Nuclear Data for Science and Technology (1988 MITO), 363- 366, Copyright © 1988 JAERI.

CHARACTERISTICS OF PULSED NEUTRON SOURCES OBTAINED WITH A LOW-ENERGY ELECTRON ACCELERATOR

Claudio Coceva, Enrico Cupini and Gabriele Fioni

ENEA, C.R.E. "E. Clementel"
Viale G.B. Ercolani 8, I-40138 Bologna, Italy

Abstract: An account is presented of a work which was undertaken to provide for an accurate computational tool for planning neutron sources based on Deuteron photo-disintegration, making use of low-energy (10-20 MeV) electron accelerator. A programme reproduces, by Monte Carlo simulation, electron Bremsstrahlung, neutron generation and slowing-down processes. Results calculated for different shapes and sizes of heavy water targets are given. In particular, characteristics are presented of targets suited to neutron time-of-flight spectrometry. Measurements carried out at the 12 MeV Linac of CNR show good agreement with calculations. The capabilities of these sources for time-of-flight spectrometry are demonstrated by a total cross-section measurement on Al.

(neutron sources, Deuterium, photoneutrons, time-of-flight)

Introduction

It is well known that intense neutron sources can be obtained by photoneutron reactions induced by low-energy (10-20 MeV) electron Bremsstrahlung on Deuterium. As pointed out in ref. |1|, their efficiency (in terms of neutrons per unit energy of the electron beam) can approach the values obtainable with a 100 MeV linear accelerator on a high-Z target, but at much lower capital and running costs, and avoiding heavy activation problems. Thermal and resonance neutron radiography, and measurements for nuclear fuel safeguards were indicated in |1| as examples of possible industrial applications.

Modern induction linacs |2|, with their extremely high current, seem to be well suited to fully exploit the Deuteron disintegration method and produce pulsed neutron sources with superior intensity.

In consideration of such attractive possibilities, we developed a program in order to calculate relevant characteristics of this kind of sources, and then help in optimizing them according to particular requirements. As an example we give the calculated characteristics of heavy water targets for time-of-flight neutron spectroscopy.

Furthermore, we deemed it advisable to carry out some experimental check of the calculations by measuring neutron spectra at the low-energy photo-neutron facility of Bologna.

The Computer Code

The computer code NEBRASCA (from the keywords neutron, Bremsstrahlung and scattering) is entirely based on the Monte Carlo method. The first part uses the code ACCEPT |3| to calculate energy spectra and angular distributions of Bremsstrahlung radiation generated by electrons impinging on a radiator target. Then, the code follows the gamma-ray trajectories which, within a given solid angle, cross the photo-neutron target containing Deuterium. Account is taken of Compton scattering and other non-nuclear interactions of gamma-rays.

The photonuclear cross section is assumed to be the sum of the electric dipole and magnetic dipole terms, with the coefficients given in ref. |4|. A $\sin^2\theta'$ dependence on the emission angle θ' (in the c.m. system) is contained in the electric dipole part. Neutrons produced by photonuclear reactions are followed in their scattering processes within the target material up to their exit or absorption. Neutrons escaping within given solid angles are classified according to their energies; for each energy bin the moderation length distribution (escape velocity multiplied by delay time) is also given. In time-of-flight spectrometers such distribution describes the part of resolution function which is due to the neutron source.

The calculation of the slowing down process can be extended to the thermal equilibrium region. Here, for the time being, we may deal with heavy water and normal water only; for other materials the appropriate scattering kernels need to be introduced.

Given a particular problem, the optimization work may be rather cumbersome because of the high number of correlated parameters to be adjusted. For this reason it was found helpful to have at disposal an auxiliary code to study the characteristics of the electron target separately. This code, which is called ETA, calculates, for given electron energy and target material and thickness, the energy distribution of the quantity $N_{\gamma}(E_{\gamma})\sigma_{\gamma n}(E_{\gamma})$, i.e. the product of the number of Bremsstrahlung photons times the photoneutron cross-section. This quantity is calculated for each preselected angular interval of the emitted photons. From this, one obtains spectra and total intensities of source neutrons generated in different angular zones, as shown by the examples in Fig. 1.

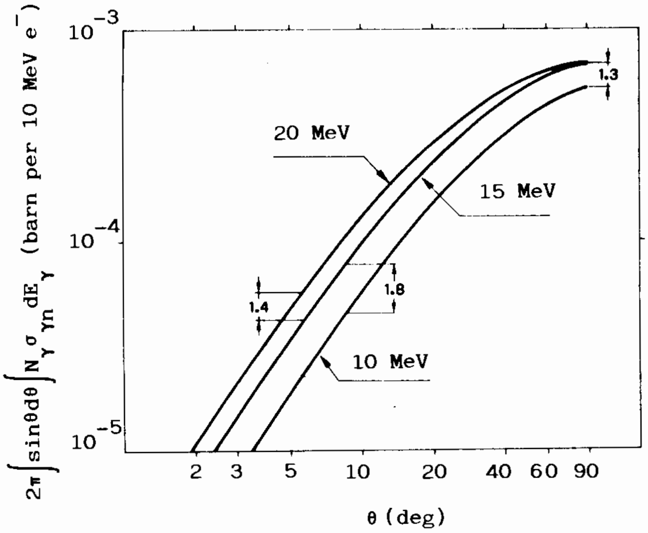

Fig. 1 Neutron production rate within a θ° cone around the electron direction. Each curve is labelled with the electron energy. The Gold radiator thickness is near the maximum efficiency for all of the three cases. The integrand $N_{\gamma}(E_{\gamma})\sigma_{\gamma n}(E_{\gamma})$ is the product of the photon number per unit solid angle and unit energy times the photoneutron cross-section of Deuterium. The curves are normalized to the same beam energy.

The Electron Target

For the study of a heavy water pulsed source for neutron time-of-flight spectroscopy in the keV-MeV range, code ETA was used first to optimize the photon production. A series of thicknesses were tried for different materials. In each case the total efficiency reaches a broad maximum. As expected, heavy elements are generally more effective, especially at low electron energy, except at very small angles of the emitted photons with respect to the direction of the electron beam.

For instance, if we compare a Gold radiator with a Silver one, having thicknesses corresponding to their maximum yields, at 10 MeV Silver is more effective for angles within 2°, but within 90° its neutron production is 24% less than Gold. At 20 MeV Silver and Gold are completely equivalent in the forward hemisphere.

The cumulative angular distributions of source neutron for a Gold radiator having optimum thickness are shown in Fig. 1 for different electron energies. From this plot one concludes that, in the case of a Deuterium target accepting Bremsstrahlung photons in a large cone, there is little profit in increasing the elctron energy above 10 MeV (see also Tab. 1). On the contrary, when the acceptance angle of the Deuterium target is small, as for a time-of-flight facility, the neutron intensity is appreciably increasing with electron energy.

The photoneutron target

For the sake of simplicity, we limit our considerations to heavy water targets. In this case, according to ref. |1|, the total neutron yield can ideally reach 10^9 neutrons per Joule of electron beam energy, i.e. half the value obtainable with a 100 MeV accelerator on a Ta target.

By applying the NEBRASCA code we find that, in practical cases, somewhat lower values are obtained. Tab. 1 gives the neutron production for D_2O cylinders with their axis in the direction of the electron beam and with an optimum thickness Au radiator placed in the middle of their basis.

Table 1. Total neutron production per Joule of electron beam. Gold radiator and D_2O cylinders arranged as indicated in Fig. 2

Electron energy (MeV)	Radius (cm)	Height (cm)	Neutrons (J^{-1})
10	7.5	10	1.87 10^8
15	7.5	10	2.54 10^8
20	7.5	10	2.60 10^8
10	15	20	3.34 10^8
15	15	20	4.56 10^8
20	15	20	4.67 10^8
10	22.5	30	4.44 10^8
15	22.5	30	6.12 10^8
20	22.5	30	6.30 10^8

Fig. 2 compares the neutron spectrum emitted by the shadowed target of the ORELA accelerator |5| with one of the cases in Tab. 1. Here we notice that the neutron yields of these two sources are almost equivalent.

The shape of D_2O targets listed in Tab. 1 is not suitable for time-of-flight spectrometry, e.g. the half-maximum width of the moderation distance distribution for the cylindrical target in Fig. 2 is approximately two to five times larger than for the ORELA case. Best results are obtained with a low thickness in flight-path direction, i.e. with slab geometry or with "pancake" shape, as sketched in Fig. 3.

In order to compare different cases, we define a figure of merit M(E) as the number of emitted neutrons per unit energy (Joule) of the electron beam, per unit neutron energy

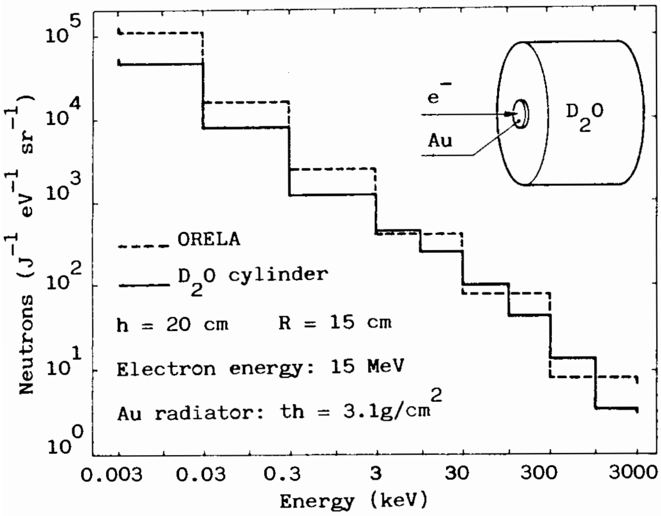

Fig. 2 Spectrum of neutrons issued by a D_2O cylinder submitted to 15 MeV electron Bremsstrahlung, compared with that obtained from the shadowed target of the Oak Ridge ORELA accelerator. Both spectra are normalized to unit energy (Joule) of electron beam.

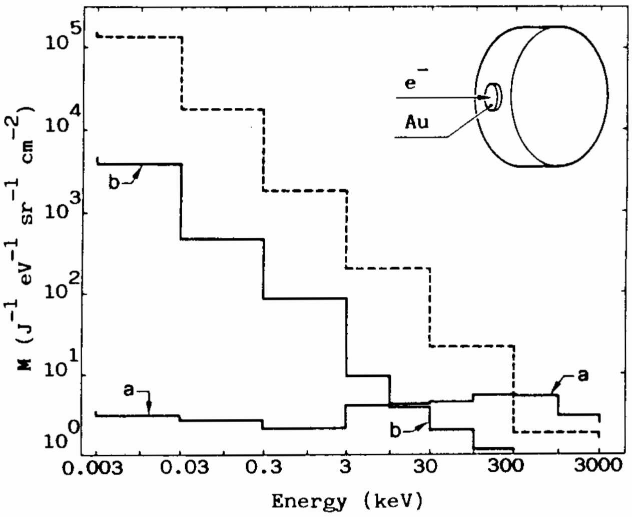

Fig. 3 Figure of merit of different edge-on cylindrical targets, compared with the target of Oak Ridge ORELA accelerator (dashed line). Electron energy: 15 MeV. Gold radiator, 3.1 g/cm^2 thick.

a) pure D_2O; radius: 4 cm, height: 2 cm.

b) 50% D_2O + 50% H_2O; radius: 9.5 cm, height: 4 cm.

(eV) and per unit solid angle (sr) divided by the variance (cm^2) of the moderation distance distribution. Fig. 3 gives plots of M(E) for the shadowed ORELA target |5| and for two different D_2O cylinders. We notice a pure D_2O target gives comparable results with ORELA in the region above 100 keV, with the advantage of being more compact. However, it is rather poor below 30 keV. This is a consequence of low moderation caused by a high escape probability from relatively thin slabs.

For time-of-flight work at low energy, we observe that the "slowing-down power" of hydrogenous moderators is much higher than for heavy water, mainly because of the higher scattering cross-section of Hydrogen with respect to Deuterium. Fig. 3 shows improvement of the figure of merit M(E) below 30 keV, obtained with a mixture of heavy and natural water.

It should be emphasized that the cases shown in Fig. 3 are not the result of an optimization, but examples of how the performances can be changed with different set-up.

Experiment

The photoneutron experimental facility in Bologna was used to check the results of the NEBRASCA code. Measurements were carried out at the 12 MeV electron linear accelerator of the "Istituto di Fotochimica e Radiazioni di Alta Energia", C.N.R., at Medicina, Bologna, Italy. The repetition frequency was 600 pps and the burst width 4 ns. Neutron spectra obtained under different conditions, specified in Tab. 2, were determined in the range 30 keV-750 keV by using ^{6}Li-loaded glass detectors with calibrated efficiency |6|. The length of the flight-path was 10.5 m. In different dispositions the measured average neutron intensity varied by as much as a factor ten. Notice the deuterated polyethylene target of the first experiment. In every case the agreement between measured and calculated spectra was very satisfactory, as shown in the example of Fig. 4.

Table 2. Experimental conditions of the neutron flux measurements

Electron energy (MeV)	Radiator; thickness (g/cm^2)	Photoneutron target	Target volume (cm^3)
10	Au; 0.66	$(C_2D_4)_n$	9.5
8	Au; 0.66	D_2O	56.4
10	Al; 7.0	D_2O	71.5
7	Au; 0.51	44%D_2O+56%H_2O	70.1

In order to demonstrate the usefulness of this kind of neutron sources in time-of-flight work, we carried out a total cross-section measurement of ^{27}Al.

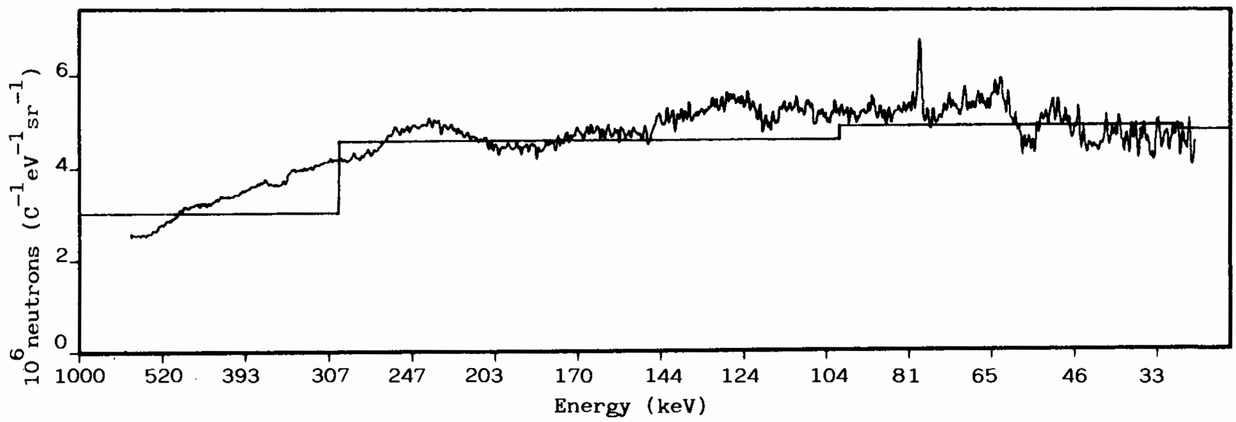

Fig. 4 Comparison between calculated (straight line) and measured neutron spectrum. The ordinate gives the number of neutrons per unit electron charge (Coulomb), per unit neutron energy (eV) and per unit solid angle (sr). Experimental conditions are given in the third line of Table 2.

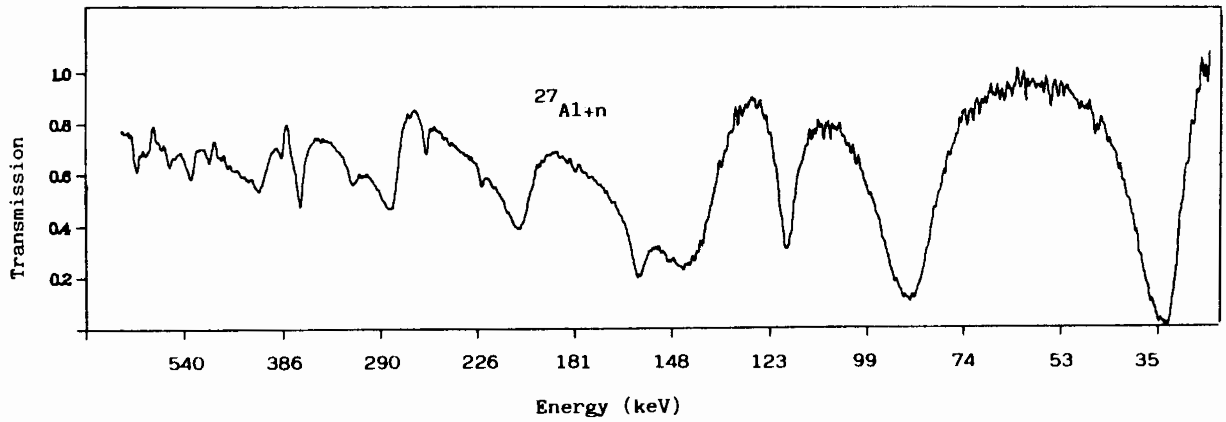

Fig. 5 Measured transmission of a 0.12 atom/barn sample of Al, determined under the same experimental conditions as for Fig. 4.

The experimental disposition was the same as in the third case listed in Tab. 2, with the radiator at 10 cm from the centre of the cylindrical D_2O target.

Fig. 5 shows the measured transmission of a 0.12 atom/barn Al sample, in the range 30 keV-700 keV. The measurement lasted about 40 hours.

We want to stress that the experimental set up was very rough, being a simple adaptation of the threshold photoneutron facility dscribed in ref. |7|. In fact, by using a radiator and target disposition as those in Fig. 3, a neutron flux about twelve times higher could be obtained for the same beam power which, in this case, was just 20 watt. In spite of these drawbacks, the transmission of Fig. 5 shows most details of the well-known total cross-section of such important structural material.

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the helpful work of G. Ferro in various revisions of the computer codes, and the assistance of A. Martelli, A. Monti and A. Mauri in the linac operation.

REFERENCES

1. C.D. Bowman: Nucl. Sci. Eng. 75, 12(1980)
2. J.E. Leiss: IEEE Trans. Nucl. Sci. NS-26, 3870(1979)
3. A. Halbleib and T.A. Mehlhorn: Sandia Report SAND 84-0573
4. E.G. Fuller: N.B.S. Report NBSIR 83-2647
5. C. Coceva, R. Simonini and D.K. Olsen: Nucl. Instr. and Meth. 211, 459(1983)
6. C. Coceva, Y.K. Ho, A. Mauri and P. Bartolomei: J. Phys. G: Nucl. Phys. 14 Suppl., S257(1988)
7. C. Coceva, A. Mauri, M. Magnani and P. Bartolomei: Proc. Int. Conf. on Nuclear Data for Basic and Applied Science, Santa Fe, Gordon & Breach Publ., p. 1407 (1985).