. 5.2), provided that PMs work in the linear amplification regime. One may note that the amplitude resolution is further deteriorated in comparison with Fig. 15, making the ^{156}Gd and ^{158}Gd peaks to merge. A combination of the limited photon statistics and fluctuations in their number, caused by the absorptive effects, is responsible for the resolution worsening.

Fig. 17 presents the rate of photon arrivals at the PM photocathodes [$\nu(t)$ in eq. (6)] from the entire detector volume at $E_n=1$ and 30 MeV, which have the corresponding distributions of the capture sites shown in Fig. 11. The instant of neutron capture is taken as the origin of time scale. One may note that significantly different distributions of capture sites only result in rather subtle differences between the two curves in Fig. 17. The width at half-maximum defines the minimum resolving time $\Delta\tau_{min} \simeq 3.6$ ns, to be imposed by the recording electronics, in order to collect all photons, irrespective of the location of light source. Further contributions to this $\Delta\tau_{min}$ come from the scintillator finite decay time (Table 5) and the electron transit time spreads in PMs, resulting in the reported [18] FWHM of the prompt peak of $\simeq 6$ ns.

Figure 17: Rate of photon arrivals from the NMM volume to the PM photocathodes at $E_n=1$ (solid curve) and 30 MeV (dashed curve), corresponding to the distributions of the capture sites shown in Fig. 11.

8 Conclusions

A Monte-Carlo program has been developed to simulate the consecutive stages of neutron detection process in a large-volume, Gd-loaded, liquid scintillation detector. A detailed account of the structure of the program and the utilized nuclear data resources is given.

The results of simulations are presented for the detector intended to count neutrons emitted by the highly excited target residue in coincidence with the charged products of the projectile fragmentation in relativistic HI collisions. The modifications of the standard geometry aimed at satisfying the requirements imposed by the physics involved and matching the existing ALADIN spectrometer environment do not affect adversely the main advantage of this detector type - high detection efficiency for the $0 \simeq 10$ MeV neutrons. This makes NMM an excellent filter to select those reactions in which many of these neutrons are emitted in the late stages of evolution of the residue, in which multifragmentation most probably occurs [30]. Supplemented with a light charged-particle multidetector, it will permit to perform measurements of excitation energy and temperature, intended to delineate the caloric curve.

The sources of distortions of the multiplicity spectra revealed by the simulations

are neutron multiplying reactions with ^{12}C and dead-time losses. The latter were estimated to reach 10% for a recording system with the 50 ns dead-time at the maximum expected [32] multiplicity, $M \approx 40$, corresponding to liberation of the entire neutron excess of the ^{197}Au nucleus.

MSX offers some additional features, not contained in the version of the code DENIS described in the early publication [33]. In particular, a simultaneous tracking of two (and more) neutrons produced in the $n+^{12}\text{C}$ interaction, an exact sampling of the radiative capture cross sections in the relevant energy range and γ -ray cascades in $^{156,158}\text{Gd}$ have been implemented. Last but not least, a simulation of the scintillation light transport, the stage entirely missing from DENIS, has been incorporated into MSX. The latter permits to evaluate NMM's performance in regimes utilizing the full amplitude information carried by the prompt and the delayed signals. It should be stressed, however, that in the modified versions of DENIS, in current use in several intermediate energy HI laboratories [23, 24, 34], some or all of these features might have already been introduced. The available information on their performance is too fragmentary to permit a detailed comparison with MSX.

An application of the recursive calling of the tracking subroutine offered an elegant and efficient solution to the problem of branchings in tracking. They appear whenever the multiplicity of the simultaneously produced particles to be tracked by the program exceeds one. The method may, therefore, find a more general application for the efficiency simulations in other detector types, in which such effects are also relevant (e.g. in the electromagnetic shower detectors).

Some additional features are planned to be included in succession determined by the priorities dictated by the local and/or external requests. Part of the presented results has been reported briefly at the Conference [61].

Acknowledgements

Sincere thanks are due to L.V. Pikelner and G.P. Georgiev, Frank Laboratory for Neutron Physics, JINR (Dubna), for the measurements of γ -ray multiplicity spectra of Sect. 3.2, performed on our request; H.D. Lemmel, Nuclear Data Section, IAEA (Vienna), for presenting the data files of Sect. 3.1 into our disposal and his expert

help in getting started with them; M. Herman and A. Marcinkowski, SINS (Warsaw), for their guidance through the program EMPIRE and the questions related to γ -ray transmission coefficients; W.U. Schröder, NSRL (University of Rochester), for the unpublished references #21 and 25; T. von Egidy (Technical University of Munich) for his expert advice on $Gd(n,\gamma)$ spectra; J. Kopecky, ECN (Petten), for Ref. #48; and M. Moszyński, SINS (Swierk), for the light-yield references #57 and 58. We acknowledge exchange of correspondence with U. Jahnke (HMI-Berlin), J. Galin (GANIL-Caen), R.P. Schmitt (Texas A&M University) and W.U. Schröder (University of Rochester) on various practical aspects of NMMs and thank them for encouragement.

References

- [1] F. Reines, C.L. Cowan, jr., F.B. Harrison, D.S. Carter, *Rev. Sci. Instr.* 25(1954)1061.
- [2] G. Chodil, R.C. Jopson, H. Mark, C.D. Swift, R.G. Thomas, M.K. Yates, *Nucl. Phys.* A93(1967)648.
- [3] V.J. Ashby, C.H. Catron, L.L. Newkirk, C.J. Taylor, *Phys. Rev.* 111(1958)616.
- [4] J. Frehaut, *Nucl. Instr. and Meth.* 135(1976)511.
- [5] M. Holmberg, J. Hansen, *Nucl. Phys.* A129(1969)305;
M. Holmberg, *Nucl. Phys.* A129(1969)327.
- [6] L.R. Veaser, E.D. Arthur, P.G. Young, *Phys. Rev.* C16(1977)1792.
- [7] V. Kneissl, G. Kuhl, H.-H. Leister, A. Weller, *Nucl. Phys.* A247(1975)91.
- [8] A. Leprêtre, H. Beil, R. Bergère, P. Carlos, J. Fagot, A. de Miniac, A. Veyssiére, *Nucl. Phys.* A367(1981)237.
- [9] A. Hicks, J. Ise, jr., R.V. Pyle, *Phys. Rev.* 101(1956)1016.
- [10] D.C. Hoffman, G.P. Ford, J.P. Balaga, L.R. Veaser, *Phys. Rev.* C21(1980)637.
- [11] D.S. Mather, P. Fieldhouse, A. Moat, *Phys. Rev.* 133(1964)1403.
- [12] M. Soleilhac, J. Frehaut, J. Gauriau, *J. Nucl. Energy* 23(1969)257.

- [13] E. Cheifetz, R.C. Jared, E.R. Giusti, S.G. Thompson, Phys. Rev. C6(1972)1348.
- [14] U. Jahnke, G. Ingold, H. Homeyer, M. Bürgel, Ch. Egelhaaf, H. Fuchs, D. Hilscher, Phys. Rev. Lett. 50(1983)1246.
- [15] U. Jahnke, G. Ingold, D. Hilscher, M. Lehmann, E. Schwinn, P. Zank, Phys. Rev. Lett. 57(1986)190.
- [16] J. Galin, U. Jahnke, J. Phys. G: Nucl. Part. Phys. 20(1994)1105.
- [17] H.-J. Becker, R. Brandt, H. Jungclas, T. Lund, D. Molzahn, Nucl. Instr. and Meth. 159(1979)75.
- [18] U. Jahnke, G. Ingold, D. Hilscher, H. Orf, E.A. Koop, G. Feige, R. Brandt, Lecture Notes in Physics vol. 178 (Springer, Berlin, 1983), p.179.
- [19] B. Cramer, D. Hilscher, G. Ingold, U. Jahnke, M. Lehmann, E. Schwinn, K. Schulz, H. Neumann, M. Rose, H. Constein, Annual Report HMI-Berlin (1986), p.84.
- [20] E. Schwinn, B. Cramer, D. Hilscher, G. Ingold, U. Jahnke, Annual Report HMI-Berlin (1987), p.80.
- [21] S.P. Baldwin, M.B. Chatterjee, J.R. Huizenga, D. Pade, W.U. Schröder, B.M. Szabo, J. Töke, University of Rochester NSRL Progress Report (Sept. 1, 1989 - Aug. 31, 1990), p.247.
- [22] W.U. Schröder, Nucl. Phys. A538(1992)439c.
- [23] J. Galin, X.M. Wang, E. Crema, D. Guerreau, D.X. Jiang, M. Morjean, J. Pouthas, F. Saint-Laurent, A. Sokolov, B. Gatty, D. Jacquet, B. Lott, U. Jahnke, E. Schwinn, E. Piasecki, J.L. Charvet, Proc. of the Second IN2P3 - RIKEN Symposium, Obernai, ed. by B. Heusch and M. Ishihara (World Scientific, Singapore, 1990), p.102.
- [24] R.P. Schmitt, L. Cooke, G. Derrig, D. Fabris, B. Hurst, J.B. Natowitz, G. Nebbia, D. O'Kelly, B.K. Srivastava, W. Turmel, D. Utley, H. Utsunomiya, R. Wada, Nucl. Instr. and Meth. A354(1995)487.
- [25] X. Zhao, S.P. Baldwin, W.U. Schröder, J. Töke, University of Rochester NSRL Progress Report (Sept. 1, 1991 - Aug. 31, 1992), p.190.

- [26] D.P. Sanderson, T. Glasmacher, J. Ottarson, W.U. Schröder, J. Töke, X. Zhao, S. Baldwin, D. Agnihotri, Michigan State University NSCL Progress Report (Jan. 1, 1991 - Aug. 31, 1993), p. 190.
- [27] T. Blaich, T.W. Elze, H. Emling, H. Freiesleben, K. Grimm, W. Henning, R. Holzmann, G. Ickert, J.G. Keller, H. Klingler, W. Kneissl, R. König, R. Kulesa, J.V. Kratz, D. Lambrecht, J.S. Lange, Y. Leifels, E. Lubkiewicz, M. Proft, W. Prokopowicz, C. Schütter, R. Schmidt, H. Spies, K. Stelzer, J. Stroth, W. Waluś, E. Wajda, H.J. Wollersheim, M. Zinser, E. Zude, Nucl. Instr. and Meth. A314(1992)136.
- [28] Hongfei Xi, T. Odeh, R. Bassini, M. Begemann-Blaich, A.S. Botvina, S. Fritz, S.J. Gaff, C. Gross, G. Imme, I. Iori, U. Kleinevoss, G.J. Kunde, W.D. Kunze, U. Lynen, V. Maddalena, M. Mahi, T. Möhlenkamp, A. Moroni, W.F.J. Müller, C. Nociforo, B. Ocker, F. Petruzzelli, J. Pochodzalla, G. Raciti, G. Riccobene, F.P. Romano, Th. Rubehn, A. Saija, M. Schnittker, A. Schüttauf, C. Schwarz, W. Seidel, V. Serfling, C. Sfienti, W. Trautmann, A. Trzcinski, G. Verde, A. Wörner, B. Zwieglinski, Z. Phys. A359(1997)397.
- [29] J. Pochodzalla, T. Möhlenkamp, T. Rubehn, A. Schüttauf, A. Wörner, E. Zude, M. Begemann-Blaich, Th. Blaich, A. Cosmo, A. Ferrero, G. Imme, I. Iori, G.J. Kunde, W.D. Kunze, V. Lindenstruth, U. Lynen, A. Moroni, W.F.J. Müller, B. Ocker, G. Raciti, A. Trzcinski, W. Trautmann, A. Tucholski, G. Verde, B. Zwieglinski, Phys. Rev. Lett. 75(1995)1040.
- [30] A. Schüttauf, W.D. Kunze, A. Wörner, M.L. Begemann-Blaich, Th. Blaich, D.R. Bowman, R.J. Charity, A. Cosmo, A. Ferrero, C.K. Gelbke, C. Gross, W.C. Hsi, J. Hubele, G. Imme, I. Iori, J. Kempter, P. Kreutz, G.J. Kunde, V. Lindenstruth, M.A. Lisa, W.G. Lynch, U. Lynen, M. Mang, T. Möhlenkamp, A. Moroni, W.F.J. Müller, M. Neumann, B. Ocker, C.A. Ogilvie, G.F. Peaslee, J. Pochodzalla, G. Raciti, F. Rosenberger, Th. Rubehn, H. Sann, C. Schwarz, W. Seidel, V. Serfling, L.G. Sobotka, J. Stroth, L. Stuttge, S. Tomasevic, W. Trautmann, A. Trzcinski, M.B. Tsang, A. Tucholski, G. Verde, C.W. Williams, E. Zude, B. Zwieglinski, Nucl. Phys. A607(1996)457.

- [31] I. Tilquin, Y. El Masri, M. Parlog, Ph. Collon, M. Hadri, Th. Keutgen, J. Lehmann, P. Leleux, P. Lipnik, A. Ninane, F. Hanappe, G. Bizard, D. Durand, P. Mosrin, J. Péter, R. Régimbart, B. Tamain, Nucl. Instr. and Meth. A365(1995)446.
- [32] E. Zude, PhD thesis, Universität Frankfurt, 1993, unpublished;
C. Gross, PhD thesis, Universität Frankfurt, 1997, unpublished.
- [33] J. Poitou, H. Nifenecker, C. Signarbieux, Report CEA-N-1282(1970);
J. Poitou, C. Signarbieux, Nucl. Instr. and Meth. 114(1974)113.
- [34] B. Quednau, D. Pade, University of Rochester NSRL Progress Report (Sept. 1, 1989 - Aug. 31, 1990), p. 170.
- [35] M. Morjean, C. Lebrun, D. Ardouin, A. Chbihi, H. Dabrowski, B. Erasmus, P. Eudes, J. Galin, D. Guerreau, F. Guilbault, C. Ghisalberti, D. Jacquet, P. Lautridou, R. Lednický, A. Péghaire, Y. Périer, J. Pluta, J. Quebert, A. Rahmani, T. Reposeur, L. Sezac, R.H. Siemssen, Nucl. Phys. A591(1995)371.
- [36] C. Ghisalberti, C. Lebrun, L. Sezac, D. Ardouin, A. Chbihi, H. Dabrowski, B. Erasmus, P. Eudes, J. Galin, D. Guerreau, F. Guilbault, P. Lautridou, R. Lednický, M. Morjean, A. Péghaire, J. Pluta, J. Quebert, A. Rhamani, T. Reposeur, R.H. Siemssen, Proc. XXXI Int. Winter Meeting on Nuclear Physics, Bormio 1993, ed. I. Iori (Università degli Studi di Milano, Milan, 1993), p. 293.
- [37] H.D. Lemmel, Nuclear Data Section, IAEA (Vienna), 1996 (private communication).
- [38] M. Herman, A. Marcinkowski, K. Stankiewicz, Comp. Phys. Commun. 33(1984)373.
- [39] J. Klorá, H.G. Börner, T. von Egidy, R. Georgii, J. Jolie, S. Judge, V.A. Khitrov, B. Krusche, V.A. Libman, H. Lindner, L.L. Litvinsky, U. Mayerhofer, A.V. Murzin, S.J. Robinson, A.M. Sukhovoý, H. Trieb, Nucl. Phys. A561(1993)1.
- [40] A. Bäcklin, G. Hedin, B. Fogelberg, M. Saraceno, R.C. Greenwood, C.W. Reich, H.R. Koch, H.A. Baader, H.D. Breitig, O.W.B. Schult, K. Schreckenbach, T. von Egidy, W. Mampe, Nucl. Phys. A380(1982)189.

- [41] R.G. Helmer, Nucl. Data Sheets 65(1992)65.
- [42] R.C. Greenwood, C.W. Reich, H.A. Baader, H.R. Koch, D. Breitig, O.W.B. Schult, B. Fogelberg, A. Bäcklin, W. Mampe, T. von Egidy, E. Schreckenbach, Nucl. Phys. A304(1978)327.
- [43] M.A. Lee, Nucl. Data Sheets 56(1989)199.
- [44] L.V. Groshev, A.M. Demidov, V.A. Ivanov, V.N. Lutsenko, V.I. Pelekhov, Izv. Akad. Nauk SSSR (Ser. Fiz.) 26(1962)1119.
- [45] A. Gilbert, A.G.W. Cameron, Can. J. Phys. 43(1965)1446.
- [46] L.V. Groshev, A.M. Demidov, V.I. Pelekhov, L.L. Sokolovskii, G.A. Bartholomew, A. Doveika, K.M. Eastwood, S. Monaro, Nucl. Data Tables A5(1968)1.
- [47] D.M. Brink, Ph.D. thesis, Oxford University (1955), unpublished;
P. Axel, Phys. Rev. 126(1962)671.
- [48] J. Kopecky, M. Uhl, R.E. Chrien, ECN-Petten Report, ECN-RX-92-011(1992).
- [49] L.V. Pikelner, G.P. Georgiev, Frank Laboratory for Neutron Physics, JINR-Dubna, private communication (1994).
- [50] F.N. Belyaev, V.P. Bolotskii, B.V. Jefimov, G.V. Muradyan, Yad. Fiz. 52(1990)625.
- [51] F. Gunsing, F. Corvi, H. Postma, F. Bečvář, Nucl. Instr. and Meth. A365(1995)410.
- [52] J.B. Birks, *The theory and practice of scintillation counting* (Pergamon, London, 1964).
- [53] F.T. Porter, J.M.S. Freedman, F. Wagner, I.S. Sherman, Nucl. Instr. and Meth. 39(1966)35;
V. O'Rielly, N.R. Colb, R.E. Pywell, Nucl. Instr. and Meth. A368(1996)745.
- [54] R.L. Craun, D.L. Smith, Nucl. Instr. and Meth. 80(1970)239.
- [55] S. Mouatassim, G.J. Costa, G. Guillaume, B. Heusch, A. Huck, M. Moszyński, Nucl. Instr. and Meth. A359(1995)530.
- [56] T.W. Armstrong, K.C. Chandler, Nucl. Instr. and Meth. 113(1973)313;
T.W. Armstrong, K.C. Chandler, Report ORNL - 4869(1973).

- [57] M. Born, E. Wolf, *Principles of Optics. Electromagnetic theory of Propagation, Interference and Diffraction of Light*, 6-th ed. (Pergamon Press, Oxford, 1980).
- [58] J. Töke, S.P. Baldwin, University of Rochester NSRL Progress Report (Sept. 1, 1988 - Aug. 31, 1989), p. 218.
- [59] M. Miyajima, S. Sasaki, H. Tawara, IEEE Trans. Nucl. Sci. NS-40/4(1993)417.
- [60] I. Holl, E. Lorenz, G. Mageras, IEEE Trans. Nucl. Sci. NS-35/1(1988)105.
- [61] A. Trzciński, B. Zwiegliński for the ALADIN Collaboration, Proc. of the XXXI Zakopane School of Physics - Trends in Nuclear Physics, Zakopane (Poland), Sept. 3-11, 1996, Acta Phys. Pol. B28(1997)145.