Neutron spectra and dosimetric features of Isotopic neutron sources: A review

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Abstract

A convenient way to produce neutrons is the isotopic neutron source, where the production is through (α, n), (γ, n), and spontaneous fission reactions. Isotopic neutron sources are small, easy to handle, and have a relative low cost. On the other hand the neutron yield is small and mostly of them produces neutrons with a wide energy distribution. In this work, a review is carried out about the the main features of ^{24}NaBe, ^{24}NaD$_2$O, ^{116}InBe, ^{140}LaBe, ^{238}PuLi, ^{239}PuBe, ^{241}AmB, ^{241}AmBe, ^{241}AmF, ^{241}AmLi, ^{242}CmBe, ^{210}PoBe, ^{226}RaBe, ^{252}Cf and ^{252}Cf/D$_2$O isotopic neutron source. Also, using Monte Carlo methods, the neutron spectra in 31 energy groups, the neutron mean energy; the Ambient dose equivalent, the Personal dose equivalent and the Effective dose were calculated for these isotopic neutron sources.

***Keywords*:** Neutron, Isotopic neutron source, Spectra, Dosimetric features.

1.- INTRODUCTION

The atomic nuclei have two types of nucleons: neutrons and protons, as a free particle neutron is unstable, decaying via the weak interaction to a proton, an electron and an antineutrino. In 1967 the neutron half-life was reported as 10.80 ± 0.16 min [Christensen *et al*., 1967]. From recent measurements the free neutron half-life is 14.8 ± 0.3% min [Yue *et al*., 2013].

After the neutron discovery by J. Chadwick in 1932 and the work of F. Joliot and I. Curie in 1934 the use of neutrons as free particles was for neutron activation with analytical purposes. The Neutron Activation Analysis (NAA), first developed by G. Hevesy and H. Levi in 1936 [Hamidatou *et al*., 2013], is the oldest use of neutrons and still is widely used nowadays [Garg and Batra 1986; Filby 1995; Yücel *et al*., 2014]. In medicine, neutrons are used in Boron Neutron Capture Therapy, BNCT, to treat cancer [Moss 2014], also are used for imaging [Pugliesi *et al*., 2011] in order to determine hydrogen in metals [Griesche *et al*., 2014] or in crude oils [Jonah and Umar 2004]. In homeland security are used to detect special nuclear materials [Andrews *et al*., 2015], explosives [Clifford *et al*., 2007; Bergaoui *et al*., 2014; Akar Tarim *et al*., 2015], and illicit drugs [Papp and Csikai 2014]. Other applications include investigating the properties of magnetic materials [Stajic 2014], as probes in soils or to measure the cross section [Bolewski *et al*., 2008], to start the nuclear fission chain reaction in reactors or to maintain the chain reaction in subcritical assemblies [Vega-Carrillo *et al*., 2015], and for nuclear waste transmutation among other applications [Walker 1982; Oláh *et al*., 1999; Martin 2000; Lacoste 2010].

Neutrons in the environment are produced as a secondary product of cosmic ray interaction with nuclei in the atmosphere, and due to the spontaneous fission occurring with natural heavy radionuclides. Also, are artificially produced through nuclear reactions [Dunai 2010; Vega-Carrillo and Manzanares-Acuña 2004].

A subcritical reactor (pile or subcritical assembly) and the nuclear reactor for research are used as source of neutrons; however the nuclear fuel, the required systems to work, and the cost are some of the drawbacks to use them in medical facilities or in industrial applications. Instead radioisotope neutron sources or small-scale accelerators are used to produce neutrons [Lacoste 2010].

The isotopic neutron sources yield neutrons with different energy and strength. These sources are compact, have small sizes, are easy to handle and are inexpensive in comparison with neutron generators and nuclear reactors. The first isotopic neutron sources were made by mixing natural occurring radioisotopes, like ^{210}Po and ^{226}Ra, with beryllium, their use was limited because the neutron output was very low [Garg and Batra 1986].

Neutron sources have a variety of applications in laboratories [DuBard and Gambhir 1994; Trainer 2002; Sajo-Bohus *et al*., 2015] where are used bare in calibration facilities [Gallego *et al*., 2004; Guzman-Garcia *et al*., 2015], in howitzers or irradiators [Tuffour-Achampong *et al*., 2012; Barros *et al*., 2014; Osman *et al*., 2014; Sogbadji *et al*., 2014; Ali *et al*., 2015].

Each source produces neutrons with a particular energy distribution, or spectrum [Hess 1959; Lorch 1973; Charlton *et al*., 1998; Vega-Carrillo *et al*., 2002; Park 2003; Vega-Carrillo *et al*., 2009; Tagziria and Looman 2012], and a particular strength [Roberts *et al*., 2011]. Knowledge of these features can be advantageous in planning work activities, to look for potential uses, and to design the shielding and the radiation protection protocols, for hosting and handling the source [Thomas 2010; Thomas *et al*., 2011; Vega-Carrillo *et al*., 2013].

Neutrons are produced by nuclear reactions induced by (α, n) and (γ, n) nuclear reactions using radioactive nuclides. Also are produced through nuclear reactions induced by charged particles such as in (d, d) and (d, T). During fission and fusion nuclear reactions neutrons are also produced or by spontaneous fission of some heavy radionuclides.

The (α, n), (γ, n) and (spontaneous fission, n) neutron sources are known as isotopic neutron sources (also are known as radionuclide or radioisotope neutron sources). These have small sizes and compact, are easy to shield, portable and do not use high voltage. The isotopic neutron sources are produced by mixing the α-emitter with a suitable target. The mixture is doubly encapsulated. In the (γ, n) sources the γ-emitter is surrounded by the photon target. In the case of spontaneous fission source, the radioisotope is also encapsulated. The amount of the radionuclide and the type of material used to encapsulate the active material of isotopic neutron source modifies the neutron spectrum [Vijaya and Kumar 1973].

1.1.- Isotopic (α, n) sources

Neutron discovery was carried out through the ^{210}Po(α, n) nuclear reaction, where the ^{210}Po was mixed with Be. ^{210}Po decays emitting 5.3 MeV α-particle that collides with ^{9}Be producing an exothermic reaction (+5.71 MeV). In this reaction ^{12}C and ^{1}n are produced. Instead of Be, other light elements like B, Li, and F can be used, however Be yields the largest neutron output per α-particle compared with other targets under the similar conditions, as is shown in table 1 [Venkatapathi Raju and Jnanananda 1964; Thompson and Taylor 1965; Garg and Batra, 1986].

Table 1. Neutron yield of some (α, n) sources.

α-emitter	Target	Reaction and Q-value		Neutron yield per α
^{241}Am	B	^{10}B(α, n)	+1.07 MeV	1.3E(-5)
^{241}Am	F	^{19}F(α, n)	-1.93 MeV	4.1E(-6)
^{241}Am	Be	^{9}Be(α, n)	+5.71 MeV	7.0E(-5)
^{238}Pu	^{13}C	^{13}C(α, n)	+2.2 MeV	1.1E(-5)
^{210}Po	Li	^{7}Li(α, n)	-2.79 MeV	1.0E(-6)

The α particles are emitted through the decay of heavy isotopes like ^{226}Ra, ^{222}Rn, ^{210}Po, ^{238}Pu, ^{239}Pu, and ^{241}Am [Anderson and Bond 1963; Notarrigo *et al*., 1969; Vijaya and Kumar 1973; Kumar and Nagarajan 1977; Vega-Carrillo et al., 2007a; Vega-Carrillo *et al*., 2007b]. In nature, beryllium has only a single isotope ^{9}Be and an (α, n) source is realized by mixing powders of Be and the α-emitter. The mixture is encapsulated and the resulting neutron source is easily handled.

The nuclear reaction of (α, n) sources is shown in equation 1.

$$ {}_{Z}X^{A} + {}_{2}He^{4} \rightarrow {}_{Z+2}Y^{A+3} + {}_{0}n^{1} + Q \qquad (1) $$

The reaction is exothermic if Q > 0 or endothermic if Q < 0 [Beckurts and Wirtz 1964]. For α-particles with energy between E_α and $E_\alpha + \Delta E_\alpha$ the neutron produced per unit energy interval in Be(α, n) sources can be estimated using the equation 2.

$$ n(E) = 2\,\pi\,\sigma(E)\,\sin\theta\,\frac{d\theta}{dE}\,\frac{\Delta E_\alpha}{\varepsilon(E_\alpha)} \qquad (2) $$

Here, σ(E) is the differential cross section, in the center of mass, for neutron production, ε is the stopping cross section for Be at E_α [Geiger and Van der Zwan 1975; Geiger 1980].

In table 2 are shown the main features of Be(α, n) sources [Geiger 1980].

In the case of PuBe sources the amount of ^{241}Pu impurity in the original mass of Pu used to build the source changes the neutron yield. The amount of ^{241}Am produced during the ^{241}Pu decay increase the amount of the a-emitter, thus these sources reach their maximum yield some years after the source fabrication [Vega-Carrillo *et al*., 2014].

Table 2.- Characteristics of Be(α, n) sources.

Source	E_α [MeV]	Neutron yield [s^{-1} per 10^6 alphas]
^{239}PuBe	5.14	65 ± 9.2%
^{210}PoBe	5.30	73 ± 9.6%
^{241}AmBe	5.48	82 ± 9.8%
^{244}CmBe	5.79	100 ± 9.0%
^{242}CmBe	6.10	118 ± 8.5%
^{226}RaBe	7.69, 6.00, 5.49, 5.30, 4.77	502 ± 10%
^{227}AcBe	7.365, 6.71, 6.56, 5.90, 5.65	702 ± 8.5%

1.2.- Isotopic (γ, n) sources

These sources are stable and produce quasi monoenergetic neutrons. In this type of sources γ-rays are used as particles to induce the reaction. The photon energy must be larger than the Q-value of the reaction. When the target is ^{9}Be the (γ, n) reactions is produced when the photon energy is at least 1.67 MeV, if the target is ^{2}D the photon energy must be at least 2.23 MeV, for other nuclides (γ, n) thresholds are above 6 MeV.

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When a photon with hν MeV collides with a nucleus with an atomic number A the energy of the emerging neutron can be calculated with equation 3, where the Q-values of the Be(γ, n) reaction and the photon energy are in MeV.

$$\mathbf{E_n = \frac{A-1}{A}\left(h\nu - |Q|\right) \pm \sqrt{\frac{2(A-1)(h\nu - |Q|)}{931\ A^3}}} \qquad (3)$$

In the equation the plus sign is used when the neutron is emitted at 0^o to the direction of the incident photon, and the sign minus applies for emission at 180^o. In table 3 are listed some of the photoneutron sources.

Usually, these sources are produced by surrounding γ-emitters with a thick layer of the target. Produced neutrons are quasi-monoenergetic however, the spread in neutron energy increase with the amount of target.

Table 3.- Photoneutron sources

γ-ray emitter	Half-life	hν [MeV]	Target	Neutron yield*
^{24}Na	15 h	2.75	Be D_2O	1.4E(5) 2.9E(5)
^{88}Y	108 days	1.8 and 2.8	Be D_2O	1E(5) 3E(3)
^{140}La	40.2 h	2.5	Be D_2O	2E(3) 7.4E(3)
^{124}Sb	60.4 h	1.7	Be	1.9E(5)

(*) In s^{-1} at 1 cm per 3.7E(10) Bq of γ-emitter and 1 g of target (Be or D_2O).

1.3.- Spontaneous fission neutron source

There are more than 100 radionuclides decaying by spontaneous fission with neutron emission, however nearly all are unsuitable as a neutron source due to difficulties in their production or because their half-lives are too short or too long. The exception to these drawbacks is Californium 252 [Karelin *et al.*, 1997]. In the table 4 are few of radionuclides that decay by α-emission and spontaneous fission.

Due to nuclear safety and safeguards related to ^{239}Pu, neutrons sources based on this radioisotope have been studied in order to determine the amount of ^{239}Pu [Nguyen 2006; Xu *et al.*, 2015]. As alternative the ^{241}AmBe are used due to its half-life, and ^{252}Cf due to its neutron yield, that is modified if light elements like Li, Be, B, F, Na or F is included. Also

during the presence of ^{250}Cf contributes to increase the neutron yield in old sources. Therefore, is necessary to calibrate the source [Gehrke *et al*., 2004].

The ^{252}Cf radioisotope is an intense neutron emitter. Decay by a-emission with a 96.91% probability and spontaneous fission (3.09% probability) resulting in an overall half-life of 2.645 years. The specific neutron yield is 2.314E(6) s^{-1}-μg^{-1} with a specific activity of 19.832 MBq μg^{-1}. The neutron spectrum is similar to a fission reactor [Martin *et al*., 2000].

$^{241}AmBe$, ^{241}AmB, bare ^{252}Cf, and D_2O moderated ^{252}Cf ($^{252}Cf/D_2O$) are the radioisotope neutron sources recommended by the ISO [2001] for routine calibration of neutron measuring devices [Gressier and Taylor 2011], like dosimeters [Ambrosi 2009], because calibration conditions are reproducible and stable [Lacoste 2010].

Table 4.- Features of some spontaneously fissionable isotopes

Radioisotope	Spontaneous fission half-life [years]	α-emission half-life [years]	Specific neutron yield [s^{-1} g^{-1}]
^{235}U	1.8E(17)	6.8E(8)	8.0E(-4)
^{238}U	8.0E(15)	4.5E(9)	1.6E(-2)
^{239}Pu	5.5E(5)	2.4E(4)	3.0E(-2)
^{240}Pu	1.2E(11)	6.6E(3)	1.0E(3)
^{242}Pu	7.2E(10)	3.8E(5)	1.6E(3)
^{244}Cm	1.3E(7)	18.1	1.1E(7)
^{246}Cm	4.8E(3)	1.8E(7)	8.8E(6)
^{248}Cm	4.2E(6)	4.0E(5)	4.1E(7)
^{252}Cf	85.5	2.73	2.3E(12)

The neutron spectra and the dosimetric features are important to characterize the isotopic neutron sources. The aim of this work was to estimate the neutron spectra and the related dosimetric parameters of a set of isotopic neutron sources.

2.- MATERIALS AND METHODS

The International Atomic Energy Agency (IAEA) published the compilation of neutron spectra for several neutron sources using 55 energy groups [IAEA 1990], and using 60 energy groups [IAEA 2001]. The neutron spectra of (α, n), (γ, n), bare ^{252}Cf, and D_2O moderated ^{252}Cf sources were used to calculate the spectra in 31 energy groups [O´Brien and Sanna 1981]. Calculations were carried out using the MCNP5 code [X5 Monte Carlo team 2003] using a point-like source in vacuum.

In order to compare the spectrum, in 55 or 60 energy groups, with the spectrum in 31 energy groups, both spectra were converted from lethargy to energy and were normalized, then were converted to per unit lethargy. The fluence-to-dose conversion coefficients [ICRP 1996] were used to calculate the Ambient dose equivalent (H*(10)), the Effective dose (E) and the Personal dose equivalent ($H_{p,s}$) per unit fluence using equation 4.

$$\Delta = \frac{\sum_{i=1}^{g} \delta(E_i)\,\Phi(E_i)}{\sum_{i=1}^{g} \Phi(E_i)} \qquad (4)$$

Here, $\delta(E_i)$ is the fluence-to-dose conversion coefficients for a particular dose (H*(10), E or $H_{p,s}$) for neutrons with energy in the ith group, $\Phi(E_i)$ is the neutron fluence in the ith energy group, Δ is the dose per unit fluence, and g is the amount of energy groups: 55 or 60.

The neutrons mean energy, E_{Av}, for each source was calculated using equation 5.

$$E_{Av} = \frac{\sum_{i}^{31} Emed_i \;\; \Phi(E_i)}{\sum_{i=1}^{31} \Phi(E_i)} \qquad (5)$$

In this equation $Emed_i$ is the energy median value for the ith energy group and $\Phi(E_i)$ is the neutron fluence in the ith energy group. The median energy for the ith group was calculated using equation 6.

$$\mathbf{Emed_i = \sqrt{Elow_i\ Eup_i}} \qquad (6)$$

Here, $Elow_i$ and Eup_i are the lower and upper energy values of the ith energy group.

3.- RESULTS

3.1.- Neutron spectra in different energy bins

In figure 1 and 2 are the ^{241}AmBe and ^{239}PuBe spectra in two energy groups.

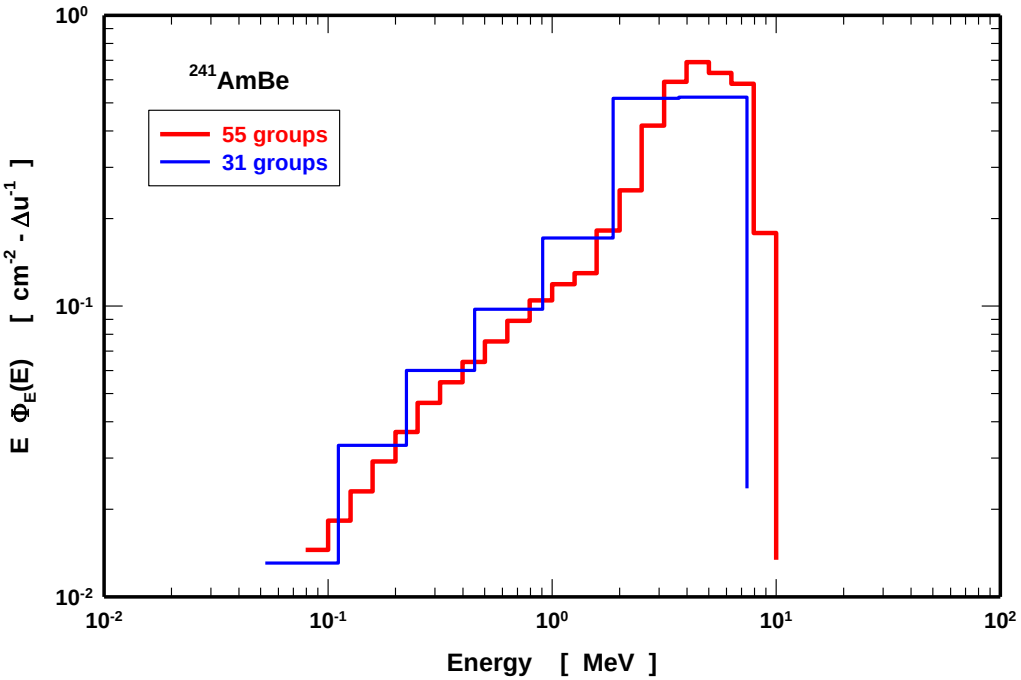

Figure 1.- ^{241}AmBe neutron spectrum

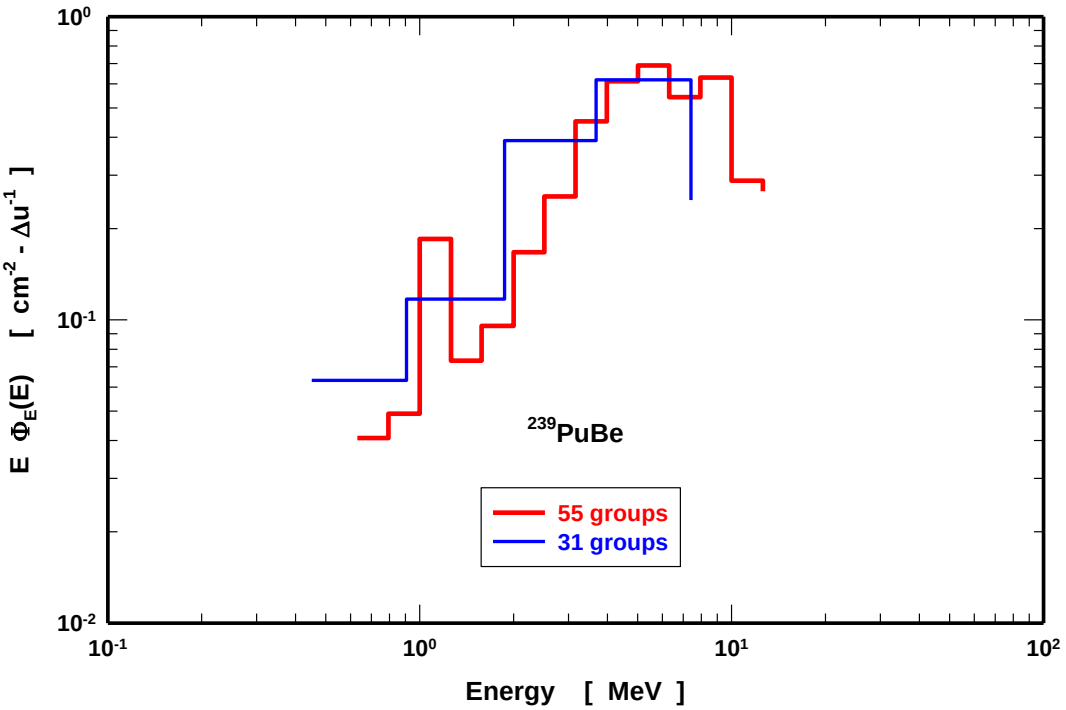

Figure 2.- ^{239}PuBe neutron spectrum

In figure 3 and 4 are the ^{24}NaBe and $^{24}NaD_2O$ spectra in two energy groups.

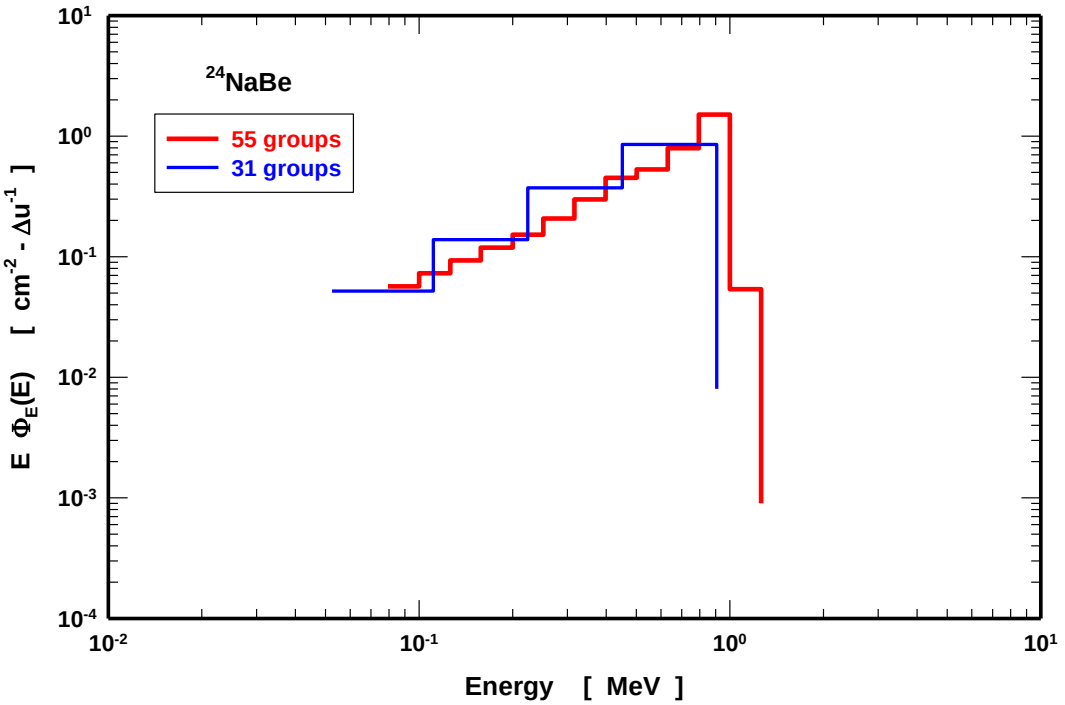

Figure 3.- ^{24}NaBe neutron spectrum

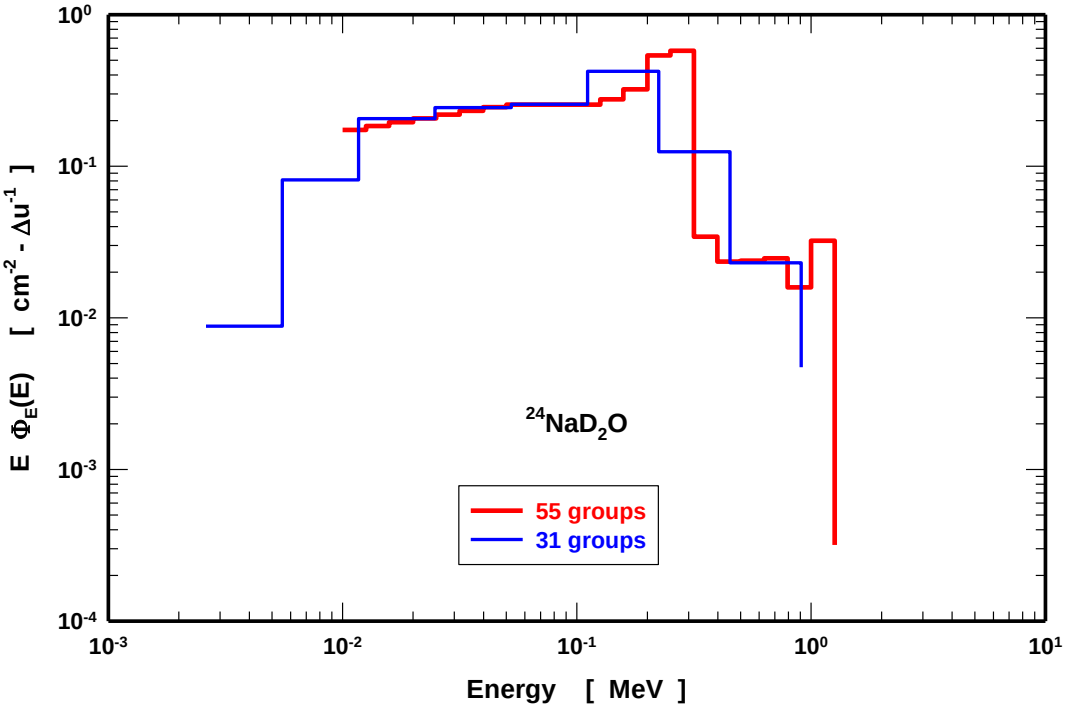

Figure 4.- $^{24}NaD_2O$ neutron spectrum

In figure 5 and 6 are the bare ^{252}Cf and D_2O moderated ^{252}Cf spectra in two energy groups.

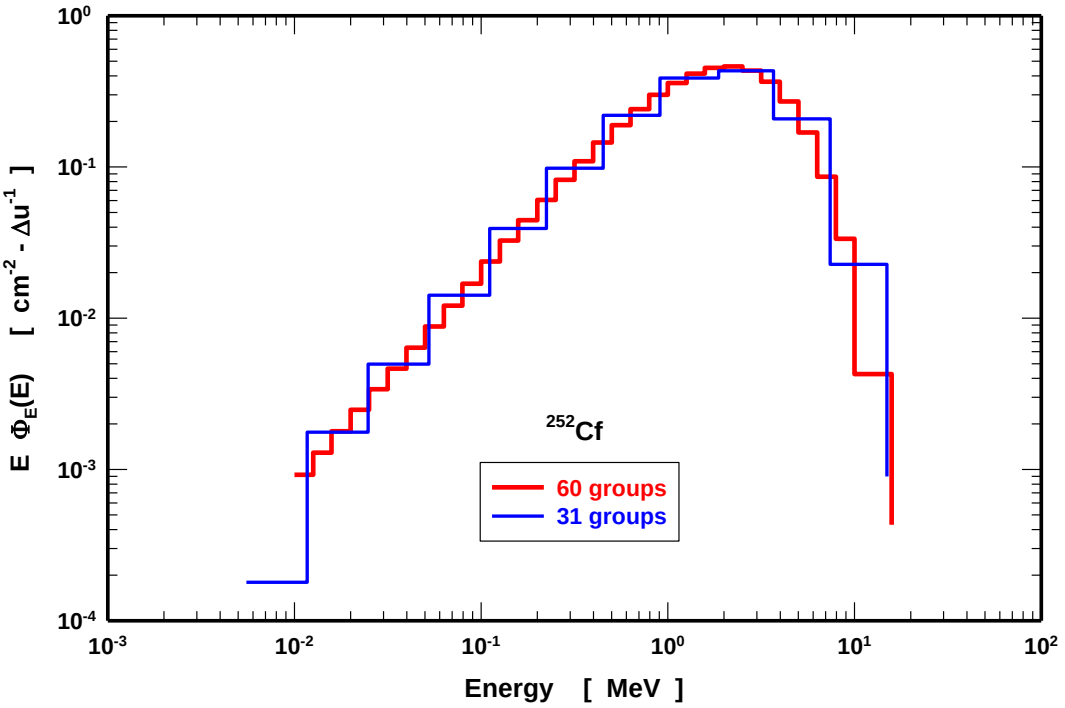

Figure 5.- ^{252}Cf neutron spectrum

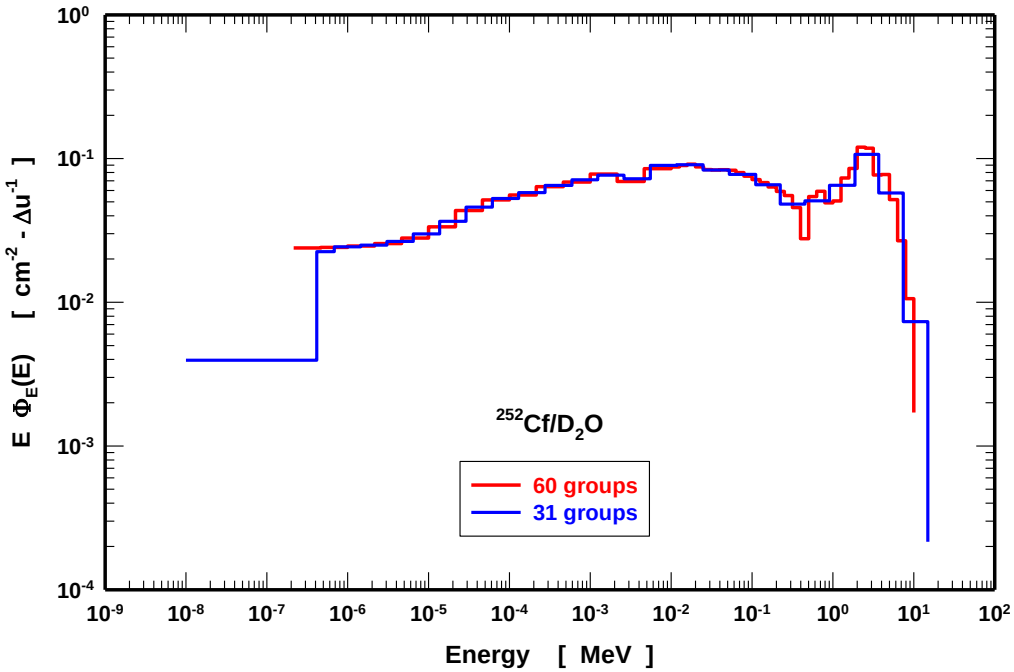

Figure 6.- $^{252}Cf/D_2O$ neutron spectrum

3.2.- Low resolution neutron spectra

In figure 7 are the $^{241}Am(\alpha, n)$ neutron spectra in 31 energy groups.

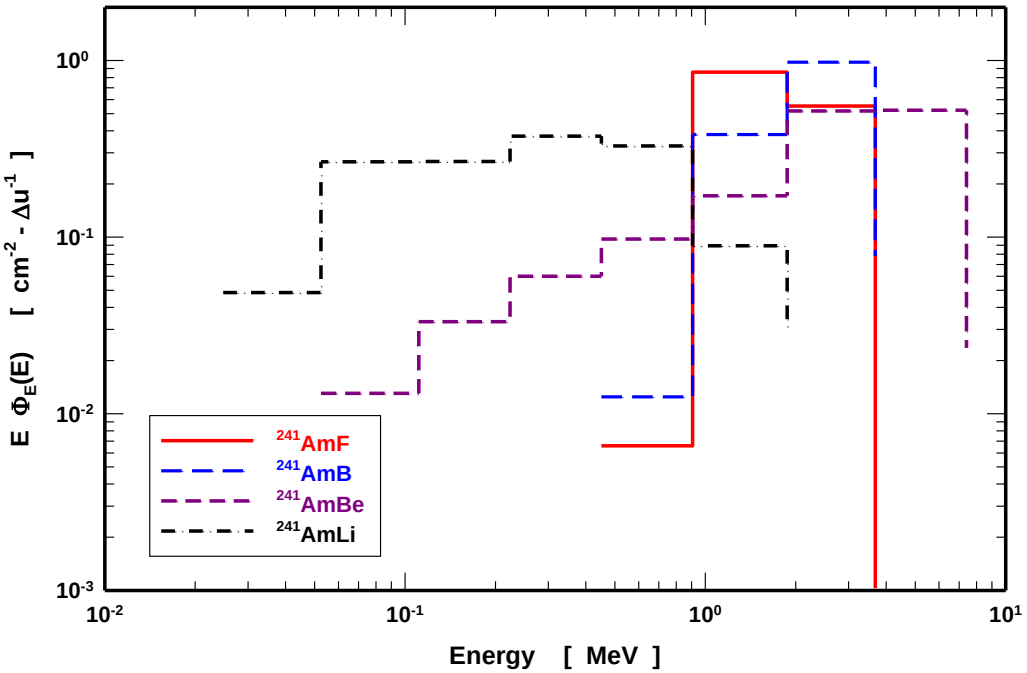

Figure 7.- Low resolution $^{241}Am(\alpha, n)$ neutron spectra

The mean energy and the dosimetric features of ^{241}AmBe(α, n) sources are in table 5.

Table 5.- Mean energy and dosimetric features of ^{241}AmBe(α, n) sources

Δ [pSv-cm^2]	^{241}AmF	^{241}AmB	^{241}AmBe	^{241}AmLi
E_{AP}	356.58	392.10	391.97	140.52
E_{PA}	222.22	261.57	279.35	82.62
E_{RLAT}	114.62	140.09	157.28	37.33
E_{LLAT}	134.23	162.65	179.27	43.46
E_{ROT}	212.79	245.46	258.72	77.48
E_{ISO}	161.72	188.75	203.68	58.98
H*(10)	420.37	416.76	391.22	220.21
$H_{p,s}(10,0^o)$	436.32	435.15	408.08	228.92
$H_{p,s}(10,15^o)$	431.74	431.69	405.47	225.45
$H_{p,s}(10,30^o)$	448.22	450.00	420.55	220.74
$H_{p,s}(10,45^o)$	427.01	434.31	408.16	196.19
$H_{p,s}(10,60^o)$	382.41	397.75	373.49	152.29
$H_{p,s}(10,75^o)$	249.08	276.86	272.49	70.92
Mean energy [MeV]	1.8	2.4	3.2	0.4

In figure 8 are the (α, n)Be and ^{238}Pu(α, n)Li neutron spectra in 31 energy groups.

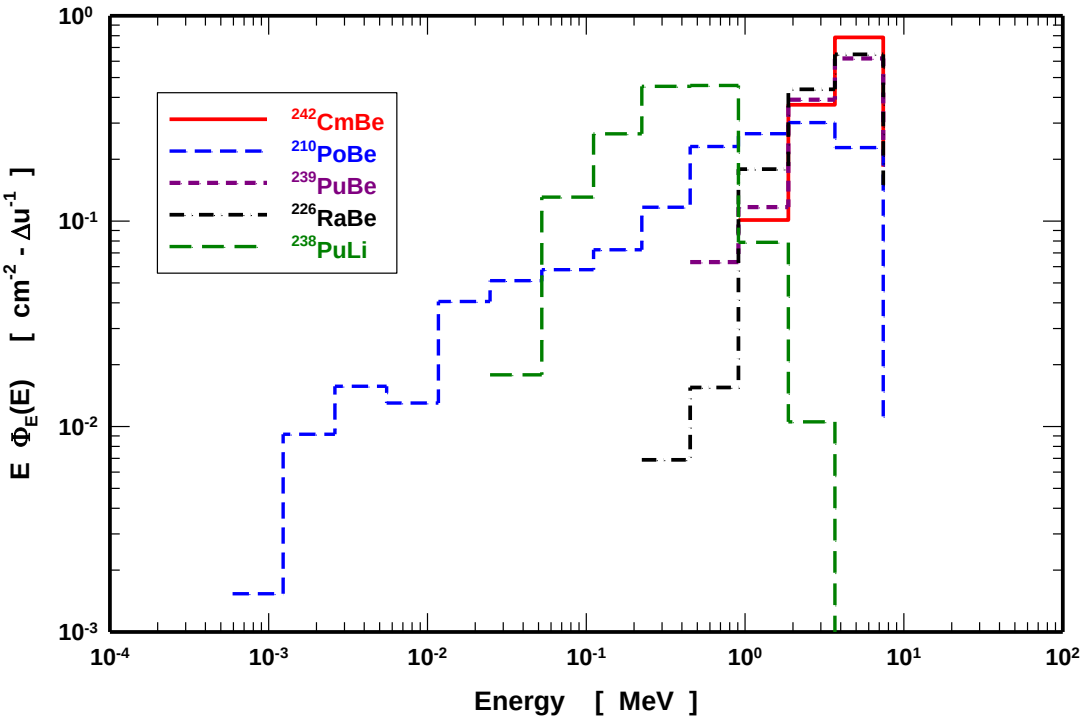

Figure 8.- Low resolution (α, n)Be and the ^{238}Pu(α, n)Li neutron spectra.

In table 6 are shown de mean energy and the dosimetric features or (α, n)Be and ^{238}Pu(α, n)Li sources.

Table 6.- Mean energy and dosimetric features or (α, n)Be and ^{238}Pu(α, n)Li sources.

Δ [pSv-cm^2]	^{242}CmBe	^{210}PoBe	^{239}PuBe	^{226}RaBe	^{238}PuLi
E_{AP}	455.36	281.79	441.02	437.69	155.28
E_{PA}	343.87	187.46	329.89	322.87	88.75
E_{RLAT}	203.41	100.37	194.49	187.58	40.10
E_{LLAT}	230.37	115.15	220.50	213.04	46.36
E_{ROT}	316.35	175.68	304.12	298.01	84.29
E_{ISO}	252.77	136.46	242.64	236.55	64.03
H*(10)	409.71	324.15	412.15	409.98	251.93
$H_{p,s}(10,0^o)$	431.13	336.85	433.46	429.82	262.03
$H_{p,s}(10,15^o)$	429.62	333.49	431.73	427.86	258.26
$H_{p,s}(10,30^o)$	447.84	341.66	449.11	445.68	253.26
$H_{p,s}(10,45^o)$	441.90	323.66	440.88	437.25	225.39
$H_{p,s}(10,60^o)$	414.72	284.29	411.88	407.25	174.79
$H_{p,s}(10,75^o)$	328.27	186.54	321.03	312.95	80.20
Mean energy [MeV]	5.0	1.8	4.9	4.4	0.4

In figure 9 are the neutron spectra, in 31 energy groups, of some (γ, n) neutron sources.

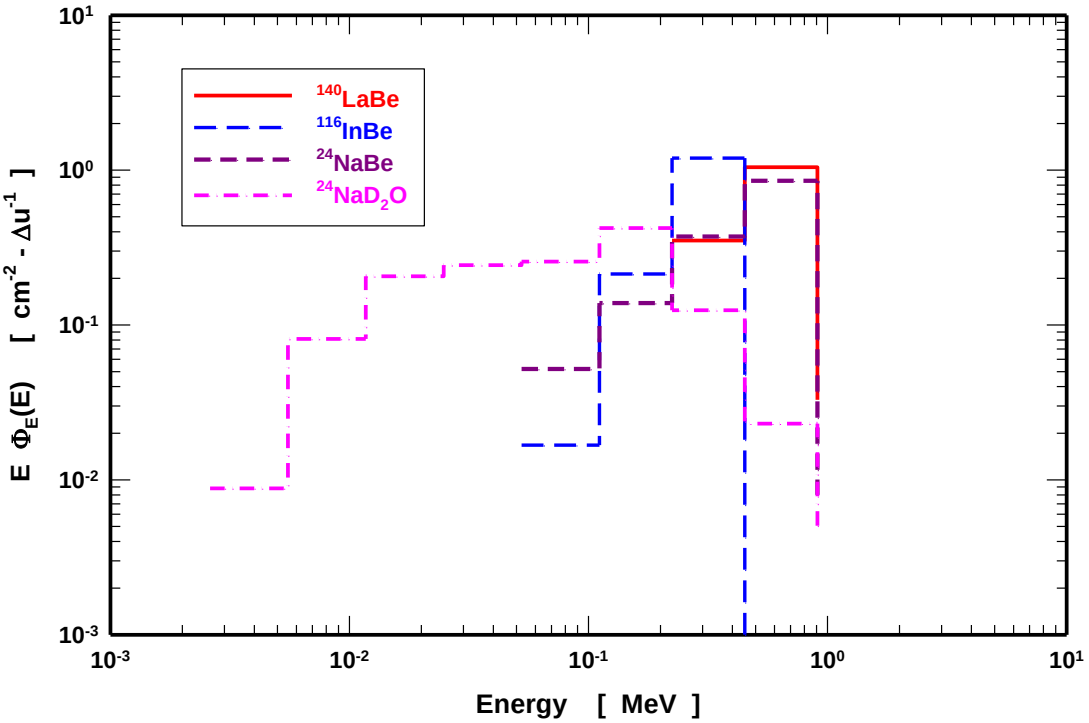

Figure 9.- Neutron spectra of (γ, n) sources.

Table 7.- Mean energy and dosimetric features or (γ, n) sources

Table 7.- Dose per unit fluence and E_{Av} for (γ, n) sources

Δ [pSv-cm^2]	^{140}LaBe	^{116}InBe	^{24}NaBe	^{24}NaD$_2$O
E_{AP}	193.11	122.58	180.96	61.00
E_{PA}	105.89	72.34	100.03	39.60
E_{RLAT}	48.46	31.04	45.62	16.13
E_{LLAT}	55.33	36.10	52.40	19.33
E_{ROT}	102.69	66.49	96.64	34.40
E_{ISO}	77.58	50.94	73.14	26.39
H*(10)	323.96	212.81	299.08	89.59
$H_{p,s}(10,0^o)$	336.48	224.59	310.39	93.33
$H_{p,s}(10,15^o)$	331.43	222.73	305.36	91.62
$H_{p,s}(10,30^o)$	328.27	210.80	301.59	85.54
$H_{p,s}(10,45^o)$	294.20	181.92	270.18	72.31
$H_{p,s}(10,60^o)$	230.24	133.57	211.12	50.64
$H_{p,s}(10,75^o)$	106.59	51.47	98.52	18.26
Mean energy [MeV]	0.6	0.3	0.5	0.1

The neutron spectrum of bare ^{252}Cf and D_2O moderated ^{252}Cf using 31 energy groups are shown in figure 10.

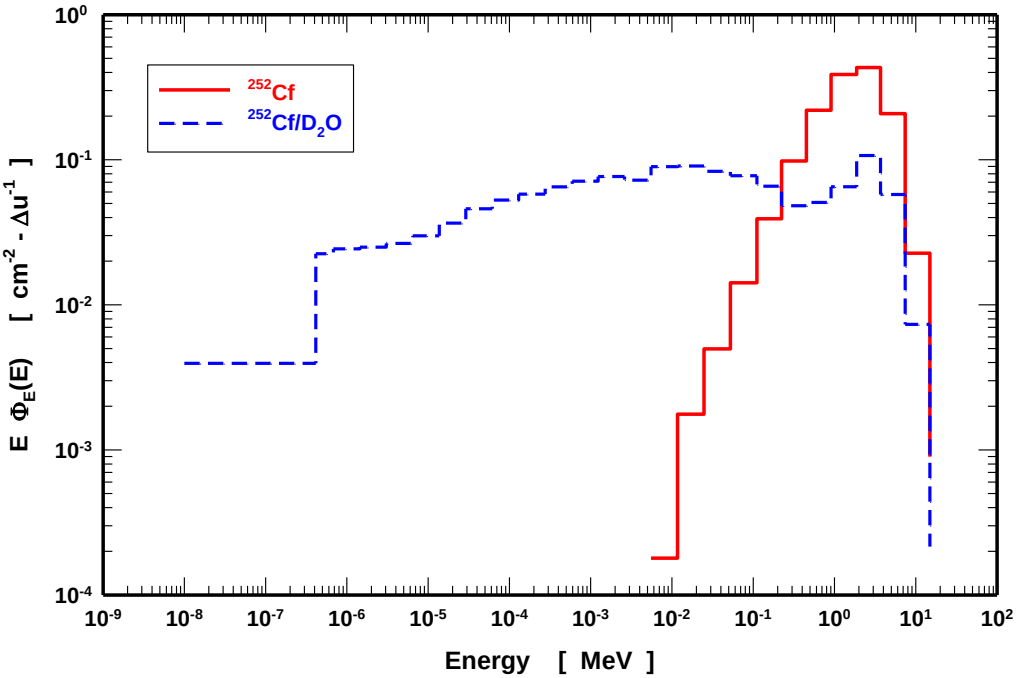

Figure 10.- Bare and D_2O moderated ^{252}Cf neutron spectra.

The neutron mean energies and the dosimetric features of bare and D_2O-moderated ^{252}Cf sources are shown in table 8.

Table 8.- E_{Av} and dosimetric features of bare and D_2O moderated ^{252}Cf sources.

Δ [pSv-cm^2]	^{252}Cf	$^{252}Cf/D_2O$
E_{AP}	335.43	97.50
E_{PA}	221.73	66.20
E_{RLAT}	119.07	33.86
E_{LLAT}	136.93	39.15
E_{ROT}	208.72	60.48
E_{ISO}	161.66	46.73
H*(10)	383.14	107.39
$H_{p,s}(10,0^o)$	398.40	112.13
$H_{p,s}(10,15^o)$	394.65	110.74
$H_{p,s}(10,30^o)$	406.46	111.53
$H_{p,s}(10,45^o)$	386.95	103.86
$H_{p,s}(10,60^o)$	343.62	89.11
$H_{p,s}(10,75^o)$	228.42	57.09
Mean energy [MeV]	2.2	0.6

3.3.- Doses in function of the neutron mean energies

For the isotopic neutron sources the $H_{p,s}(10, \theta)$ and the H*(10) in function of the neutron mean energy are shown in figure 11. For all energies the H*(10) is higher the $H_{p,s}(10, \theta)$, for $\theta = 60$ and 75^o.

In figure 12 are shown the Effective doses and the H*(10). Here the Ambient dose equivalent doses per unit neutron fluence are higher, except for the EAP for sources whose mean energy is larger than 4.4 MeV.

In figure 13 the doses per unit fluence of the isotopic neutron sources are shown.

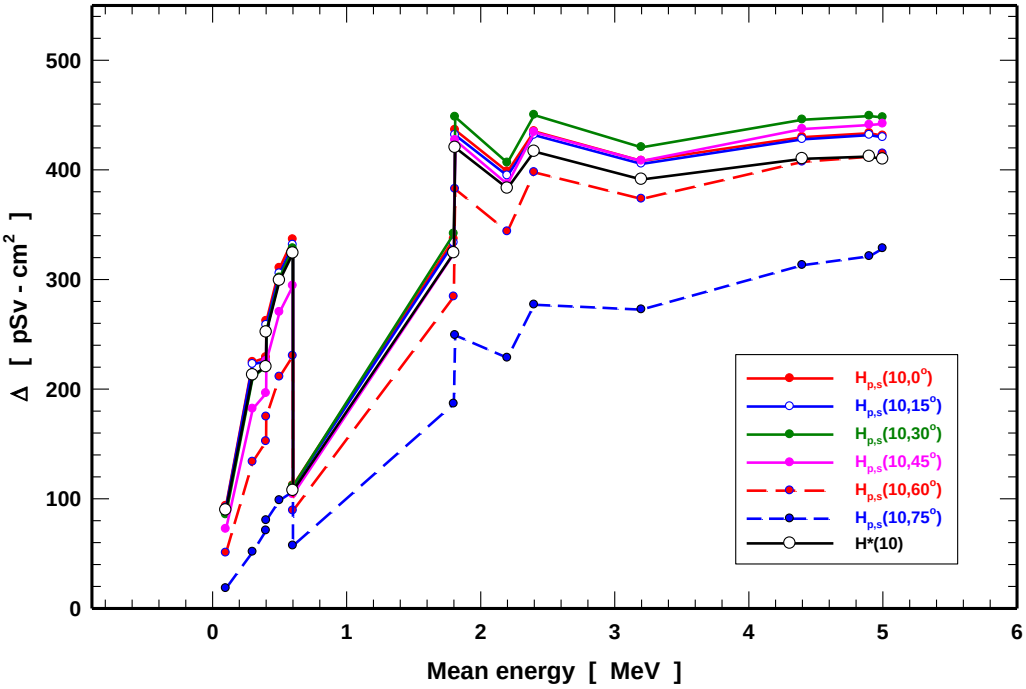

Figure 11.- $H_{p,s}(10, \theta)$ and H*(10) in function of mean neutron energy.

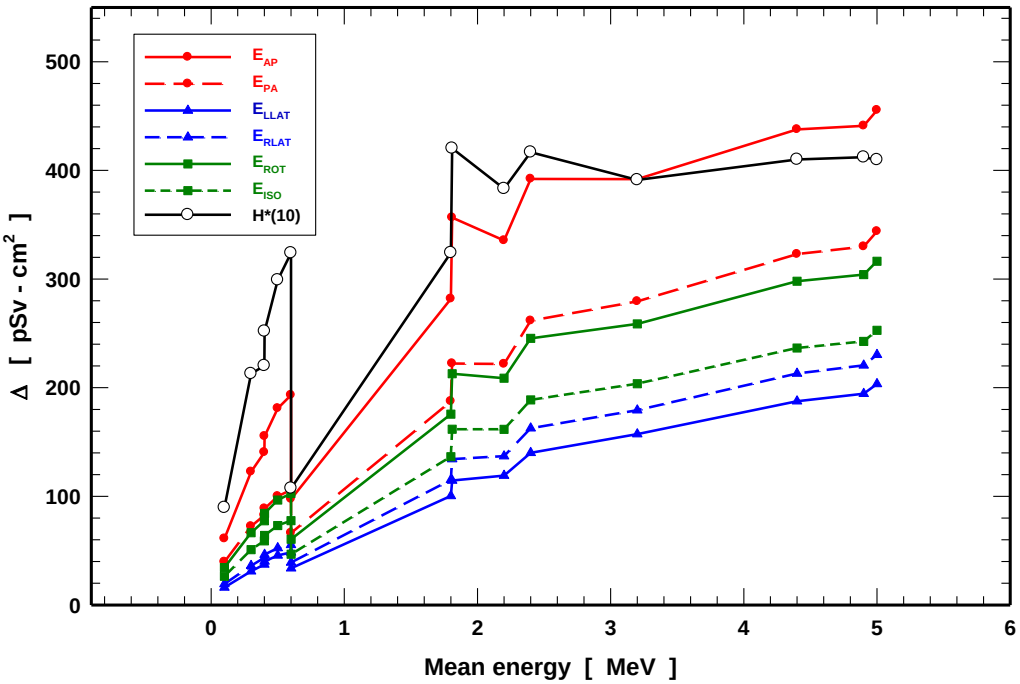

Figure 12.- Effective doses and H*(10) in function of mean neutron energy.

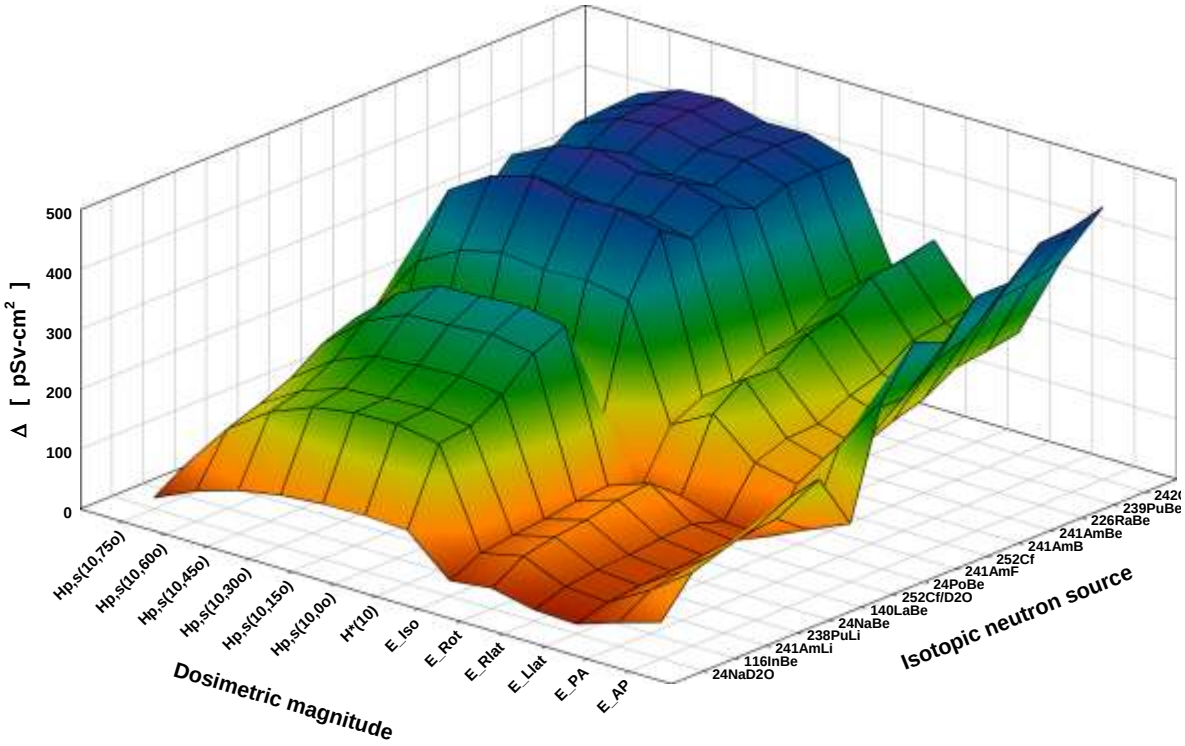

Figure 13.- Doses per unit fluence for the isotopic neutron sources.

4.- DISCUSSION

Using Monte Carlo method the neutron spectra of several isotopic neutron source were calculated from 55 or 60 energy groups to 31 groups.

4.1.- Neutron spectra in different energy bins

In figures 1 to 6 are shown the neutron spectra in 55 and 60 energy groups and the spectra in 31 energy groups. The low resolution spectra resemble the original spectra keeping the main features.

4.2.- Low resolution neutron spectra

In figure 7 are shown the neutron spectra of ^{241}Am(α, n) sources, with F, B and Be targets, and the ^{241}Am(α, n)Li source. The narrow spectra are produced by ^{241}AmF and ^{241}AmB sources. The ^{241}AmBe neutron spectrum has the wider distribution, producing neutrons from 0.5 to 8 MeV; the ^{241}AmLi source produce neutrons from 0.2 to 2 MeV. Changing the neutron spectra from 55 energy groups to 31 energy groups [O´Brien and Sanna 1981] reduce the lower and upper energy range, but it is compensated with the amount of neutrons in each group. The ^{241}AmBe neutron spectrum is alike the spectrum, in the high-energy region, measured by Gallego *et al* [2004] with a Bonner sphere spectrometer with a ^{6}LiI, and calculated by Guzman-Garcia *et al* [2015] using Monte Carlo methods.

In table 5 the mean energy, using the median of each energy group, indicates that the lower mean energy is produced by the ^{241}AmLi neutron source and the largest neutron mean energy is produced by the ^{241}AmBe neutron source. The value for ^{241}AmBe agrees with the ISO value and for the ^{241}AmB our values is approximately 2.4% larger; this difference is not significant.

For ^{241}AmBe amd ^{241}AmB the H*(10) is 391 and 408 pSv-cm^2 respectively [ISO 2001; IAEA 2001]. The H*(10) for ^{241}AmBe here calculated is 391.22 pSv-cm^2, this is approximately 92% larger than the H*(10) obtained through the Bonner sphere spectrometer [Vega-Carrillo *et al*., 2002]. This difference is due the room-return [Vega-Carrillo *et al*., 2007; Khabaz 2015] and the polyethylene moderator of the ^{241}AmBe source that produce epithermal and thermal neutrons. Gallego *et al* [2004] have measured the spectrum and the H*(10) of a ^{241}AmBe source in a low room-return facility at different distances. At 50 cm their spectrum shows the presence of epithermal and thermal neutrons and the H*(10) is 359 pSv-cm^2. The H*(10) here calculated is 9% larger because their spectrum is softer. This effect is also reported by Guzman-Garcia *et al* [2015], however they reported values for H*(10) from 388 to 391 pSv-cm^2, which are in agreement with our results.

The ^{242}CmBe, ^{239}PuBe, and ^{226}RaBe isotopic neutron sources have the narrow energy bin being the largest contribution neutrons from approximately 3.5 to 8 MeV (Figure 8). Their neutron mean energies are 5, 4.9, and 4.4 MeV (Table 6). For the ^{239}PuBe this energy is in agreement with 4.5-5 MeV reported by the NCRP [1991].

The H*(10) for ^{239}PuBe is 19.7% larger than 344 pSv-cm^2 obtained through the neutron spectrum using the Bonner sphere spectrometer [Vega-Carrillo *et al*., 2002], this difference is probably due the room-return and the neutron attenuation in air.

The ^{238}PuLi source produces neutrons from approximately 0.02 to 4 MeV, being the largest contribution from 0.2 to 1 MeV. The wider distribution is produced by the ^{210}PoBe source ranging from 6E(-4) to 8 MeV. Both sources have the lowest mean energy and the lowest doses per neutron fluence.

The (γ, n) sources produce neutrons whose energy is less than 1 MeV (Figure 9). The ^{24}NaD_2O produce neutrons from approximately 2E(-3) to 0.9 MeV. Neutrons with a narrow energy distribution are produced by ^{140}LaBe, ^{116}InBe, and ^{24}NaBe sources. The mean neutron energy of these sources is from 0.1 to 0.6 MeV, having the lowest doses per unit fluence (Table 7).

Regardless the use of few energy groups the neutron spectra of bare and D_2O-moderated ^{252}Cf sources resembles the spectra defined with a larger energy groups (Figure 10). The spectrum of bare ^{252}Cf is alike to the spectrum reported by Guzman-Garcia *et al* [2015]. Bare ^{252}Cf produce neutrons from approximately 0.02 MeV to 15 MeV. When this source is inserted in a 15 cm-radius D_2O sphere the moderation produce neutrons from 1E(-8) MeV to 15 MeV [ISO 1991].

The neutron mean energies are 2.2 and 0.6 MeV for ^{252}Cf and ^{252}Cf/D_2O respectively (Table 8), both values are in agreement with 2-2.4 and 0.4-0.6 MeV reported in literature for ^{252}Cf and ^{252}Cf/D_2O sources respectively [NCRP 1991].

The H*(10) for ^{252}Cf approximately the same reported by the IAEA [2001] and is 2.3% larger for $^{252}Cf/D_2O$. Also, is 1.9% larger that the H*(10) reported by Guzman-Garcia *et al* [2015].

4.3.- Doses in function of the neutron mean energies

The operative magnitude, H*(10), is approximately larger than the protection magnitude $H_{p,s}(10, \theta)$ for all angles when the mean neutron energy is less than 1 MeV. For energies larger than 1 MeV H*(10) is larger just when $\theta > 60^o$, therefore the operative magnitude cannot be used as protection criteria in this range (Figure 11).

In figure 12 the H*(10) is larger for all mean energies, but for EPA for energies larger than 4.5 MeV, therefore the operative magnitude can be used conservatively to avoid larger effective doses.

The $^{252}Cf/D_2O$ has the lowest doses per unit fluence (Figure 13), however it does not has the lowest mean energy. However it shows a large contribution of thermal and epithermal neutrons. This is probably to the shape of the fluence-to-dose conversion coefficients that are low for energies below 10^{-2} MeV and increases for neutrons above 10^{-2} MeV.

5.- CONCLUSIONS

The size of isotopic neutron sources allows using it as a point-like source with calibration purposes. Each source produces neutron with a particular energy distribution that characterize its dosimetric properties.

Here, the neutron spectrum, and the mean neutron energy of several isotopic neutron sources was calculated. The neutron spectrum was calculated using 31 energy groups. The

Ambient dose equivalent, the Personal dose equivalent for different angles, and the Effective dose for all the irradiation conditions per unit fluence were calculated for the isotopic neutron sources.

Regardless the amount of energy bins the neutron spectra is a key feature of the neutron source.

Due to the shape of the fluence-to-dose conversion coefficients the dose per unit fluence tends to raises as the mean neutron energy increases for mostly of the sources, but the $^{252}Cf/D^2O$ because it has a large amount of thermal and epithermal neutrons.

Research needs

Isotopic neutron source is a convenient way to have neutron in low budget laboratories. They can be used for limited neutron activation analysis, to estimate the nucleus size, to measure the absorption and removal cross sections, for prompt gamma-ray neutron activation, to produce low half-life radioisotopes, as a calibration source, to study the molecular response of cells, for dosimetry, etc.

Mostly all applications require the design of a moderator whose features depend on the neutron source application. The study of moderating properties of different materials is a research trend nowadays to obtain the largest amount of thermal neutrons. Also, is a research opportunity to produce neutron spectra with features alike to realistic neutron fields for calibration of spectrometers, neutron measuring devices or neutron area monitors or dosimeters. Another feature that needs to be investigated is the response of passive and active detectors (bare or moderated) to neutrons produced by isotopic neutron sources bare or moderated.

Another area to be explored is the experimental determination of neutron shielding properties of materials, as well as the study of detector responses and the source array to

detect illicit drugs, explosives and special nuclear materials. To more than 80 years of the neutron discovery still is an important tool for basic and applied research, as well as for innovation.

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