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THE CONNECTION BETWEEN THE TIME-MOMENTS AND THE FUNDAMENTAL DECAY CONSTANT OF A THERMALIZED NEUTRON PULSE

by

H. HEMBD

1967

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Reactor Theory and Analysis

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SUMMARY

The decay of a thermalized neutron pulse in a large moderating sample is studied by the time moments method applied to the Boltzmann equation. The time moments define the mean emission time or lifetime for neutrons before escaping or being absorbed at a certain energy. The decay constant of the neutron pulse is derived as a mean value of the inverse emission time. The first three coefficients in the expansion of the decay constant in terms of the geometrical buckling are identical with those obtained by Nelkin in his eigenvalue approach. Further properties of the time moments and their connection with the experiment are pointed out.

THE CONNECTION BETWEEN THE TIME-MOMENTS AND THE FUNDAMENTAL DECAY CONSTANT OF A THERMALIZED NEUTRON PULSE (*)

The time behaviour of a neutron pulse in a large thermalizing medium can be described by the time dependent Boltzmann equation in the diffusion approximation

$$\frac{1}{v} \cdot \frac{\partial \phi}{\partial t} + (\Sigma_a + DB^2) \phi = \mathcal{L} \phi + S(E,B) \cdot \delta(t) \qquad (1)$$

where

$\phi(E,B,t)$ is the neutron flux,
B the buckling,
$S(E,B) \cdot \delta(t)$ the source distribution induced as a pulse at t = 0,
D(E) the diffusion coefficient,
$\Sigma_a(E)$ the absorption cross section, and
$\mathcal{L}$ the thermalization operator defined in the usual way by

$$\mathcal{L} \phi \equiv \int_0^\infty \Sigma_s(E' \rightarrow E) \, \phi(E') dE' - \Sigma_s(E) \, \phi(E) \qquad (1a)$$

with

$$\Sigma_s(E) = \int_0^\infty \Sigma_s(E \rightarrow E') dE$$

The problem of solving eq. (1) becomes more simple by assuming $^1/v$ - absorption

$$v \cdot \Sigma_a(E) = a = \text{const}, \qquad (1b)$$

a condition generally fulfilled in practical situations. The substitution

$$\phi(E,B,t) = e^{-at} \varphi(E,B,t) \qquad (1c)$$

reduces eq. (1) to the absorption free case

(*) Manuscript received on December 13, 1966.

$$\frac{1}{v}\frac{\partial \varphi}{\partial t} + DB^2\varphi = \mathcal{L}\varphi + S\cdot\delta(t) \qquad (2)$$

which will be the basis of the following investigation. Nelkin [1] has studied the eigensolutions of the source-free eq. (1) by the ansatz

$$\phi(E,B,t) = e^{-\alpha t}\cdot\phi(E,B). \qquad (3a)$$

This is equivalent to applying the ansatz

$$\varphi(E,B,t) = e^{-(\alpha - a)t}\cdot\varphi(E,B) \qquad (3b)$$

to eq. (2). For the fundamental eigenvalue in terms of the buckling he finds

$$\lambda \equiv \alpha - a = D_0 B^2 - C B^4 + \ldots \qquad (4)$$

with

$$D_0 = \frac{\int_0^\infty D(E)\, M(E)dE}{\int_0^\infty \frac{1}{v} M(E)dE} \qquad (4a)$$

$$C = \frac{\int_0^\infty (D(E) - \frac{D_0}{v})\,\phi_{2,0}(E)dE}{\int_0^\infty \frac{1}{v} M(E)dE} \qquad (4b)$$

where M(E) is a Maxwellian and $\phi_{2,0}(E)$ the solution of

$$(\frac{D_0}{v} - D(E))\, M(E) = \mathcal{L}\,\phi_{2,0}(E). \qquad (4c)$$

At it is wellknown, the solution of eq. (1) by a superposition of eigenfunctions cannot be done in the classical way since the eigenfunctions do not form a complete set [2] . However, instead of solving eq. (1) explicitly in time and energy we can obtain the same information by considering the time moments which satisfy a simpler equation. The time moments of order k are defined as

$$M_k(E,B) \equiv \int_0^\infty t^k \, \phi(E,B,t)\, dt = \int_0^\infty e^{-at}\, t^k \varphi(E,B,t) dt , \qquad (5)$$

or

$$m_k(E,B) \equiv \int_0^\infty t^k \, \varphi(E,B,t)\, dt \qquad (5a)$$

in the absorption free case of eq. (2).

The time moments are of interest for three reasons:

(i) They can be drawn out from pulsed experiments with great precision since they are time-integrated quantities. Moreover, the time- and energy-integrated reaction rates measured by a $^1/v$ - detector

$$r_k(B) = \int_{E\,min}^{E\,max} \frac{1}{v}\, m_k(E,B)\, dE \qquad (6)$$

are connected with the fundamental eigenvalue λ in the following way

$$\frac{r_0(B)}{r_1(B)} = \lambda(B), \qquad (\text{for } B^2 \ll \Sigma_s^2) \qquad (7)$$

a result which will be shown afterwards.

(ii) They satisfy a Boltzmann equation which is stationary but with a modified source term. Hence they may be calculated by a routine program like GATHER [3] . The latter provides an option for time moments.

(iii) The ratio

$$\tau(E) \equiv \frac{m_1(E,B)}{m_0(E,B)} \tag{8}$$

has a physical meaning. Called "emission time" it is the mean lifetime of a neutron before escaping with an energy E.

To derive the equations for the time moments we multiply eq. (2) by t^k and integrate from zero to infinity:

$$DB^2 m_0(E,B) = \Sigma m_0(E,B) + S(E,B); \qquad (k = 0) \tag{9,0}$$

$$DB^2 m_k(E,B) = \Sigma m_k(E,B) + \frac{k}{v} m_{k-1}(E,B). \qquad (k \geq 1) \tag{9,k}$$

To solve eqs. (9) we expand all quantities in a power series of B^2 and compare terms of the same order in B^2:

$$m_0(E,B) = m_{00}(E) + B^2 m_{02}(E) + B^4 m_{04}(E) + \ldots \tag{10,0}$$

$$m_1(E,B) = \frac{1}{B^2}\left[m_{10}(E) + B^2 m_{12}(E) + B^4 m_{14}(E) + \ldots\right] \tag{10,1}$$

$$m_2(E,B) = \frac{1}{B^4}\left[m_{20}(E) + B^2 m_{22}(E) + B^4 m_{24}(E) + \ldots\right]. \tag{10,2}$$

The expansions (10,k) observe the fact that the k-th moment is an order of magnitude (in B^2) larger than the (k-1)-th. This can be seen from the condition of neutron conservation

$$B^2(D,m_k) = \int_0^\infty \mathcal{L}\, m_k\, dE + k\cdot(\tfrac{1}{v}\,,\, m_{k-1}), \tag{11}$$

since for all distributions $\varphi(E)$

$$\int_0^\infty \mathcal{L}\,\varphi\, dE \equiv 0 \tag{11a}$$

which is a consequence of the definition of the operator(1a). The brackets mean

$$(u,v) \equiv \int_0^\infty u(E)\, v(E)\, dE.$$

The source in (9,0) must be of the same order as the leakage term on the left, hence

$$S(E,B) = B^2 S_2(E) + B^4 S_4(E) + \ldots \tag{12}$$

Eq. (9,0) splits up into

$$0 = \mathcal{L}\, m_{00} \tag{13,0}$$

$$Dm_{00} = \mathcal{L}\, m_{02} + S_2 \tag{13,1}$$

$$Dm_{02} = \mathcal{L}\, m_{04} + S_4 \tag{13,2}$$

We infer the solution

$$m_{00} = M(E) = \frac{E}{T}\cdot \exp(-E/kT) \tag{14,0}$$

and, observing eq. (11a), the conservation conditions

$$(D,M) = \int_0^\infty S_2\, dE \tag{14,1}$$

$$(D,m_{02}) = \int_0^\infty S_4\, dE \tag{14,2}$$

Eq. (9,1) splits up into

$$0 = \mathcal{L}\, m_{10} \tag{15,0}$$

$$Dm_{10} = \mathcal{L}\, m_{12} + \frac{m_{00}}{v} \tag{15,1}$$

$$Dm_{12} = \mathcal{L}\, m_{14} + \frac{m_{02}}{v}\,, \tag{15,2}$$

with the conservation conditions

$$m_{10} = c_1\, M(E) \tag{16,0}$$

$$c_1(D,M) = (\tfrac{1}{v}\,,\, M) \quad \text{or} \quad c_1 = D_o^{-1} \text{ (see eq. (4a))} \tag{16,1}$$

$$(D, m_{12}) = (\tfrac{1}{v}\,,\, m_{02})\,. \tag{16,2}$$

For the determination of the ratio (7) of reaction rates (6) we have for small B^2

$$r_o(B) = (\tfrac{1}{v}\,,\, M) + B^2\,(\tfrac{1}{v}\,,\, m_{02}) + \ldots$$

or with (16,2)

$$= (\tfrac{1}{v}\,,\, M) + B^2\,(D,\, m_{12}) + \ldots$$

and

$$r_1(B) = \frac{1}{B^2}\left[\frac{1}{D_o}\,(\tfrac{1}{v}\,,\, M) + B^2(\tfrac{1}{v}\,,\, m_{12}) + \ldots\right].$$

Hence

$$\frac{r_o(B)}{r_1(B)} = D_o B^2 - B^4 \cdot \frac{D_o\,(\frac{D_o}{v} - D,\, m_{12})}{(\frac{1}{v}\,,\, M)} + O(B^6)\,. \tag{17}$$

This is the same result as given by Nelkin (see eqs. (4)) for the fundamental eigenvalue. The solution $m_{12}(E)$ of eq. (15,1) satisfies

$$\mathcal{L}(-D_0 m_{12}) = \left(\frac{D_0}{v} - D\right) M(E)$$

which is exactly Nelkin's equation for his ϕ_{20}.

The reciprocal emission time in terms of B^2 is given by

$$\frac{1}{\tau(E)} = \frac{m_0(E,B)}{m_1(E,B)} = \frac{M(E)\left[1 + B^2 \frac{m_{02}(E)}{M(E)} + \ldots\right]}{(B^2 D_0)^{-1} M(E)\left[1 + B^2 D_0 \frac{m_{12}(E)}{M(E)} + \ldots\right]}$$

$$= D_0 B^2 \cdot \left[1 - \frac{B^2}{M(E)}\left[D_0 m_{12}(E) - m_{02}(E)\right] + O(B^4)\right]. \qquad (18)$$

Averaging this quantity over all energies with a Maxwellian density as weight function

$$\left\langle \frac{1}{\tau} \right\rangle \equiv \frac{\int_0^\infty \frac{1}{\tau(E)} \frac{M(E)}{v} dE}{\int_0^\infty \frac{M(E)}{v} dE} \qquad (19)$$

yields same right hand side as eq. (17) so that we have the agreement

$$\left\{ \frac{1}{\tau} - \lambda \right\} = O(B^6) \qquad (20)$$

for small B^2. From a physical point of view it may be more justified not to use the Maxwellian density in the averaging prescription (19) but the actual neutron density connected with the solution of eq.(9,0). Operating with $m_0(E,B)$ we get the same asymptotic relation (20), now with another coefficient of B^6.

The behaviour of the emission time for small values of the energy is of interest. For the functions m_{02} and m_{12} which enter eq. (18) we make the ansatz

$$m_{02}(E) = M(E)\left[a_0 + a_1 E + \ldots\right] \qquad (21,0)$$

$$m_{12}(E) = M(E)\left[b_0 + b_1 E + \ldots\right]. \qquad (21,1)$$

These expansions are coupled by the condition of neutron conservation written in the form of eq. (16,2). With the help of eq. (16,1) we find

$$(D_o b_o - a_o)\,(\tfrac{1}{v}, M) = a_1\,(\tfrac{1}{v}, EM) - b_1\,(D,EM). \qquad (22)$$

The desired expression to be inserted into eq. (18) is

$$\frac{D_o}{M(E)}\left[D_o\, m_{12}(E) - m_{o2}(E)\right] = \left[(D_o b_o - a_o) + E\,(D_o b_1 - a_1)\right]\cdot D_o$$

or, again with (16,1) and (22)

$$= \frac{D_o}{(\tfrac{1}{v}, M)}\left\{ a_1\left[(\tfrac{1}{v}, EM) - E(\tfrac{1}{v}, M)\right] + b_1\left[(D,M)E - (D,EM)\right]\right\}. \qquad (23)$$

Averaging in the sense of definition (19) cancels the cofactor of a_1, whereas the second member in (23) yields a diffusion coefficient C_1 which is an approximation to the true diffusion coefficient C due to the fact that we have retained only two terms in the expressions (21,0) and (21,1):

$$C_1 = D_o b_1 \cdot (\tfrac{1}{v}, M)^{-1}\,(\tfrac{D_o}{v} - D, EM). \qquad (24)$$

The coefficients a_1, b_1 can be determined from eqs. (13,1) and (15,1). The equation for a_1 is

$$D(E)\,M(E) = a_1\,\mathcal{L}[EM] + S_2(E).$$

The common way to solve for a_1 is to multiply by E and to integrate. But then the mean source energy would dominate in the above equation. This is not desirable since the source has not been specified, except that it is concentrated near a mean source energy E_s in the high energy range. Instead, we weigh by E^{-1} so that

$$\int_o^\infty \frac{1}{E} S_2(E)dE = \frac{1}{E_s}\int_o^\infty S_2 dE = \frac{1}{E_s}\cdot(D,M) \ll (\tfrac{1}{E}, DM)$$

can be neglected. (Use has been made of eq. (14.1)). Now

$$a_1 = \frac{(\frac{1}{E}, DM)}{(\frac{1}{E}, \mathcal{L} EM)} = \frac{2}{\mu^*} \cdot (\frac{1}{E}, DM) \qquad (25)$$

where the energy transfer moment

$$\mu^* = \int_0^\infty \frac{(E'-E)^2}{EE'} M(E') \Sigma_s (E' \to E) \, dE' dE = 2 (\frac{1}{E}, \mathcal{L} EM) \geq 0 \qquad (25a)$$

has been introduced (For the heavy gas operator $\mu^* = 2 \cdot \xi \Sigma_s$, where $\xi \Sigma_s$ is the constant slowing down power). In the same manner we get from

$$\frac{D(E)}{D_o} M(E) = b_1 \mathcal{L} [EM] + \frac{1}{v} M(E)$$

the coefficient

$$b_1 = \frac{2}{\mu^*} \cdot (\frac{D}{D_o} - \frac{1}{v}, \frac{M}{E}). \qquad (26)$$

In the limit of zero energy the emission time τ is given by

$$\frac{1}{\tau(0)} = D_o B^2 - C_o B^4 + O(B^6). \qquad (27)$$

According to eq. (23)

$$C_o = D_o (\frac{1}{v}, M)^{-1} \left[a_1 (\frac{1}{v}, EM) - b_1 (D, EM) \right]. \qquad (28)$$

The difference of the C-values turns out to be

$$C_o - C_1 = \frac{2}{\mu^*} \cdot D_o^2 \cdot \frac{(\frac{1}{v}, EM)(\frac{1}{v}, \frac{M}{E})}{(\frac{1}{v}, M)} > 0, \qquad (29)$$

so that on the basis of the linear (two terms) approximation (21,0) and (21,1) the relation

$$\left\{ \frac{1}{\tau(0)} - \lambda \right\}_{\text{lin}} = - (C_0 - C_1)\, B^4 \tag{30}$$

holds. Since the difference (20) is only of order B^6 we state that the correct substitute for the fundamental eigenvalue up to corrections of order B^6 is $\left\langle \frac{1}{\tau(E)} \right\rangle$ instead of $\frac{1}{\tau(0)}$.

So far we have studied the absorption free case with time moments $m_k(E,B)$. What is really measured or calculated by GATHER is the time moment $M_k(E,B)$ over the true flux established under the influence of absorption. Assuming the absorption to be small we may expand in (5) with respect to the small parameter a:

$$M_k(E,B) = m_k(E,B) - a\, m_{k+1}(E,B) + \frac{a^2}{2} m_{k+2}(E,B) - + \ldots . \tag{31}$$

Then the inverse of the emission time comprising absorption $\tau_a(E)$ is

$$\frac{1}{\tau_a(E)} \equiv \frac{M_0(E,B)}{M_1(E,B)} = \frac{m_0(E,B)}{m_1(E,B)} + a \left(\frac{m_0(E,B)\, m_2(E,B)}{m_1(E,B)^2} - 1 \right) + O(a^2) . \tag{32}$$

We find $m_2(E,B)$ by introducing the ansatz (10,2) into eq. (9,2) and comparing quantities of the same order in B^2:

$$0 = \mathcal{L}\, m_{20} \tag{33,0}$$

$$Dm_{20} = \mathcal{L}\, m_{22} + \frac{2}{v} m_{10} \tag{33,1}$$

$$Dm_{22} = \mathcal{L}\, m_{24} + \frac{2}{v} m_{12} . \tag{33,2}$$

It follows

$$m_{20} = c_2\, M(E) \tag{34,0}$$

$$c_2 = \frac{1}{D_o} \frac{(\frac{2}{v}, M)}{(D,M)} = \frac{2}{D_o^2} \tag{34,1}$$

$$(D, m_{22}) = 2\,(\tfrac{1}{v}, m_{12})\,. \tag{34,2}$$

Further

$$\frac{m_o \cdot m_2}{m_1^2} = 2 \cdot \frac{\left[1 + B^2 \frac{m_{02}}{M(E)} + \cdots\right] \cdot \left[1 + \frac{B^2 D_o^2}{2} \frac{m_{22}}{M(E)} + \cdots\right]}{\left[1 + D_o B^2 \frac{m_{12}}{M(E)} + \cdots\right]^2}$$

$$= 2\left[1 + B^2 \left(\frac{m_{02}(E)}{M(E)} + \frac{D_o^2}{2} \frac{m_{22}(E)}{M(E)} - 2 D_o \frac{m_{12}(E)}{M(E)}\right)\right] + O(B^4)$$

thus the average value of (32) in the sense of (19) becomes

$$\left\langle \frac{1}{\tau_a} \right\rangle = a + \left\langle \frac{1}{\tau} \right\rangle + \langle \mathcal{E}(E) \rangle\,. \tag{35}$$

We will show that the error term $\langle \mathcal{E}(E) \rangle$ vanishes so that

$$\left\langle \frac{1}{\tau_a} \right\rangle = a + \left\langle \frac{1}{\tau} \right\rangle = a + D_o B^2 - C B^4 \tag{36}$$

agrees - up to terms of higher order - completely with Nelkin's result (4) for the fundamental eigenvalue $\alpha = a + \lambda$.

The error term is

$$\langle \mathcal{E}(E) \rangle = aB^2 (\tfrac{1}{v}, M)^{-1} \cdot \left[2(\tfrac{1}{v}, m_{02}) + D_o^2 (\tfrac{1}{v}, m_{22}) - 4 D_o (\tfrac{1}{v}, m_{12}) \right]$$

or, using (16,2) and (34,2)

$$= a B^2 (\tfrac{1}{v}, M)^{-1} \cdot \left[2 \int_o^\infty (D - \frac{D_o}{v}) m_{12}\, dE - D_o \int_o^\infty (D - \frac{D_o}{v}) m_{22}\, dE \right]. \tag{37}$$

Equation (15,1) can be written

$$\mathcal{L}\, m_{12} = \left(\frac{D}{D_o} - \frac{1}{v}\right) \cdot M(E), \tag{38}$$

and equation (33,1), because of (34,1) and (16,0),

$$\mathcal{L}\, m_{22} = \frac{2}{D_o} \cdot \left(\frac{D}{D_o} - \frac{1}{v}\right) \cdot M(E)\ . \tag{39}$$

Consequently the difference $2\, m_{12} - D_o m_{22}$ is a solution of the homogeneous equation

$$\mathcal{L}\left[2\, m_{12} - D_o\, m_{22}\right] = 0,$$

that means a Maxwellian:

$$2\, m_{12} - D_o\, m_{22} = \text{const} \cdot M(E). \tag{40}$$

Due to the definition (4a) of D_o the error term (37) vanishes if we insert expression (40).

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[1] M. NELKIN: Nucl. Sc. Eng. 7, 210-216, (1960)

[2] M. NELKIN: Physica 29, 261-273 (1963)

[3] G.D. JOANOU et al.: GATHER-II, GA-4132, General Dynamics 1963, San Diego.

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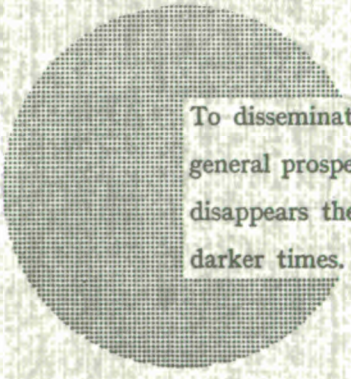

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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