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ON THE ABSOLUTE EFFICIENCY OF LARGE NEUTRON DETECTORS FOR MCF

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1 Introduction

At the Dubna phasotron the **d+t** and **d+d** Muon Catalized Fusion reactions are studied to determine basic catalysis parameters [1]. These measurements yield amongst others the quantity [2]: $\omega/(1-\omega)\epsilon_n$. To extract the effective sticking probability ω it is imperative to know the absolute neutron detection efficiency ϵ_n of the setup.

Neutron detectors with organic scintillators are widely used in modern physical experiments. The advantages are: a high detection efficiency and a good timing characteristic, at low costs. Organic scintillators are sensitive to neutrons because elastic scattering off the hydrogen nuclei leads to recoil protons. Other reactions also contribute significantly. Such reactions are for instance: elastic and inelastic scattering off Carbon, ${}^{12}C(n,n')C^* \rightarrow 3\alpha$ or ${}^{12}C(n,\alpha)^9Be$.

It is not trivial to determine the absolute neutron detection efficiency for organic scintillation counters, because it is influenced by factors like the geometry of the surrounding material, the generation of light by the various reaction products and because many energy dependent cross sections are involved. However, in our case, the outcome of the experiment directly depends on the absolute value of the neutron intensity. Because in calibration measurements the experimental conditions can not be reproduced accurately and because the lack of neutron calibration sources with well known intensity and with sufficiently high energy (14 MeV), the efficiency has to be calculated. We used Monte Carlo simulation techniques to do this.

2 Monte Carlo Simulation

For performing Monte Carlo calculations there are many 'standard' codes available. All have their specific limitations with regard to types of particles and interactions which can be assessed, geometries which can be handled and the energy ranges for which the cross sections are valid.

For the neutron efficiency calculations the CERN package GEANT [3] has been used. This package has excellent geometry handling and particle tracking capabilities, but it lacks the appropriate slow neutron interaction cross sections. Therefore use has been made of the GEANT-CALOR [4, 5] interface, which links GEANT with the CALOR89 [6] package. A schematic top view of the calculational geometry is shown in figure 1, together with a few calculated tracks.

2.1 Neutron cross sections

In CALOR89 it is the MICAP [7] code which handles neutron cross sections from 20 MeV down to thermal energies (10^{-5} eV). MICAP uses all experimental neutron cross sections from the ENDF/B-VI data base in a pre-processed form. This includes: partial cross sections, angular distributions, energy distributions of reac-

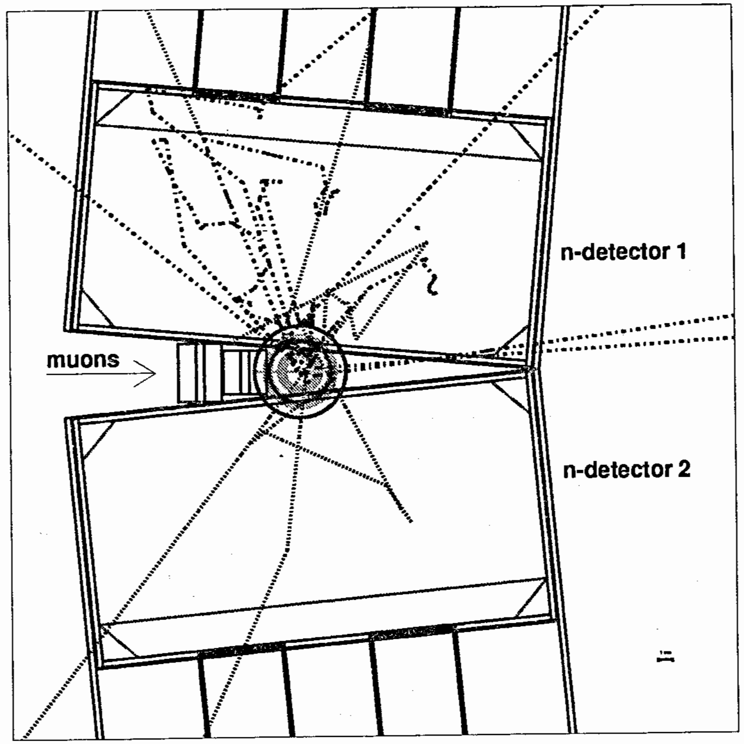

Figure 1: Top view of the target intimately surrounded by the two neutron detectors. A few calculated tracks are shown (dash–dotted for neutrons, dotted for gammas)

tion products and de-excitation photons in case the residual nucleus remains in an excited state after the interaction.

MICAP uses point–cross sections, which means that the cross section values are evaluated at precisely the current energy. This is in contrast to many other neutron codes, where a cross section value is used which is averaged over a certain energy interval. This latter approach is likely to give erroneous results in resonance regions. In addition, the version of the MICAP code used with the GEANT-CALOR interface is fully analogue. This means that secondary particles are explicitly generated according to the sampling of a Poisson distribution with a mean of the generated particle weight. Also final states are sampled.

The pre-processed ENDF/B-VI data represent the experimental data within 2%. The process types implemented via the MICAP code in the GEANT-CALOR interface are listed in table 1.

Type of reaction	Secondary particle
Elastic scattering	n
(nA,n'A')	n
(nA,2n'A')	2n
(nA,n'αA')	n, α
(nA,2n'αA')	2n, α
(nA,n'pA')	n, p
(nA,n'3αA')	n, 3α
(nA,γA)	γ
(nA,pA')	p
(nA,DA')	D
(nA,TA')	T
(nA,^{3}HeA')	^{3}He
(nA,αA')	α
(nA,2αA')	2α
(nA,3αA')	3α
(nA,2pA')	2p
(nA,pαA')	p, α
(nA,D2αA')	D, 2α
(nA,T2αA')	T, 2α
Fission	n, p, α

Table 1: List of processes implemented by MICAP.

2.2 Neutron tracking

In the Monte Carlo calculations a particle (neutron) is tracked through the geometry in a number of discrete 'steps' in space. The determination of the step length is a critical task; GEANT does this automatically. The step length depends primarily on the intrinsic properties of the particle (mass, charge etc.) and on parameters which are set for the material where the particle is moving through.

A central subroutine in this respect is GUSTEP. This subroutine is called on some of the following occasions:

- **at the end of a step**
  When photo electric or hadronic interactions are switched on the program will *not* step over the (discrete) occurrences of such processes,
- **when entering a new volume or exiting from a volume**
- **if the particle has disappeared**
  This can happen in some interactions, or when the particle decays
- **when the energy has fallen below a threshold**
  A lower threshold of 1 keV has been used throughout

GUSTEP has to be provided by the user, who can, depending on the setting of some indicators, detect the circumstances leading to the call of GUSTEP and take the appropriate action. A stream diagram of GUSTEP is shown in figure 2.

2.3 Light response

After the calculation of the energy deposited inside the scintillator the electric output signal is obtained by first converting the energy into scintillation light considering the particle type, and next converting the total light output into an electric signal by applying the detector response function.

2.3.1 Electron equivalent light yield, MeVee

The amount of light produced by a charged particle in scintillator material depends not only on the particle energy, but also on the mass and charge of the particle. The light output of electrons is known to be a linear function of the electron energy. The light output of other charged particles is always less then the electron light output and not linear with energy. For different particles the quantity of light which they produce is conveniently expressed in terms of an equivalent electron energy, MeVee. MeVee is the energy required by an electron to yield the same amount of light as the particle considered. MeVee will always be lower then the particle energy itself.

Many empirical relations for MeVee exist [8, section 2.5.1]. Since our scintillator material closely resembles NE102 or BC404, we used the following relations (all energy values in MeV):

1. **electrons** Ref. [9]
   $$\mathtt{MeVee}_e = E_e - 0.005$$
2. **protons** Ref. [10, 11]
   $$\mathtt{MeVee}_p = -8.0(1 - e^{-0.1E_p^{0.9}}) + 0.95E_p \qquad \text{for } E_p > 1.19$$
   $$\mathtt{MeVee}_p = 0.0735E_p + 0.0787E_p^4 \qquad \text{for } E_p < 1.19$$
   at the switch over energy both formulas yield the same value. The energy ranges quoted in the literature references are respectively: $2.43 < E_p < 19.55$ and $E_p < 1.05$
3. **deuterons** Ref. [12]
   This light yield is derived from the proton value with:
   $$\mathtt{MeVee}_d = 0.75\mathtt{MeVee}_p$$
4. **alphas** Ref. [13]
   $$\mathtt{MeVee}_\alpha = -5.9(1 - e^{-0.065E_\alpha^{1.01}}) + 0.41E_\alpha$$
5. **Beryllium-9** Ref. [14]
   $$\mathtt{MeVee}_{^9Be} = 0.013E_{^9Be}$$

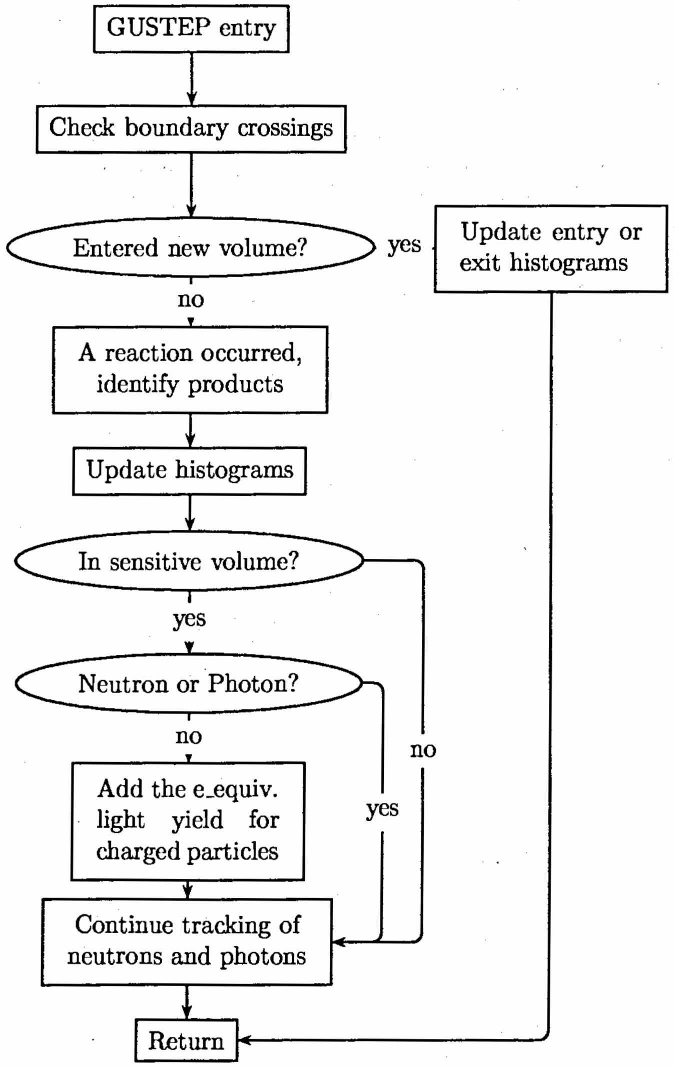

Figure 2: Stream diagram of routine GUSTEP

6. **Borium-11** Ref. [14]
   $\texttt{MeVee}_{^{11}B} = 0.0097 E_{^{11}B}$

7. **Carbon** Ref. [11, 15]
   $\texttt{MeVee}_C = 0.016 E_C + 0.0004 E_C^2$ for $E_C < 5$
   $\texttt{MeVee}_C = 0.01 E_C$ for $E_C > 5$

2.3.2 Detector response

When the light has been released inside the scintillator volume it is transformed into an electric signal by four photo multiplier tubes, mounted on the back side of the scintillator. The response function describing the transformation of the light into an electric signal is Gaussian shaped. This shape is due to factors such as non-uniform light collection depending on the position of light generation inside the scintillator and to photon statistics. For the detectors employed here it has been shown [16] that the sigma of the Gaussian is approximately:

$$\sigma = 0.05 \left(1 + \frac{1}{\sqrt{\texttt{MeVee}}}\right)$$

with MeVee in MeV. The mean of the Gaussian of course is MeVee. The actual output signal of course depends on the amplifier settings.

2.4 Simulation program execution

The simulations were carried out on a number of DECalpha systems in parallel using PVM [17]. PVM, or *P*arallel *V*irtual *M*achine, is a package which "$\cdots$ enables a collection of heterogeneous computers to be used as a coherent and flexible concurrent computational resource". It allows the parallel and simultaneous execution of parts of a job on a number of computers. The computers operate in fact as the components of a larger parallel processing system, thereby increasing the processing power.

We used three machines for calculating the events with GEANT. These machines send their histogram data to a fourth one. This machine acts as the controlling master, which starts the other 'slave' machines, collects the histogram data, and builds the histograms using the CERN HBOOK package [18]. The histograms are maintained in a resident memory region. This has the advantage that the histograms can be inspected while the data are coming in, using the CERN analysis program PAW [19]. Also, the histograms are not lost in case of a program crash, since the memory region remains intact. Normal execution times are in the order of one day.

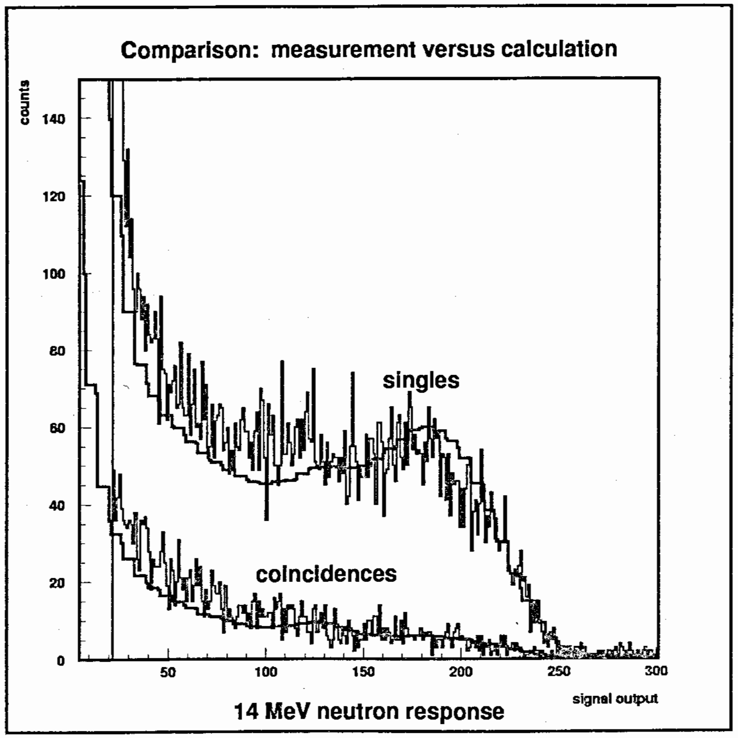

Figure 3: Measured and calculated (heavy line) spectra for singles and coincidences.

3 Results

One neutron generated from the hydrogen may generate a response from one detector or, due to scattering or to generated gamma rays, from both detectors. This leads to a singles rate and a coincidence rate. The corresponding spectra are shown in figure 3, together with the measured spectra [1]. Because of pulse pile-up due to a low neutron multiplicity the measured spectrum shapes are somewhat flattened compared to the calculated ones.

The intensity and calibration of the calculated singles spectrum has been normalized to the singles data. The normalization thus obtained is then applied to the calculated coincidence spectrum, which then neatly coincides with the corresponding data. This means that the total–coincident ratio is well predicted by the calculations, which is considered to be a sensitive validation check.

The total efficiency amounts to some 65±2 %, slightly dependent on the target filling conditions.

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Об абсолютной эффективности больших нейтронных детекторов для мюонного катализа

Абсолютная эффективность большого органического сцинтилляционного нейтронного детектора была определена методом Монте-Карло для нейтронов с энергией 14 МэВ. Было учтено влияние окружающей геометрии (рассеяние на источнике и т.д.) и использованы полные дифференциальные сечения, включая резонансы. Вычисленная функция отклика хорошо совпадает с измеренной.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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On the Absolute Efficiency of Large Neutron Detectors for MCF

The absolute efficiency for a large organic scintillator neutron detector has been calculated by Monte Carlo simulation for neutrons of 14 MeV. The influence of the environmental geometry (source scattering etc.) has been taken into account. Full differential cross sections, including resonances, have been used. The calculated response function compares well with the measured one.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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