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Neutron Energy Flux and Dosage in the LAMPF π^- Biomedical Channel

by

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ABSTRACT

Rough working estimates are obtained from published data for the neutron energy flux and dosage for use of experimenters at the LAMPF Biomedical Channel. This compilation emphasizes the need for experimental confirmation of the several Monte Carlo theoretical predictions which have been made and are being made in preparation for π^- therapy of humans in the near future.

I. INTRODUCTION

The purpose of this report is to provide rough working estimates of the neutron energy flux and dosage for the several groups now carrying out experiments at the Clinton P. Anderson Meson Physics Facility (LAMPF) Biomedical Channel at the Los Alamos Scientific Laboratory.

Research Proposal No. 151, for which Dr. H. B. Knowles is Acting Spokesman, specifies about 10^7 π^- /sec of primary beam is required for reasonable running times in which SDTR, FFTD, TLD, and SiD passive detectors are used to measure the dosage distribution in and around an approximately tissue-equivalent (T-E) human phantom. Research Proposal No. 84, for which Dr. G. C. Phillips is Spokesman, uses a 0.1 cm^3 T-E ionization chamber immersed in a T-E solution to determine the depth distribution of absorbed dose. It is of interest to know the neutron portion of this dose. This information is also of considerable interest to the MP-3 Practical Applications Group under Dr. John Dicello.

It is clear that experimental confirmation of the several theoretical treatments of this problem

is needed in order for π^- therapy of humans to be carried out with confidence.

II. AVAILABLE CALCULATIONS

Schillaci and Roeder made calculations of neutron and gamma dosage based on a simple spherical geometry of tissue.¹ Treatment volumes of 0.01, 0.1, and 1 litre were used, representing a range of tumor sizes. The photon dose was found to be negligible in comparison to the neutron dose. The ANDY Monte Carlo computer program used is only capable of handling neutrons up to 17 MeV in energy.² As discussed in the next section, a significant fraction of the π^- capture neutrons in tissue have energies > 17 MeV.

III. NEUTRON SOURCE

Approximately half of the 140 MeV released on π^- capture appears as kinetic energy of neutrons. In fact, about one-third of the π^- captures in emulsions show no charged-particle tracks.

The neutrons are of two types called "direct" and "evaporation," named for the nuclear processes by which they are emitted. The "direct" neutrons are emitted essentially instantaneously with the capture of a π^- by a neutron-proton pair in the nucleus. Nearly all neutrons above 10 MeV in energy are of this type. They appear largely in pairs back-to-back with little nuclear recoil energy. For this reason, it seems likely that nearly all "direct" neutrons are emitted isotropically in the lab system for the capture of zero energy π^- 's. "Evaporation" neutrons are emitted isotropically by the residual nucleus following this direct emission. The energy (E) distribution of these neutrons appears to have an exponential dependence $e^{-E/\theta}$ where θ is the temperature of the first residual nucleus formed in the cascade evaporation process. Emissions of charged particles (p,d,t, ^3He , and α), being slower than neutron emission, follow in the evaporation process forming the familiar stars seen in emulsions and bubble chambers. These charged particles and their accompanying recoil nuclei cause the localized ionization that is of primary interest in π^- radiation therapy.

Schillaci and Roeder used as their neutron source spectra the Monte Carlo intranuclear cascade and evaporation model of Guthrie, et al,^{1,3} for ^{16}O , ^{12}C , and ^{14}N . They assumed the probability of π^- capture is the same for these three atoms and is negligible for hydrogen. Table I gives the Guthrie, et al, neutron spectra.⁴ We have divided these data into three energy groups for purposes of later discussion. The number of neutrons in each energy group is shown. The totals are multiplicities $\nu = 2.92$ for ^{16}O , 2.78 for ^{12}C , and 2.81 for ^{14}N . These values of ν agree with those reported by Guthrie, et al,³ showing that we have properly interpreted their normalization of the neutron number-energy distributions. It is also of interest to note from Table II that these values of ν agree, within the reported statistical uncertainties, of the experimental values from three groups of investigators (c,d,e in Table II). Strictly the value of $\nu = 2.8 \pm 0.3$ for carbon reported by Anderson, et al, does not include neutrons below 1.78 MeV in energy. If we add Guthrie's, et al, $\nu = 0.102$ for $E_n = 0$ to 1 MeV and $\nu = 0.78 \times .116 = 0.13$ for $E_n = 1$ to 1.78 MeV, we obtain for carbon $\nu = 3 \pm 0.3$ which is still in agreement,

within the statistical uncertainty, with the normalization value $\nu = 2.79$ of Guthrie, et al. Future calculations for carbon might better be normalized to $\nu = 3.0$.

IV. NEUTRON ENERGY GROUPS

From Table I we see that 66.4% of the ^{16}O neutrons have energies below 17 MeV, 61.7% for ^{12}C , and 63.0% for ^{14}N .

Because the highest energy group in the ANDY² cross-section library is 15 - 17 MeV, Schillaci and Roeder attempted to take into account the high-energy neutrons ($E_n = 17$ to 100 MeV) by two rather crude approximations.¹ Approximation I lumped all the 17 - 100 MeV neutrons in with the highest energy ANDY group from 15 - 17 MeV. The justification given for this approximation is that the linear energy transfer (LET) for fast neutrons decreases with increasing energy. Hence, according to Schillaci and Roeder, approximation I should be "reasonably good for regions of tissue close to the stopping region of the pions."¹ Approximation II assumes that the total energy carried by the neutrons with energy greater than 17 MeV can be included in the ANDY 15 - 17 MeV group by increasing this group by 2.87 times that resulting from Approximation I. Schillaci and Roeder then state that Approximation II "obviously overestimates the dose delivered to regions of tissue that are close to the stopping region of the pions."¹ Unfortunately, these authors do not define the radial distance implied by the word "close." Thus, it is difficult to estimate the degree of reliability of the dose distributions in tissue which they present in Fig. 3 of their paper (included here as Fig. 1). The authors also state that "it can be expected that an accurate treatment of the higher energy (> 17 MeV) neutrons would result in a dose curve intermediate between the two shown in each of Figs. 3(a), (b), and (c) (Hamm and Turner, private communication)." Maybe this is true. However, until an "accurate treatment of the higher energy" is carried out, we believe the curves of Fig. 1 should be used with caution in estimating the unwanted radiation dosage in the treatment of human patients. Our reasons for such reservation are presented in the next section.

Fig. 1. Dose distributions in tissue from star neutrons for (a) 0.01 litre, (b) 0.1 litre and (c) 1 litre treatment volumes, using approximations I and II (see text). The total doses within these treatment volumes are (a) 7.5×10^{-8} rad/ π^2 stop, (b) 7.5×10^{-9} rad/ π^2 stop and (c) 7.5×10^{-10} rad/ π^2 stop. (Ref. 4.)

V. NEUTRON CROSS SECTIONS

We understand the ANDY Monte Carlo transport program is based on experimentally determined neutron cross sections obtained from T-2 Group at LASL.² These are extensive below 17 MeV because there are many sources of monoenergetic neutrons in this energy region and because numerous investigators have used these sources over the past 30 to 40 years to determine neutron cross sections. Between 17 and 100 MeV monoenergetic sources are less plentiful. Hence, reliable cross sections in this region are sparse.⁵

Another factor to consider in planning an extension of the ANDY program to include 17- to 100-MeV neutrons is the increase in significance of (n,p), (n, α), (n,2p), and (n,2n) and (n,pn) cross sections as well as the anisotropic inelastic scattering of these high-energy neutrons.⁶ It is conceivable that the accelerated reduction in the energy of the neutrons by (n,2n) and (n,pn) reactions more than offsets the increased dosages caused by (n, charged particle) reactions in tissue. Certainly there is an urgent need for an accurate treatment of the 17- to 100-MeV neutron transport relations since these are the more lethal neutrons even though they are only half as prevalent as those below 17 MeV.

For purposes of the LAMPF Biomedical Channel dosage measurements with emulsions, we will now review the cross sections of the elements in the more commonly used Ilford plates.

Shein has given the composition of Ilford 6-5 emulsion shown in Table III.⁷ He has also listed cross sections per nucleus at an unspecified energy. We estimate this energy to be 140 MeV based on the tabulated values of 59.4 mb for H, and 30.9 mb for C. In place of these high-energy cross sections, we need data for the energy groups listed in Table I, especially those above 17 MeV. Table IV lists the experimentally determined total cross sections σ_t plus a few interpolated or extrapolated values. These microscopic cross sections in barns are multiplied by the atomic densities N_i (in units of 10^{24} atoms per cm^3) to obtain the tabulated total macroscopic cross sections ($N_i \sigma_i$) for H, C, O, N, Ag, and Br. Comparison of these ($N_i \sigma_i$) values allows estimates to be made of the relative number of collisions which will occur in the emulsions for an estimated incident neutron flux. However, care must be taken in such estimates with respect to Ag and Br,⁸ because these atoms are clumped into grains of AgBr instead of being uniformly distributed throughout the emulsion as are the H, C, O, and N atoms. (We have simply ignored the I and S atoms because of their low atomic densities.) Other cross sections of interest in tissue as well as in emulsions are summarized in Table V.

VI. EMULSION TECHNIQUES

In his review paper, Rosen states that,⁹ "at 14 MeV, a neutron flux* of approximately $2 \times 10^8/\text{cm}^2$

* i.e., $\theta\tau = 2 \times 10^8$ neutrons/ cm^2 .

is required to project, within a pyramid of half-angle 10 deg, 25 tracks/mm² that begin and terminate within an emulsion layer 200-μ-thick." Accepting this as a good working figure and noting from Table IV that at this energy $\sigma_t(H) = 0.7$ b and $N(H)\sigma_t(H) = 0.023$ cm⁻¹, then $\phi N(H)\sigma_t(H) = 4.6 \times 10^6$ collisions with H per cm². Because the cross section at 50 - 60 MeV is only one-fourth that at 14 MeV, it will require about four times as much flux, i.e., 8×10^8 /cm², to attain the same track density in the emulsion. From part (a) of Fig. 1, we see that midway between curves I and II the neutron dosage is about 1.08×10^{-11} rad/ π^- stop for a 0.01 liter treatment volume ($r_0 = 1.34$ cm). Goldstein cites a conversion factor of 7×10^{-9} rad per n/cm² for 10-MeV neutrons.¹⁰ If we use this as a rough working figure for the average neutrons in Fig. 1, we see that the neutron flux is $\frac{1.08 \times 10^{-11} \text{ rad n/cm}^2}{7 \times 10^{-9} \text{ rad } \pi^- \text{ stop}} = 1.5 \times 10^{-3}$ n/cm² at $r = 10$ cm per π^- stops. To obtain a flux of 2×10^8 neutrons/cm² would require $\frac{2 \times 10^8}{1.5 \times 10^{-3}} \approx 10^{11}$ π^- stops. This would require an exposure of 10^3 seconds for 10^8 stopped π^- /sec or 10^4 seconds for 10^7 stopped π^- /sec. Something between 10^3 and 10^4 seconds is considered a reasonable beam time in the Biomedical Channel. A factor of ten higher beam time (28 hours) is not considered reasonable. Yet this exposure time would be required if the radial distance is only increased to 22 cm according to Fig. 1(a). It is also questionable whether a beam current of 10^7 stopped π^- /sec is attainable at present in the Biomedical Channel. Thus, it appears that neutron energy spectra measurements using emulsions as detectors are of marginal usefulness in the phantoms now being irradiated with π^- beams in the Biomedical Channel.

Ed Hungerford of the Univ. of Houston has suggested the use of a stack of ten emulsion plates with one-tenth the track density of a single plate in order to achieve the same statistics in the emulsion experiment. We understand this approach will greatly increase the track-scanning time. As so often happens in planning a physics experiment, we need to find the optimum balance between intensity and data-collection time. In this case, the solution, as usual, is left as an exercise for the graduate student, Gary Pfeufer (Rice Univ.).

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TABLE I
NEUTRON SPECTRA FROM π^- CAPTURE

ΔE_n (MeV)	Neutrons per MeV per		π^- Capture				
	$^{16}_O$	$^{12}_C$	$^{14}_N$				
0-1	0.135	0.102	0.128		20-25	0.0296	0.0278 0.0288
1-2	0.211	0.166	0.178		25-30	0.0134	0.0104 0.0177
2-3	0.196	0.170	0.193		30-40	0.0126	0.0121 0.0120
3-4	0.192	0.158	0.158		40-50	0.0131	0.0164 0.0136
4-5	0.186	0.156	0.160		50-60	0.0140	0.0162 0.0143
5-6	0.149	0.120	0.140		60-70	0.0116	0.0131 0.0125
6-7	0.140	0.106	0.120		70-80	0.00857	0.00904 0.00867
7-8	0.122	0.103	0.111		80-90	0.00459	0.00437 0.00510
8-9	0.100	0.109	0.095		90-100	<u>0.00184</u>	<u>0.00281</u> <u>0.00262</u>
9-10	<u>0.086</u>	<u>0.0927</u>	<u>0.083</u>	Σ_n	17-100	0.97440	1.0598 1.0376
Σ_n 0-10	1.517	1.2827	1.366	Σ_n	0-100	2.9178	2.7755 2.8062
10-12	0.0812	0.0733	0.0802	Note: the number of neutrons Σ_n for: 0-10 MeV are multiplied by 1 MeV 10-16 MeV are multiplied by 2 MeV 16-17 MeV are multiplied by 1 MeV 17-18 MeV are multiplied by 1 MeV 18-20 MeV are multiplied by 2 MeV			
12-14	0.0619	0.0629	0.0534				
14-16	0.0507	0.0558	0.0476				
16-17	<u>0.0388</u>	<u>0.0490</u>	<u>0.0402</u>				
Σ_n 10-17	0.4264	0.4330	0.4026				
Σ 0-17	1.9434	1.7157	1.7686				
17-18	0.0388	0.0490	0.0402				
18-20	0.0288	0.0398	0.0385				

TABLE II
CALCULATED AND EXPERIMENTAL VALUES OF MULTIPLICITIES ν FOR π^- CAPTURES

Cap. El.	ν Calc. (a)	ν Calc. (b)	ν Exp. (c)	ν Exp. (d)	ν Exp. (e)
O	2.94	2.92	2.7 ± 0.15		2.77 ± 0.34
C	2.79	2.78	2.68 ± 0.10	2.8 ± 0.3	2.92 ± 0.36
N	2.80	2.81			2.65 ± 0.35
Al	2.84			3.2 ± 0.3	3.07 ± 0.42

- a) Guthrie et al, Ref. 3.
b) Ref. 1 integrated in present report.
c) Fowler and Mayes, Proc. Phys. Soc. (Lond.), 92 377 (1961), a reworking of other's experimental values.
d) Anderson et al, Phys. Rev. 133 B392 (1964).
e) Hattersley et al, Nuc. Phys. 67 309-314 (1965).

TABLE III
COMPOSITIONS AND CROSS SECTIONS OF ILFORD G-5 EMULSION

Element	Atomic Weight A_i	Density of Emulsion Components in g/cm ³ ρ_i	Numbers of Atoms per cm ³ N_i	Cross Section per Nucleus in cm ² σ_i	Cross Section of N_i Nuclei per cm ³ $N_i \times \sigma_i$
⁴⁷ Ag	107.9	1.85	1.056×10^{22}	1.338×10^{-24}	1.411×10^{-2}
³⁵ Br	79.9	1.36	1.025×10^{22}	1.094×10^{-24}	1.121×10^{-2}
⁵³ I	126.9	0.024	0.01139×10^{22}	1.49×10^{-24}	1.698×10^{-4}
⁶ C	12.0	0.27	1.3545×10^{22}	0.309×10^{-24}	4.18×10^{-3}
¹ H	1.01	0.056	3.34×10^{22}	0.0594×10^{-24}	19.8×10^{-4}
⁸ O	16.0	0.27	0.939×10^{22}	0.3745×10^{-24}	3.52×10^{-3}
¹⁶ S	32.1	0.010	0.01873×10^{22}	0.596×10^{-24}	11.18×10^{-6}
⁷ N	14.0	0.067	0.2875×10^{22}	0.343×10^{-24}	9.86×10^{-4}
Total		3.907	8.032×10^{22}		361.67×10^{-4}

TABLE IV

MEAN TOTAL MICROSCOPIC AND MACROSCOPIC CROSS SECTIONS

FOR MAJOR CONSTITUENTS OF ILFORD G-5 EMULSION FOR VARIOUS ENERGY GROUPS (FROM BNL-325 + SUPPLEMENTS)

ΔE_n (MeV)	$\sigma_t(H)$ $\times 10^{24} \text{ cm}^2$	$N(H)\sigma_t(H)$ cm^{-1}	$\sigma_t(c)$ $\times 10^{24} \text{ cm}^2$	$N(c)\sigma_t(c)$ cm^{-1}	20-25	1.65	0.015	(1.6)	0.0046
0-1	20 to 4.3	0.67 to 0.14	3.5	0.047	25-30	1.55	0.015	(1.5)	0.0043
1-2	3.0	0.1	2.1	0.028	30-40	1.4	0.013	(1.3)	0.0037
2-3	2.5	0.084	2.0	0.027	40-50	1.25	0.012	1.15	0.0033
3-4	2.0	0.067	2.0	0.027	50-60	1.1	0.010	(0.95)	0.0027
4-5	1.7	0.057	1.5	0.020	60-70	0.96	0.0090	(0.82)	0.0024
5-6	1.5	0.050	1.1	0.015	70-80	0.86	0.0081	(0.72)	0.0021
6-7	1.35	0.045	1.0	0.014	80-90	0.76	0.0071	0.64	0.0018
7-8	1.2	0.040	1.5	0.020	90-100	0.70	0.0066	0.57	0.0016
8-9	1.1	0.037	1.3	0.018	$\sigma_t(N)$ in () are interpolations between experimental values.				
9-10	1.0	0.033	1.15	0.016	ΔE_n	$\sigma_t(Ag)$	$N(Ag)\sigma_t(Ag)$	$\sigma_t(Br)$	$N(Br)\sigma_t(Br)$
10-12	0.86	0.029	1.2*	0.015	(MeV)	$\times 10^{24} \text{ cm}^2$	cm^{-1}	$\times 10^{24} \text{ cm}^2$	cm^{-1}
12-14	0.75	0.025	1.3*	0.018	0-1	7.0	0.074	5**	0.051
14-16	0.64	0.021	1.4	0.019	1-2	6.0	0.063	4.5	0.046
16-17	0.59	0.020	1.4	0.019	2-3	4.7	0.050	3.8	0.039
17-18	0.55	0.018	1.4	0.019	3-4	4.2	0.044	3.8	0.039
18-20	0.51	0.017	1.5	0.020	4-5	4.0	0.042	3.9	0.040
20-25	0.46	0.015	1.4	0.019	5-6	4.0	0.042	3.9	0.040
25-30	0.34	0.011	1.3	0.018	6-7	4.05	0.043	4.1	0.042
30-40	0.27	0.009	1.15	0.016	7-8	4.1	0.043	4.1	0.042
40-50	0.20	0.0067	0.98	0.013	8-9	4.2	0.044	4.0	0.041
50-60	0.17	0.0057	0.84	0.011	9-10	4.3	0.045	3.9	0.040
60-70	0.13	0.0043	0.72	0.010	10-12	4.3	0.045	3.8	0.039
70-80	0.105	0.0035	0.63	0.0085	12-14	4.3	0.045	3.6	0.037
80-90	0.096	0.0032	0.57	0.0077	14-16	4.3	0.045	3.3	0.034
90-100	0.08	0.0027	0.52	0.0070	16-17	4.2	0.044	3.2	0.033
ΔE_n	$\sigma_t(O)$	$N(O)\sigma_t(O)$	$\sigma_t(N)$	$N(N)\sigma_t(N)$	17-18	4.0	0.042	3.0	0.031
(MeV)	$\times 10^{24} \text{ cm}^2$	cm^{-1}	$\times 10^{24} \text{ cm}^2$	cm^{-1}	18-20	(4.0)	0.042	3.0	0.031
0-1	3.0	0.028	2.5	0.0072	20-25	3.7	0.039	(3.0)	0.031
1-2	2.5	0.023	2.0	0.0058	25-30	(3.6)	0.038	(3.0)	0.031
2-3	1.6	0.015	1.6	0.0046	30-40	(3.3)	0.035	(3.0)	0.031
3-4	2.4	0.023	1.7	0.0049	40-50	3.1	0.033	2.9	0.030
4-5	1.5	0.014	1.5	0.0043	50-60	(2.8)	0.030	(2.8)	0.029
5-6	1.4	0.013	1.45	0.0043	60-70	(2.6)	0.028	(2.7)	0.028
6-7	1.5	0.014	1.35	0.0039	70-80	(2.55)	0.027	(2.6)	0.027
7-8	1.2	0.011	1.4	0.0040	80-90	(2.4)	0.025	(2.5)	0.026
8-9	1.15	0.011	1.35	0.0039	90-100	(2.3)	0.024	(2.4)	0.025
9-10	1.2	0.011	1.3	0.0037	$\sigma_t(Ag)$ and $\sigma_t(Br)$ in () are interpolated between experimental values or extrapolated from experimental value at the highest observed energy.				
10-12	1.3	0.012	1.4	0.0040	* Averaged over several resonances.				
12-14	1.4	0.013	1.5	0.0043	** Averaged over many resonances.				
14-16	1.6	0.015	1.6	0.0046					
16-17	1.6	0.015	(1.6)	0.0046					
17-18	1.6	0.015	(1.6)	0.0046					
18-20	1.65	0.015	(1.6)	0.0046					

TABLE V
OTHER EMULSION CROSS SECTIONS

ΔE_n (MeV)	$\sigma_{\text{nonelastic}} (c)$ $\sigma_{np} (c)$ $\times 10^{24} \text{ cm}^2$	$N(c)\sigma_{np} (c)$ cm^{-1}		$\sigma(n,\alpha\gamma) N$.075	0.00022
5-6	.11	0.0015	12-14	$\sigma(n,2n) N$.004	1.15×10^{-5}
6-7	.15	0.0020	14-16	.008	2.3×10^{-5}
7-8	.25	0.0034	16-18	.010	2.9×10^{-5}
8-9	.45	0.0061	18-20	.011	3.2×10^{-5}
9-10	.53	0.0072	20-30	.011	3.2×10^{-5}
	$\sigma(n,2n) (c)$		30-40	.011	3.2×10^{-5}
20-25	.005	6.8×10^{-5}		$\sigma(n,p) N$	
25-30	.013	0.00018	1-2	.050*	0.00014
30-40	.015	0.00020	2-3	.050*	0.00014
	$\sigma(n,\alpha) (c)$		3-4	.050	0.00014
7-8	.06	0.00081		$\sigma(n,\alpha) N$	$N(N)\sigma(N)$
8-9	.05	0.00068	1-2	.05	0.00014
	$\sigma(n,\alpha) (0)$		2-3	.15	0.00043
4-5	0.1	0.00094	3-4	.30	0.00086
12-14	0.2	0.0019	4-5	.25	0.00072
14-16	0.34	0.0032		$\sigma(n,n'\gamma) Ag$	$N(Ag)\sigma(Ag)$
16-17	0.34	0.0032	1-2	0.4	0.0042
17-18	0.30	0.0028		$\sigma(n,2n) Ag$	
18-20	0.20		12-14	0.6	0.0063
	$\sigma(n,p) (0)$		14-16	0.7	0.0074
10-12	0.06	0.00056	16-18	0.65	0.0069
12-14	0.04	0.00038	18-20	0.55	0.0058
14-16	0.038	0.00037		$\sigma(n,\gamma) Ag$	
16-20	0.023	0.00022	1-2	0.08	0.00084
	$\sigma(n,2n) 0$	$N(0)\sigma(0)$	2-3	0.05	0.00053
18-20	.002	1.9×10^{-5}	3-4	0.04	0.00042
20-25	.008	7.5×10^{-5}		$\sigma(n,\alpha) Br$	$N(Br)\sigma(Br)$
25-30	.015	1.4×10^{-4}	13-14	0.006	6.2×10^{-5}
30-40	.015	1.4×10^{-4}	14-16	0.011	0.00011
	$\sigma(n,\gamma) 0$		16-17	0.014	0.00014
14-15	.150	0.0014		$\sigma(n,\gamma) Br$	
15-16	.060	0.00056	1-2	0.018	0.00018
16-18	.080	0.00075	2-3	0.010	0.00010
	$\sigma(n,n'\gamma) N$	$N(N)\sigma(N)$	3-4	0.007	7.2×10^{-5}
6-8	.125	0.00036	4-5	0.005	5.1×10^{-5}

* Averaged over resonances to 0.2 b.