DD

CRN 94-68

The light yield response of NE213 organic scintillators to
charged particles resulting from neutron interactions

S. MOUATASSIM, G.J. COSTA, G. GUILLAUME, B. HEUSCH,
A. HUCK and M. MOSZYNSKI

Accepted for publication in NIM A

• • • • •

SCAN-9506094

CERN LIBRARIES, GENEVA

SW9525

CENTRE DE RECHERCHES NUCLEAIRES
STRASBOURG

IN2P3
CNRS

UNIVERSITE
LOUIS PASTEUR

The light yield response of NE213 organic scintillators to charged particles resulting from neutron interactions

S. Mouatassim, G.J. Costa, G. Guillaume, B. Heusch, A. Huck and
M. Moszyński¹

*Centre de Recherches Nucléaires, IN2P3-CNRS/Université Louis Pasteur, BP 28,
F-67037 Strasbourg Cedex 2, France*

Abstract

The n - γ discrimination by the charge integration method has been used with a NE213 liquid cell associated with a specific photomultiplier Philips XP4512B. Such a device, which is part of the DEMON array (French abbreviation for DEtecteur MODulaire de Neutrons), permitted us to identify up to six high energy neutron reaction channels in an organic scintillator. Through the analysis of recoil charged-particle spectra, light yields of protons, deuterons, tritons and alphas were deduced. Experimental results were fitted by the method of least squares to the two parametric formulae proposed respectively by Birks and Chou. Depending on the type of the detected charged particles, the KB and C parameters are extracted and compared to some values reported in the literature.

1 INTRODUCTION

Neutrons, unaffected by the coulomb interaction, are emitted with high multiplicities in heavy ion reactions. Their measurements permit the calculation of initial excitation energies and allow the determination of reaction time scales with less uncertainty than do charged-particle measurements [1]. Thus, neutron detection is of great importance for the study of heavy ion reaction mechanisms, and allows fusion-fission and quasifission

¹On leave from the Soltan Institute for Nuclear Studies, PL 05-400 Świerk-Otwock, Poland (present address).

dynamics to be studied more profoundly. The understanding of these processes has been improved especially in the last decade through neutron measurements [2, 3]. However, further progress will surely occur with better knowledge and command of high energy neutron detection.

Up to now, organic scintillators seem to be the best tool for neutron detection, even if their intrinsic efficiencies are far from 100%. The detection efficiency of the neutrons, which are indirectly detected by means of charged particles produced through $^{12}\text{C}(n, a)\text{A}$ reactions and n - p elastic scattering, depends on the cross-sections of these different interaction channels. On the other hand, the contribution to the neutron efficiency of each reaction channel depends on the detection threshold and is governed, in scintillators, by the light yield of the resulting charged particles. The comparison of experimental measurements and Monte Carlo based calculations of the neutron detection efficiency for organic scintillators has shown disagreement which becomes significant at high neutron energies [4, 5, 6]. Moreover, in the Monte Carlo programs only proton and α -particle light responses are taken into account [7]. Thus, precise measurements of differential $^{12}\text{C}(n, a)\text{A}$ reaction cross sections and charged-particle light yield in organic scintillators are needed for improving the Monte Carlo based programs.

We recently reported on the results concerning the identification of the reaction channels involved in the high energy (40 and 56 MeV) neutron detection and estimation, for some of those channels, of the total cross-section [8]. The aim of this paper is to present experimental light yield data which were derived from the reported spectra [8] for protons, deuterons, tritons and α -particles and also from recent measurements made in our laboratory for protons. These available data are fitted by using parametric formulae based on Birks's [9] and Chou's [10] theoretical works. The fitted curves can be used in efficiency calculation programs for determining the light yield response for protons, deuterons, tritons and α -particles.

2 Theoretical approaches

In organic scintillators, the light yield response to heavy charged particles is a nonlinear function of the incident particle energy. Only a relatively small fraction of the excitation

energy communicated to molecules by a charged particle in the scintillator is converted into fluorescent light energy. The rest of the energy is dissipated non-radiatively mainly by the internal quenching effect and also by radiative and non-radiative migration of the excitation energy to neighbouring molecules and self-absorption [9]. Birks in 1951 [9], assuming that the quenching effect occurs for the primary excitation by the high density of ionized and excited molecules within a short time compared to the fluorescent time scales ($\leq 1\text{ns}$), proposed the following relationship :

$$\frac{dL}{dx} = S \left(\frac{dE}{dx} \right) \left\{ 1 + KB \left(\frac{dE}{dx} \right) \right\}^{-1} \quad (1)$$

$\frac{dL}{dx}$: fluorescence light energy emitted per unit path length

S : scintillation efficiency

$\frac{dE}{dx}$: specific energy loss for a given type of charged particle

In the Birks description [9], the molecules all along the ionizing particle's path are divided into two groups : the first one for damaged molecules and the second for undamaged ones. The ratio of the number of damaged molecules to that of undamaged ones is represented by the term $B(dE/dx)$ and K is the relative quenching probability for one damaged particle. Some permanently damaged molecules are not excluded and contribute to the long-term deterioration of the scintillator properties. These are not considered in the Birks theory.

Since there is no possibility to measure the parameters K and B separately, the product KB is obviously treated as a single parameter.

Later on, Chou (1952) [10] gave a semi-empirical analysis which leads to a sort of modified Birks relationship between the specific fluorescence emission and the energy loss in a small element of the track of a charged particle, by introducing an additional free parameter in the Birks formula (2). His mathematical expression is the following :

$$\frac{dL}{dx} = S \left(\frac{dE}{dx} \right) \left\{ 1 + KB \left(\frac{dE}{dx} \right) + C \left(\frac{dE}{dx} \right)^2 \right\}^{-1} \quad (2)$$

where C is a constant. This Chou equation can be considered a generalization of that of Birks.

By attributing the non-radiative dissipation of molecular excitation energy to both the unimolecular and bimolecular quenching effect, Wright in 1953 treated the problem as follows [11]. Considering a sample of molecules belonging to the length dx of the path with excess electronic energy ϵ , we have :

$$d\epsilon = -(p + k + a\epsilon)\epsilon dt \quad (3)$$

where $a\epsilon$, k and p are the rates of energy dissipation by bimolecular quenching, unimolecular quenching and fluorescent emission respectively. The following expression is then obtained by integrating the fluorescent emission energy over time :

$$\frac{dL}{dx} = \frac{p}{a} \log_e \left(1 + \frac{a}{p+k} \frac{dE}{dx} \right) \quad (4)$$

The three parametric formulae of Birks, Chou and Wright were used to fit our experimental light yield data. The best fits were obtained with Chou and Birks formulae. The Wright relationship overestimates the light yield for the high charged-particle energies. Thus, only the results concerning the Birks and Chou expressions for the light yield are presented in this work.

Coming back to the Chou expression, the scintillation efficiency factor assumed to be independent of the specific energy loss, eq. (2) can be written :

$$\frac{dL}{dE} = S \left\{ 1 + KB \left(\frac{dE}{dx} \right) + C \left(\frac{dE}{dx} \right)^2 \right\}^{-1} \quad (5)$$

The light yield is then obtained by integrating this expression over the energy range :

$$L = S \int_0^E \left\{ 1 + KB \left(\frac{dE}{dx} \right) + C \left(\frac{dE}{dx} \right)^2 \right\}^{-1} dE \quad (6)$$

where L corresponds to the fluorescence emission energy of the scintillator for a charged-particle of energy E , with the assumption that the scintillator is large enough for complete deposition of the energy of the particle.

The specific energy losses (dE/dx) required for this work were calculated from data of the references [12, 13]. We used a stopping power parametrisation for protons and alphas of the following form :

$$\frac{dE}{dx} = \exp\{a_0 + a_1 \log_e E + a_2(\log_e E)^2 + a_3(\log_e E)^3\} \quad (7)$$

The numerical values given by this parametric expression correspond within 1% to the values determined from the reported data [12, 13]. For the specific energy loss of deuterons and tritons in the NE213 liquid scintillator the following relations have been used :

$$\left(\frac{dE}{dx}\right)_d(E) = \left(\frac{dE}{dx}\right)_p\left(\frac{E}{2}\right) \quad \text{and} \quad \left(\frac{dE}{dx}\right)_t(E) = \left(\frac{dE}{dx}\right)_p\left(\frac{E}{3}\right)$$

3 EXPERIMENTAL DETAILS

In all our measurements two dimensions of cylindrical cells filled with the organic liquid scintillator were used :

- a) 5 cm in diameter and 5 cm in depth b) 16 cm in diameter and 20 cm in depth

Two types of organic liquid scintillator were used : NE213 and BC501A. Both having the same physico-chemical and optical properties, the measurements allowed a qualitative comparison to be made which is treated in another paper [14]. All the types of scintillator were coupled to the same 130 mm diameter Philips XP4512B photomultiplier [15]. Part of our experiments were done at the cyclotron CYCLONE of Louvain-la-Neuve through the ${}^7\text{Li}(p,n)$ reaction. A 3 mm thick ${}^7\text{Li}$ target was bombarded by a proton beam of different energies. The small (5 cm $\times$ 5 cm) and the large (16 cm $\times$ 20 cm) scintillators were set at 1.6 and 5 m distance from the target, respectively, to subtend the same solid angle. Other experiments were performed at the 4 MV Van de Graaff of the Centre de Recherche Nucléaires in Strasbourg by detecting neutrons from the ${}^3\text{H}({}^2\text{H},n)$ reaction. In this case we were able to obtain a wide range of neutron energies by moving the detector module of DEMON [16, 17, 18] to different angular positions ($12 \leq E_n \leq 19$ MeV).

For the n - γ discrimination, we used the digital charge comparison method. The details of this technique are explained in references [8, 19]. The total charge (Q_1) and the charge of the slow component (Q_2) of the anode signal are compared in a two-dimensional spectrum

(Q_1, Q_2) . Moreover, the data acquisition system, built in VME, was gated by the signal corresponding to the neutron time of flight for the rejection of direct γ -rays. The counter mounted with the small NE213 scintillator cell ($5 \text{ cm} \times 5 \text{ cm}$) is characterised by a high photoelectron yield and an excellent power of n - γ discrimination reflected by a factor of merit $M = 3.6$ for 1 MeV electron equivalent (MeVee) [14]. A MeVee is a conventional unit which corresponds to the energy deposited by a 1 MeV electron in the detector.

4 ANALYSIS AND RESULTS

By using the large liquid scintillator cell ($20 \text{ cm} \times 16 \text{ cm}$) we were able to separate clearly the contribution of neutrons and γ -rays. It was also possible to identify protons from both the n - p elastic scattering and the $^{12}\text{C}(n, p)^{12}\text{B}$ reaction, deuterons produced in the $^{12}\text{C}(n, d)^{11}\text{B}$ reaction and α -particles either from the $^{12}\text{C}(n, \alpha)^9\text{Be}$ or $^{12}\text{C}(n, n'3\alpha)$ reactions [8].

Fig. 1 represents a typical bidimensional n - γ discrimination spectrum (Q_1, Q_2) obtained with the small scintillator cell ($5 \text{ cm} \times 5 \text{ cm}$) for monoenergetic neutrons of 56 MeV produced at the cyclotron CYCLONE of Louvain-la-Neuve [8]. The quality of the n - γ discrimination performed with the digital charge comparison technique has permitted, especially with the small scintillator, to distinguish clearly between all the different reaction channels involved in the neutron detection. The different components indicated (by A, B, C, ...) in Fig. 1 were interpreted as resulting from $^{12}\text{C}(n, a)A$ reaction channels and elastic scattering on protons [8], as follows :

- A : Compton electrons produced by interaction of γ -rays from $^{12}\text{C}(n, n'\gamma)^{12}\text{C}$
- B : escaped protons due to both elastic scattering and the $^{12}\text{C}(n, p)^{12}\text{B}$ reaction channel
- C : protons from both elastic scattering and the $^{12}\text{C}(n, p)^{12}\text{B}$ reaction channel
- D : deuterons resulting from the $^{12}\text{C}(n, d)^{11}\text{B}$ reaction channel
- E : tritons resulting from the $^{12}\text{C}(n, t)^{10}\text{B}$ reaction channel
- F : corresponds to tritons produced simultaneously with excited states of ^{10}B which decays essentially by alpha emission [20].

G : ^3He particles produced in the $^{12}\text{C}(n,^3\text{He})^{10}\text{Be}$ reaction channel

H : α -particles formed in either the $^{12}\text{C}(n,\alpha)^9\text{Be}$ or $^{12}\text{C}(n,n' 3\alpha)^9\text{Be}$ reaction channel

Since the light yield of heavy charged particles ($Z \geq 4$) is negligible [21] compared to that of protons, deuterons, tritons and α -particles, only fluorescence emission energy of light charged particles will be considered. Thus from biparametric discrimination spectra (Fig. 1), by using a specific two-dimensional analysis program, we have extracted the light charged-particle energy spectra. In Fig. 2 typical proton, deuteron, triton and α -particle spectra are presented resulting from 40 and 56 MeV neutrons respectively [8].

With neutron energies ranging between 12 and 19 MeV produced at the Van de Graaff accelerator in Strasbourg, only proton energy spectra are available. The reaction channels which lead to ^3H and ^3He particles, having reaction thresholds of 20.5 and 21.1 MeV neutron energy respectively, are energetically excluded at these energies. On the other hand, deuterons from the $^{12}\text{C}(n,d)^{11}\text{B}$ channel, having 14.9 MeV as a reaction threshold, do not have enough energy to overcome the separation threshold (around 5.2 MeVee for 56 MeV neutron energy). This threshold corresponds to the low energy limit above which the separation between the different components (charged-particles) is well established. Typical proton energy spectra obtained in our laboratory are shown Fig. 3. For energy calibration, ^{137}Cs , ^{60}Co and Am-Be sources have been used. The conventional MeVee unit was adopted.

Assuming that for the protons resulting from n - p elastic scattering, the maximum recoil proton energy corresponds to the half-height of the maximum in the downward slope of the front edge of the spectrum [22], the light yield of protons was extracted. The relative error in the proton light yield determination ranges between 4.5% and 10%. For deuterons, tritons and α -particles, the light yield was determined taking into account the kinematics of the corresponding reactions. The estimated errors for these particle light yields are about 1.1 MeVee. Table 1 resumes our whole set of light yield data for protons, deuterons, tritons and α -particles.

The preceding theoretical approaches do not express explicitly the light yield as a function of the type of the charged-particle considered. However, as well as the dependence

of the light yield on the type of charged-particle through the specific energy loss (dE/dx) function, the parameters KB and C also depend on the charged-particle. Thus the light yield data have been fitted for each charged-particle type separately with the formula given in eq. (6). We have developed a computer program which searches for the best-fit parameters by the minimization of the quantity :

$$\chi^2 = \sum_i [\{L(E_i) - L_i\}/\Delta L_i]^2 \quad (8)$$

where $L_i \pm \Delta L_i$ is the measured value with experimental uncertainty of the light output response to particle energy E_i , and $L(E_i)$ is calculated from eq. (6). For each charged-particle type, the fit was performed first with one free parameter KB [$C = 0$] (Birks formula [9]) and second with the two free parameters KB and C (Chou formula [10]).

The two-parameter fits of experimental data for protons, deuterons, tritons and α -particles are shown in Fig. 4. The best-fit parameters using the Birks and Chou equations are listed in Table 2 and compared for protons with some reported experimental results [21, 23].

The one- and two-parameter fits to experimental data for the NE213 organic scintillator are almost identical and give a good approximation to experimental results. The small values of the chi-square χ^2 associated with deuterons, tritons and α -particles are due to the limited degrees of freedom (two for deuterons and tritons and three for α -particles). However, according to the chi-square criteria, the confidence probabilities relative to our fits fall in within 97.5-99% for deuterons, $> 80\%$ for tritons and 92.5-99% for α -particles.

The C parameter values are very small, in agreement with Chou [10] and also with the values given in reference [23]. It is not known how the C parameter should be interpreted physically. Nevertheless all its values are positive and permit a fair comparison with experimental results.

References

- [1] D.J. Hinde, Nucl. Phys. A553(1993)255
- [2] D.J. Hinde, D. Hilscher, H. Rossner, B. Gebauer, M. Lehmann and M. Wilpert, Phys. Rev. C, vol. 45 (1992) 1229
- [3] D. Hilscher, H. Rossner, B. Cramer, B. Gebauer, U. Jahnke, M. Lehmann, E. Schwinn, M. Wilpert, Th. Wilpert, H. Frobeen, E. Mordhost and W. Scobel, Phys. Rev. Lett. 62(1989)1099
- [4] S. Mouatassim, PhD Thesis (Université Louis Pasteur de Strasbourg, 1994)
- [5] S.T. Thornton and J.R. Smith, Nucl. Instr. and Meth. 96(1971)551
- [6] J. Cub, E. Finckh, K. Gebhardt, K. Geissdörfer, R. Lin, J. Strate and H. Klein, Nucl. Instr. and Meth. A274(1989)217
- [7] R.A. Cecil, B.D. Anderson and R. Madey, Nucl. Instr. and Meth. 161 (1979) 439
- [8] M. Moszyński, G.J. Costa, G. Guillaume, B. Heusch, A. Huck, S. Mouatassim, Y. El Masri, P. Leleu, P. Lipnik, I. Tilquin, F. Hanappe, G. Bizard, D. Durand, J. Peter and B. Tamain, Nucl. Instr. and Meth. A343(1994)563
- [9] J.B. Birks, The theory and practice of scintillation counting (Macmillan, New York, 1964)
- [10] C.N. Chou, Phys. Rev. 87 (1952) 904
- [11] G.T. Wright, Phys. Rev. 91 (1953) 1282
- [12] J.F. Ziegler, Helium stopping powers and ranges in all elements. Organized by J.F. Ziegler (The stopping and ranges of ions in matter) Vol. 3, New York, Toronto, Pergamon Press, 1977
- [13] H.H. Andersen and J.F. Ziegler, Hydrogen stopping powers and ranges in all elements. Organized by J.F. Ziegler (The stopping and ranges of ions in matter) Vol. 4, New York, Toronto, Pergamon Press, 1977

- [14] M. Moszyński, G.J. Costa, G. Guillaume, B. Heusch, A. Huck and S. Mouatassim, Nucl. Instr. and Meth. A 350 (1994) 226
- [15] M. Moszyński, G. J. Costa, G. Guillaume, B. Heusch, A. Huck and S. Mouatassim, Nucl. Instr. and Meth. A307 (1991) 97
- [16] DEMON Proposal, November 1988. Internal Report U.C.L./U.L.B./C.R.N
- [17] B. Heusch, Second IN2P3-RIKEN Symposium on Heavy-ion collisions, Obernai, France, April 9-12, 1990
- [18] G. Bizard et al., International Conference on New Nuclear Physics with Advanced Techniques, Ierapetra, Greece, June 23-29, 1991 (World Scientific) p. 173
- [19] M. Moszyński, G. Bizard, G.J. Costa, D. Durand, Y. El Masri, G. Guillaume, F. Hanappe, B. Heusch, A. Huck, J. Peter, Ch. Ring and B. Tamain, Nucl. Instr. and Meth. A317(1992)262
- [20] C.M. Lederer and V.S. Shirley (eds.), Table of Isotopes (Wiley, New York,1979)
- [21] R. Batchelor, W.B. Gilboy, J.B. Parker and J.H. Towle, Nucl. Instr. and Meth. 13 (1961) 70
- [22] V.V. Verbinski, W.R. Burrus, T.A. Love, W. Zobel, N.W. Hill and R. Textor, Nucl. Instr. and Meth. 65 (1986) 8
- [23] R.L. Craun and D.L. Smith, Nucl. Instr. and Meth. 80 (1970) 239

Table 1

Light output L in units of MeVee, for protons, deuterons, tritons, and α -particles in the NE213 organic scintillator.

Particle	Energy (MeV)	Light yield $L(\text{MeVee})$	ΔL
Proton	12.3	7.3	0.7
"	13.4	7.8	0.8
"	14.4	8.5	0.9
"	15.6	9.4	0.9
"	16.9	10.3	1.0
"	17.9	10.9	1.1
"	18.5	11.1	1.1
"	19.0	11.3	1.1
"	27.3	20.3	1.8
"	38.9	28.5	1.8
"	40.0	31.1	1.6
"	43.3	34.0	1.8
"	56.0	43.1	1.9
Deuteron	26.2	16.7	1.1
"	42.0	29.5	1.1
Triton	36.3	22.7	1.1
"	20.8	10.5	1.1
Alpha	46.3	17.2	1.1
"	40.6	14.4	1.1
"	31.7	9.7	1.1

Table 2

Parameters obtained from least-squares fits of the one- and two-parameter formulae to experimental data for protons, deuterons, tritons and α -particles. ν is the number of degrees of freedom.

Particle	Energy (MeV)	KB_1 ($\text{g cm}^{-2} \text{ MeV}^{-1}$)	KB_2	C ($\text{g}^2 \text{ cm}^{-4} \text{ MeV}^{-2}$)	χ_1^2	χ_2^2	ν	Ref.
Proton	10-56	$91 \cdot 10^{-4}$	$87 \cdot 10^{-4}$	$5 \cdot 10^{-6}$	3.03	3.01	13	
Proton	0.24-15	$125 \cdot 10^{-4}$	$73.5 \cdot 10^{-4}$	$14.5 \cdot 10^{-6}$	67.8	28.9	19	[23]
Proton	0.24-1.5	$100 \cdot 10^{-4}$						[21]
Deuteron	26-42	$69 \cdot 10^{-4}$	$69 \cdot 10^{-4}$	$2 \cdot 10^{-7}$	$38 \cdot 10^{-3}$	$37 \cdot 10^{-3}$	2	
Triton	20-36	$70 \cdot 10^{-4}$	$40 \cdot 10^{-4}$	$28 \cdot 10^{-6}$	$28 \cdot 10^{-2}$	$34 \cdot 10^{-4}$	2	
Alpha	30-46	$51 \cdot 10^{-4}$	$46 \cdot 10^{-4}$	$14 \cdot 10^{-7}$	$39 \cdot 10^{-2}$	$18 \cdot 10^{-2}$	3	

Figure captions

Fig. 1 Two-dimensional diagram showing the charge of the slow component versus the total charge measured with the small scintillator NE213 (5 cm $\times$ 5 cm). The components marked [A] to [H] were identified as : (A) γ -rays, (B) Part of escaping protons, (C) Protons, (D) Deuterons, (E) Tritons, (F) Tritons followed by α -decay of excited states of ^{10}B , (G) ^3He particles, (H) α -particles (adapted from ref. [8]).

Fig. 2 Energy spectra corresponding to protons, deuterons, tritons and α -particles as measured with the small NE231 scintillator at 40 and 56 MeV neutron energies respectively (from ref. [8]).

Fig. 3 Typical proton energy spectra measured at the indicated neutron energies.

Fig. 4 Light response of NE213 scintillator for protons, deuterons, tritons and α -particles. The curves correspond to the calculated light response using the two-parameter equation of Chou [10].

Fig. 1

Fig. 2

Fig. 3

Fig. 4