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UNIVERSITI SAINS MALAYSIA

Peperiksaan Semester Pertama  
Sidang Akademik 2004/2005

Oktober 2004

**ZCE 331/4 - Biofizik Sinaran**

Masa : 3 jam

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Sila pastikan bahawa kertas peperiksaan ini mengandungi **SEMBILAN** muka surat yang bercetak sebelum anda memulakan peperiksaan ini.

Jawab **EMPAT** soalan sahaja. Kesemuanya wajib dijawab dalam Bahasa Malaysia.

1. (a) Bincangkan proses-proses reputan melalui:
- (i) pancaran  $\beta^+$
  - (ii) tawanan elektron.
- (20/100)
- (b) Bincangkan secara ringkas keseimbangan sekular dan keadaan tiada keseimbangan. Lakarkan gambarajah aktiviti dengan masa bagi nukleus induk dan nukleus anak bagi setiap kes.
- (30/100)
- (c) Suatu sumber radium mengandungi 50 mg  $^{226}_{88}\text{Ra}$  dan masa setengah hayatnya  $t_{1/2} = 1602$  tahun.
- (i) Hitungkan pemalar reputan bagi  $^{226}_{88}\text{Ra}$
  - (ii) Hitungkan nilai purata hayat
  - (iii) Berapakah bilangan atom  $^{226}_{88}\text{Ra}$  yang terkandung dalam sumber?
  - (iv) Hitungkan masa  $t_m$  untuk anak nukleus  $^{222}_{86}\text{Rn}$  menjadi maksimum ( $t_{1/2} = 3.82$  hari). Anggapkan pada masa  $t = 0$ , aktiviti anak nukleusnya sifar.
  - (v) Hitungkan aktiviti dan bilangan atom  $^{222}_{86}\text{Rn}$  pada masa  $t_m$ .
- (50/100)
2. (a) Bincangkan secara ringkas proses fotoelektrik, Compton dan penghasilan pasangan.
- (20/100)
- (b) Nyatakan jenis saling tindakan yang berlaku antara foton yang bertenaga 1 MeV dengan jirim karbon. Berikan kepentingan relatif bagi setiap saling tindakan itu.
- (20/100)
- (c) Hitungkan tenaga purata yang dipindahkan pada karbon jika fluens fotonnya  $10^6 \text{ cm}^{-2}$  dan ketebalan karbonnya  $10^{-2} \text{ gcm}^{-2}$ .
- (30/100)
- (d) Bacaan berikut bagi serapan sinar gama didapati dengan menggunakan penyerap plumbum:
- |                        |      |     |     |     |     |
|------------------------|------|-----|-----|-----|-----|
| Ketebalan plumbum (mm) | 0    | 4   | 8   | 15  | 25  |
| Bilangan per minit     | 1000 | 770 | 600 | 390 | 210 |
- (i) Tentukan pekali pengecilan linear dan pekali pengecilan jisim.

...3/-

- (ii) Nyatakan ciri-ciri berkaitan dengan tenaga sinar gama.

$$\rho_{\text{Pb}} = 11.3 \text{ gcm}^{-3}$$

Berat atom plumbum = 207.21.

(30/100)

3. (a) Bincangkan perbezaan di antara kerma dan dos serapan. (20/100)
- (b) Bincangkan kepentingan seimbangan zarah bercas (CPE) dalam pengukuran dedahan. (20/100)
- (c) Nyatakan anggapan-anggapan yang digunakan dalam teorem Bragg-Gray. (20/100)
- (d) Fluens foton pada suatu titik P ialah  $10^{10}$  foton  $\text{m}^{-2}$ . Tenaga fotonnya 3 MeV.
- (i) Hitungkan tenaga fluens, dedahan dan dos serapan dalam udara pada titik P.
- (ii) Hitungkan bilangan pasangan ion yang dihasilkan jika dedahan itu dibaca dari kebuk pengionan (ion chamber) yang mengandungi 0.6 cc udara.

$$[\rho_{\text{udara}} = 1.293 \text{ kgm}^{-3} \text{ pada STP}]$$

$$\left(\frac{w}{e}\right)_{\text{udara}} = 33.97 \text{ J C}^{-1}$$

- (iii) Katakan dosimeter memenuhi syarat Bragg-Gray, hitungkan dos dalam dinding yang dibina dari Teflon

$$e = 1.602 \times 10^{-19} \text{ C}$$

(40/100)

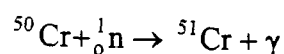
4. (a) Bandingkan pengesanan semikonduktor Ge(Li) dengan pengesanan NaI(Tl) (20/100)
- (b) Katakan 4 MeV sinar  $\gamma$  melalui pengesanan NaI(Tl). Lakarkan spektrum differensial yang didapati. Berikan nama yang sepadan dengan setiap puncak dan jelaskan proses-proses berkenaan dengan setiap puncak. Hitungkan tenaga yang berkaitan dengan puncak itu.

(40/100)

...4/-

- (c) Suatu sampel mengandungi suatu kuantiti kromium. Sampel itu disinari dengan fluks neutron terma  $10^{11}$  n/cm<sup>2</sup>/saat untuk satu minggu. <sup>51</sup>Cr yang dihasilkan memancarkan sinar  $\gamma$  yang bertenaga 0.323 MeV dan setengah hayatnya 27.8 hari. Kebarangkalian bagi pemancarannya ialah 0.098.

Suatu pembilang yang kecekapannya 10% mengesan 600 bilangan per mimit bagi sinar  $\gamma$  itu. Hitungkan jisim kromium yang wujud di dalam sampel asal.



$$\sigma = 13.5 \text{ barn}$$

<sup>50</sup>Cr hanya membentuk 4.31% daripada kromium asli yang wujud di bumi.

$$1 \text{ barn} = 10^{-28} \text{ m}^2.$$

(40/100)

5. (a) Bincangkan kesan 'tindakbalas terus' dan kesan 'tindakbalas bukan terus' dalam sel maut. (20/100)
- (b) Huraikan dengan teliti bagaimana suatu lengkung penghidupan bagi sel mammalia (mammalian cell survival curve) didapati merujuk pada dos sinaran. Label semua parameter yang penting dalam lengkung itu. (30/100)
- (c) Bagi dos serapan 200 cGy, nisbah penghidupan bagi sel untuk sinar  $\gamma$  dan zarah  $\alpha$  masing-masing adalah 0.1 dan 0.001. Mengapakah nisbah penghidupannya berbeza walaupun dos serapannya sama? Terangkan. (25/100)
- (d) Huraikan kesan-kesan yang manusia boleh dapat dari sinaran dos rendah. Nyatakan langkah-langkah yang dilakukan untuk mengurangkan dos dari luar dan dalam bagi pekerja sinaran. (25/100)

...5/-

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$$1 \text{ kg} = 5.6095 \times 10^{29} \text{ MeV}$$

$$1 \text{ amu} = 931.50 \text{ MeV}$$

$$\text{Electron rest mass} = 0.51100 \text{ MeV}$$

$$\text{Proton rest mass} = 938.26 \text{ MeV}$$

$$\text{Neutron rest mass} = 939.55 \text{ MeV}$$

$$1 \text{ electron volt (eV)} = 1.6022 \times 10^{-19} \text{ J}$$

$$= 1.6022 \times 10^{-12} \text{ erg}$$

$$1 \text{ joule (J)} = 10^7 \text{ erg}$$

$$1 \text{ coulomb (C)} = 2.9979 \times 10^9 \text{ esu}$$

$$1 \text{ gray (Gy)} = 1 \text{ J/kg} = 10^2 \text{ rad} = 10^4 \text{ erg/g}$$

$$1 \text{ sievert (Sv)} = 1 \text{ J/kg}$$

Energy-wavelength conversion:

$$1.23985 \times 10^{-6} \text{ eV m}$$

$$12.3985 \text{ keV \AA}$$

Exposure conversion:

$$1 \text{ roentgen (R)} = 2.58 \times 10^{-4} \text{ C/kg}$$

$$1 \text{ C/kg} = 3876 \text{ R}$$


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Carbon, Z = 6  
 Multiply data by 0.05014 to get cm<sup>2</sup>/g  
 or by 0.005014 to get m<sup>2</sup>/kg

| Photon Energy (MeV) | Compton With and Without Coherent $\times 10^{-28}$ |          | Photoelectric $\times 10^{-28}$ | Nuclear and Electron Pair |                 | Total With and Without Coherent |                  |
|---------------------|---|----------|---------------------------------|---------------------------|-----------------|---------------------------------|------------------|
|                     | $\sigma + \sigma_R$                                 | $\sigma$ |                                 | $\sigma_{nuc}$            | $\sigma_{elec}$ | $\mu$                           | $\mu - \sigma_R$ |
| 1.00 -02            | 6.11 +00  | 3.84 +00 | 3.93 +01                        | —                         | —               | 4.54 +01                        | 4.31 +01         |
| 1.50 -02            | 5.06 +00  | 3.77 +00 | 1.06 +01                        | —                         | —               | 1.57 +01                        | 1.44 +01         |
| 2.00 -02            | 4.53 +00  | 3.71 +00 | 4.01 +00                        | —                         | —               | 8.54 +00                        | 7.72 +00         |
| 3.00 -02            | 4.00 +00  | 3.58 +00 | 9.99 -01                        | —                         | —               | 5.00 +00                        | 4.58 +00         |
| 4.00 -02            | 3.73 +00  | 3.47 +00 | 3.79 -01                        | —                         | —               | 4.10 +00                        | 3.85 +00         |
| 5.00 -02            | 3.54 +00  | 3.37 +00 | 1.93 -01                        | —                         | —               | 3.73 +00                        | 3.56 +00         |
| 6.00 -02            | 3.39 +00  | 3.27 +00 | 1.15 -01                        | —                         | —               | 3.51 +00                        | 3.39 +00         |
| 8.00 -02            | 3.17 +00  | 3.10 +00 | 4.50 -02                        | —                         | —               | 3.21 +00                        | 3.15 +00         |
| 1.00 -01            | 3.00 +00  | 2.96 +00 | 2.16 -02                        | —                         | —               | 3.02 +00                        | 2.98 +00         |
| 1.50 -01            | 2.69 +00  | 2.66 +00 | 5.75 -03                        | —                         | —               | 2.69 +00                        | 2.67 +00         |
| 2.00 -01            | 2.45 +00  | 2.44 +00 | 2.29 -03                        | —                         | —               | 2.45 +00                        | 2.44 +00         |
| 3.00 -01            | 2.13 +00  | 2.12 +00 | 6.46 -04                        | —                         | —               | 2.13 +00                        | 2.12 +00         |
| 4.00 -01            | 1.90 +00  | 1.90 +00 | 2.77 -04                        | —                         | —               | 1.91 +00                        | 1.90 +00         |
| 5.00 -01            | 1.74 +00  | —        | 1.49 -04                        | —                         | —               | 1.74 +00                        | —                |
| 6.00 -01            | 1.61 +00  | —        | 9.27 -05                        | —                         | —               | 1.61 +00                        | —                |
| 8.00 -01            | 1.41 +00  | —        | 4.68 -05                        | —                         | —               | 1.41 +00                        | —                |
| 1.00 +00            | 1.27 +00  | —        | 2.89 -05                        | —                         | —               | 1.27 +00                        | —                |
| 1.50 +00            | 1.03 +00  | —        | 1.35 -05                        | 1.60 -03                  | —               | 1.03 +00                        | —                |
| 2.00 +00            | 8.79 -01  | —        | 8.61 -06                        | 6.40 -03                  | —               | 8.86 -01                        | —                |
| 3.00 +00            | 6.92 -01  | —        | 4.82 -06                        | 1.84 -02                  | 2.41 -04        | 7.11 -01                        | —                |
| 4.00 +00            | 5.77 -01  | —        | 3.29 -06                        | 2.98 -02                  | 9.91 -04        | 6.08 -01                        | —                |
| 5.00 +00            | 4.98 -01  | —        | 2.52 -06                        | 4.00 -02                  | 1.95 -03        | 5.40 -01                        | —                |
| 6.00 +00            | 4.40 -01  | —        | 2.01 -06                        | 4.90 -02                  | 3.00 -03        | 4.93 -01                        | —                |
| 8.00 +00            | 3.60 -01  | —        | 1.44 -06                        | 6.42 -02                  | 5.12 -03        | 4.30 -01                        | —                |
| 1.00 +01            | 3.07 -01  | —        | 1.12 -06                        | 7.66 -02                  | 7.01 -03        | 3.90 -01                        | —                |
| 1.50 +01            | 2.27 -01  | —        | —                               | 1.00 -01                  | 1.09 -02        | 3.38 -01                        | —                |
| 2.00 +01            | 1.82 -01  | —        | —                               | 1.17 -01                  | 1.40 -02        | 3.14 -01                        | —                |
| 3.00 +01            | 1.33 -01  | —        | —                               | 1.41 -01                  | 1.87 -02        | 2.93 -01                        | —                |
| 4.00 +01            | 1.05 -01  | —        | —                               | 1.58 -01                  | 2.21 -02        | 2.86 -01                        | —                |
| 5.00 +01            | 8.80 -02  | —        | —                               | 1.71 -01                  | 2.48 -02        | 2.84 -01                        | —                |
| 6.00 +01            | 7.59 -02  | —        | —                               | 1.81 -01                  | 2.71 -02        | 2.84 -01                        | —                |
| 8.00 +01            | 5.98 -02  | —        | —                               | 1.96 -01                  | 3.06 -02        | 2.86 -01                        | —                |
| 1.00 +02            | 4.97 -02  | —        | —                               | 2.07 -01                  | 3.31 -02        | 2.90 -01                        | —                |

## Air (Dry)

| ENERGY<br>MeV | STOPPING POWER                      |                                     |                                 | CSDA<br>RANGE<br>g/cm <sup>2</sup> | RADIATION<br>YIELD | DENS. EFF.<br>CORR.<br>(DELTA) |
|---------------|-------------------------------------|-------------------------------------|---------------------------------|------------------------------------|--------------------|--------------------------------|
|               | COLLISION<br>MeV cm <sup>2</sup> /g | RADIATIVE<br>MeV cm <sup>2</sup> /g | TOTAL<br>MeV cm <sup>2</sup> /g |                                    |                    |                                |
| 0.0100        | 1.975E+01                           | 3.897E-03                           | 1.976E+01                       | 2.883E-04                          | 1.082E-04          | 0.0                            |
| 0.0125        | 1.663E+01                           | 3.921E-03                           | 1.663E+01                       | 4.269E-04                          | 1.299E-04          | 0.0                            |
| 0.0150        | 1.445E+01                           | 3.937E-03                           | 1.445E+01                       | 5.886E-04                          | 1.506E-04          | 0.0                            |
| 0.0175        | 1.283E+01                           | 3.946E-03                           | 1.283E+01                       | 7.726E-04                          | 1.706E-04          | 0.0                            |
| 0.0200        | 1.157E+01                           | 3.954E-03                           | 1.158E+01                       | 9.781E-04                          | 1.898E-04          | 0.0                            |
| 0.0250        | 9.753E+00                           | 3.966E-03                           | 9.757E+00                       | 1.451E-03                          | 2.267E-04          | 0.0                            |
| 0.0300        | 8.492E+00                           | 3.976E-03                           | 8.496E+00                       | 2.001E-03                          | 2.618E-04          | 0.0                            |
| 0.0350        | 7.563E+00                           | 3.986E-03                           | 7.567E+00                       | 2.626E-03                          | 2.955E-04          | 0.0                            |
| 0.0400        | 6.848E+00                           | 3.998E-03                           | 6.852E+00                       | 3.322E-03                          | 3.280E-04          | 0.0                            |
| 0.0450        | 6.281E+00                           | 4.011E-03                           | 6.285E+00                       | 4.085E-03                          | 3.594E-04          | 0.0                            |
| 0.0500        | 5.819E+00                           | 4.025E-03                           | 5.823E+00                       | 4.912E-03                          | 3.900E-04          | 0.0                            |
| 0.0550        | 5.435E+00                           | 4.040E-03                           | 5.439E+00                       | 5.801E-03                          | 4.197E-04          | 0.0                            |
| 0.0600        | 5.111E+00                           | 4.057E-03                           | 5.115E+00                       | 6.750E-03                          | 4.488E-04          | 0.0                            |
| 0.0700        | 4.593E+00                           | 4.093E-03                           | 4.597E+00                       | 8.817E-03                          | 5.049E-04          | 0.0                            |
| 0.0800        | 4.198E+00                           | 4.133E-03                           | 4.202E+00                       | 1.110E-02                          | 5.590E-04          | 0.0                            |
| 0.0900        | 3.886E+00                           | 4.175E-03                           | 3.890E+00                       | 1.357E-02                          | 6.112E-04          | 0.0                            |
| 0.1000        | 3.633E+00                           | 4.222E-03                           | 3.637E+00                       | 1.623E-02                          | 6.618E-04          | 0.0                            |
| 0.1250        | 3.172E+00                           | 4.348E-03                           | 3.177E+00                       | 2.362E-02                          | 7.826E-04          | 0.0                            |
| 0.1500        | 2.861E+00                           | 4.485E-03                           | 2.865E+00                       | 3.193E-02                          | 8.968E-04          | 0.0                            |
| 0.1750        | 2.637E+00                           | 4.633E-03                           | 2.642E+00                       | 4.103E-02                          | 1.006E-03          | 0.0                            |
| 0.2000        | 2.470E+00                           | 4.789E-03                           | 2.474E+00                       | 5.082E-02                          | 1.111E-03          | 0.0                            |
| 0.2500        | 2.236E+00                           | 5.126E-03                           | 2.242E+00                       | 7.212E-02                          | 1.311E-03          | 0.0                            |
| 0.3000        | 2.084E+00                           | 5.495E-03                           | 2.089E+00                       | 9.527E-02                          | 1.502E-03          | 0.0                            |
| 0.3500        | 1.978E+00                           | 5.890E-03                           | 1.984E+00                       | 1.199E-01                          | 1.688E-03          | 0.0                            |
| 0.4000        | 1.902E+00                           | 6.311E-03                           | 1.908E+00                       | 1.456E-01                          | 1.869E-03          | 0.0                            |
| 0.4500        | 1.845E+00                           | 6.757E-03                           | 1.852E+00                       | 1.722E-01                          | 2.048E-03          | 0.0                            |
| 0.5000        | 1.802E+00                           | 7.223E-03                           | 1.809E+00                       | 1.995E-01                          | 2.225E-03          | 0.0                            |
| 0.5500        | 1.769E+00                           | 7.708E-03                           | 1.776E+00                       | 2.274E-01                          | 2.401E-03          | 0.0                            |
| 0.6000        | 1.743E+00                           | 8.210E-03                           | 1.751E+00                       | 2.558E-01                          | 2.577E-03          | 0.0                            |
| 0.7000        | 1.706E+00                           | 9.258E-03                           | 1.715E+00                       | 3.135E-01                          | 2.929E-03          | 0.0                            |
| 0.8000        | 1.683E+00                           | 1.036E-02                           | 1.694E+00                       | 3.722E-01                          | 3.283E-03          | 0.0                            |
| 0.9000        | 1.669E+00                           | 1.151E-02                           | 1.681E+00                       | 4.315E-01                          | 3.638E-03          | 0.0                            |
| 1.0000        | 1.661E+00                           | 1.271E-02                           | 1.674E+00                       | 4.912E-01                          | 3.997E-03          | 0.0                            |
| 1.2500        | 1.655E+00                           | 1.588E-02                           | 1.671E+00                       | 6.408E-01                          | 4.906E-03          | 0.0                            |
| 1.5000        | 1.661E+00                           | 1.927E-02                           | 1.680E+00                       | 7.900E-01                          | 5.836E-03          | 0.0                            |
| 1.7500        | 1.672E+00                           | 2.284E-02                           | 1.694E+00                       | 9.382E-01                          | 6.784E-03          | 0.0                            |
| 2.0000        | 1.684E+00                           | 2.656E-02                           | 1.711E+00                       | 1.085E+00                          | 7.748E-03          | 0.0                            |
| 2.5000        | 1.712E+00                           | 3.437E-02                           | 1.747E+00                       | 1.374E+00                          | 9.716E-03          | 0.0                            |
| 3.0000        | 1.740E+00                           | 4.260E-02                           | 1.783E+00                       | 1.658E+00                          | 1.173E-02          | 0.0                            |
| 3.5000        | 1.766E+00                           | 5.115E-02                           | 1.817E+00                       | 1.935E+00                          | 1.377E-02          | 0.0                            |
| 4.0000        | 1.790E+00                           | 5.999E-02                           | 1.850E+00                       | 2.208E+00                          | 1.583E-02          | 0.0                            |
| 4.5000        | 1.812E+00                           | 6.908E-02                           | 1.882E+00                       | 2.476E+00                          | 1.792E-02          | 0.0                            |
| 5.0000        | 1.833E+00                           | 7.838E-02                           | 1.911E+00                       | 2.740E+00                          | 2.001E-02          | 0.0                            |
| 5.5000        | 1.852E+00                           | 8.787E-02                           | 1.940E+00                       | 2.999E+00                          | 2.211E-02          | 0.0                            |
| 6.0000        | 1.870E+00                           | 9.754E-02                           | 1.968E+00                       | 3.255E+00                          | 2.422E-02          | 0.0                            |
| 7.0000        | 1.902E+00                           | 1.173E-01                           | 2.020E+00                       | 3.757E+00                          | 2.845E-02          | 0.0                            |
| 8.0000        | 1.931E+00                           | 1.376E-01                           | 2.068E+00                       | 4.246E+00                          | 3.269E-02          | 0.0                            |
| 9.0000        | 1.956E+00                           | 1.584E-01                           | 2.115E+00                       | 4.724E+00                          | 3.692E-02          | 0.0                            |
| 10.0000       | 1.979E+00                           | 1.795E-01                           | 2.159E+00                       | 5.192E+00                          | 4.113E-02          | 0.0                            |
| 12.5000       | 2.029E+00                           | 2.337E-01                           | 2.262E+00                       | 6.323E+00                          | 5.156E-02          | 0.0                            |
| 15.0000       | 2.069E+00                           | 2.895E-01                           | 2.359E+00                       | 7.405E+00                          | 6.181E-02          | 0.0                            |
| 17.5000       | 2.104E+00                           | 3.464E-01                           | 2.451E+00                       | 8.444E+00                          | 7.185E-02          | 0.0                            |
| 20.0000       | 2.134E+00                           | 4.042E-01                           | 2.539E+00                       | 9.446E+00                          | 8.167E-02          | 0.0                            |
| 25.0000       | 2.185E+00                           | 5.219E-01                           | 2.707E+00                       | 1.135E+01                          | 1.006E-01          | 0.0                            |
| 30.0000       | 2.226E+00                           | 6.417E-01                           | 2.868E+00                       | 1.315E+01                          | 1.186E-01          | 7.636E-03                      |
| 35.0000       | 2.257E+00                           | 7.630E-01                           | 3.020E+00                       | 1.485E+01                          | 1.357E-01          | 5.984E-02                      |
| 40.0000       | 2.282E+00                           | 8.855E-01                           | 3.167E+00                       | 1.646E+01                          | 1.520E-01          | 1.378E-01                      |
| 45.0000       | 2.302E+00                           | 1.009E+00                           | 3.311E+00                       | 1.801E+01                          | 1.676E-01          | 2.266E-01                      |
| 50.0000       | 2.319E+00                           | 1.133E+00                           | 3.452E+00                       | 1.948E+01                          | 1.825E-01          | 3.192E-01                      |
| 55.0000       | 2.334E+00                           | 1.258E+00                           | 3.592E+00                       | 2.090E+01                          | 1.968E-01          | 4.120E-01                      |
| 60.0000       | 2.347E+00                           | 1.384E+00                           | 3.731E+00                       | 2.227E+01                          | 2.104E-01          | 5.029E-01                      |
| 70.0000       | 2.369E+00                           | 1.637E+00                           | 4.006E+00                       | 2.486E+01                          | 2.361E-01          | 6.762E-01                      |
| 80.0000       | 2.387E+00                           | 1.892E+00                           | 4.279E+00                       | 2.727E+01                          | 2.598E-01          | 8.365E-01                      |
| 90.0000       | 2.403E+00                           | 2.148E+00                           | 4.551E+00                       | 2.954E+01                          | 2.818E-01          | 9.842E-01                      |

## Teflon

| ENERGY<br>MeV | STOPPING POWER                      |                                     |                                 | CSDA<br>RANGE<br>g/cm <sup>2</sup> | RADIATION<br>YIELD | DENS. EFF.<br>CORR.<br>(DELTA) |
|---------------|-------------------------------------|-------------------------------------|---------------------------------|------------------------------------|--------------------|--------------------------------|
|               | COLLISION<br>MeV cm <sup>2</sup> /g | RADIATIVE<br>MeV cm <sup>2</sup> /g | TOTAL<br>MeV cm <sup>2</sup> /g |                                    |                    |                                |
| 0.0100        | 1.843E+01                           | 4.211E-03                           | 1.843E+01                       | 3.105E-04                          | 1.249E-04          | 0.0                            |
| 0.0125        | 1.553E+01                           | 4.247E-03                           | 1.554E+01                       | 4.589E-04                          | 1.502E-04          | 0.0                            |
| 0.0150        | 1.351E+01                           | 4.271E-03                           | 1.351E+01                       | 6.320E-04                          | 1.743E-04          | 0.0                            |
| 0.0175        | 1.200E+01                           | 4.287E-03                           | 1.201E+01                       | 8.287E-04                          | 1.975E-04          | 0.0                            |
| 0.0200        | 1.084E+01                           | 4.300E-03                           | 1.084E+01                       | 1.048E-03                          | 2.199E-04          | 0.0                            |
| 0.0250        | 9.141E+00                           | 4.316E-03                           | 9.146E+00                       | 1.553E-03                          | 2.629E-04          | 0.0                            |
| 0.0300        | 7.965E+00                           | 4.329E-03                           | 7.970E+00                       | 2.140E-03                          | 3.037E-04          | 0.0                            |
| 0.0350        | 7.098E+00                           | 4.341E-03                           | 7.102E+00                       | 2.806E-03                          | 3.428E-04          | 0.0                            |
| 0.0400        | 6.430E+00                           | 4.353E-03                           | 6.435E+00                       | 3.547E-03                          | 3.805E-04          | 0.0                            |
| 0.0450        | 5.900E+00                           | 4.366E-03                           | 5.904E+00                       | 4.359E-03                          | 4.169E-04          | 0.0                            |
| 0.0500        | 5.468E+00                           | 4.380E-03                           | 5.472E+00                       | 5.239E-03                          | 4.522E-04          | 0.0                            |
| 0.0550        | 5.109E+00                           | 4.395E-03                           | 5.113E+00                       | 6.185E-03                          | 4.865E-04          | 0.0                            |
| 0.0600        | 4.806E+00                           | 4.410E-03                           | 4.810E+00                       | 7.194E-03                          | 5.200E-04          | 0.0                            |
| 0.0700        | 4.321E+00                           | 4.444E-03                           | 4.325E+00                       | 9.391E-03                          | 5.847E-04          | 0.0                            |
| 0.0800        | 3.951E+00                           | 4.483E-03                           | 3.955E+00                       | 1.181E-02                          | 6.467E-04          | 0.0                            |
| 0.0900        | 3.658E+00                           | 4.525E-03                           | 3.663E+00                       | 1.444E-02                          | 7.065E-04          | 0.0                            |
| 0.1000        | 3.421E+00                           | 4.571E-03                           | 3.426E+00                       | 1.727E-02                          | 7.643E-04          | 0.0                            |
| 0.1250        | 2.989E+00                           | 4.700E-03                           | 2.994E+00                       | 2.511E-02                          | 9.021E-04          | 0.0                            |
| 0.1500        | 2.697E+00                           | 4.844E-03                           | 2.702E+00                       | 3.392E-02                          | 1.032E-03          | 0.0                            |
| 0.1750        | 2.487E+00                           | 5.000E-03                           | 2.492E+00                       | 4.357E-02                          | 1.156E-03          | 0.0                            |
| 0.2000        | 2.330E+00                           | 5.167E-03                           | 2.335E+00                       | 5.395E-02                          | 1.275E-03          | 0.0                            |
| 0.2500        | 2.111E+00                           | 5.530E-03                           | 2.117E+00                       | 7.651E-02                          | 1.503E-03          | 0.0                            |
| 0.3000        | 1.968E+00                           | 5.928E-03                           | 1.974E+00                       | 1.010E-01                          | 1.721E-03          | 0.0                            |
| 0.3500        | 1.869E+00                           | 6.353E-03                           | 1.875E+00                       | 1.271E-01                          | 1.931E-03          | 0.0                            |
| 0.4000        | 1.797E+00                           | 6.805E-03                           | 1.804E+00                       | 1.543E-01                          | 2.137E-03          | 2.294E-03                      |
| 0.4500        | 1.742E+00                           | 7.279E-03                           | 1.749E+00                       | 1.824E-01                          | 2.341E-03          | 2.338E-02                      |
| 0.5000        | 1.699E+00                           | 7.775E-03                           | 1.707E+00                       | 2.114E-01                          | 2.543E-03          | 4.753E-02                      |
| 0.5500        | 1.665E+00                           | 8.291E-03                           | 1.674E+00                       | 2.410E-01                          | 2.744E-03          | 7.398E-02                      |
| 0.6000        | 1.639E+00                           | 8.823E-03                           | 1.647E+00                       | 2.711E-01                          | 2.945E-03          | 1.022E-01                      |
| 0.7000        | 1.600E+00                           | 9.937E-03                           | 1.610E+00                       | 3.326E-01                          | 3.347E-03          | 1.623E-01                      |
| 0.8000        | 1.573E+00                           | 1.111E-02                           | 1.585E+00                       | 3.952E-01                          | 3.753E-03          | 2.253E-01                      |
| 0.9000        | 1.555E+00                           | 1.233E-02                           | 1.568E+00                       | 4.587E-01                          | 4.162E-03          | 2.896E-01                      |
| 1.0000        | 1.543E+00                           | 1.360E-02                           | 1.557E+00                       | 5.227E-01                          | 4.575E-03          | 3.541E-01                      |
| 1.2500        | 1.527E+00                           | 1.697E-02                           | 1.544E+00                       | 6.841E-01                          | 5.631E-03          | 5.127E-01                      |
| 1.5000        | 1.522E+00                           | 2.057E-02                           | 1.542E+00                       | 8.462E-01                          | 6.719E-03          | 6.637E-01                      |
| 1.7500        | 1.522E+00                           | 2.437E-02                           | 1.546E+00                       | 1.008E+00                          | 7.837E-03          | 8.056E-01                      |
| 2.0000        | 1.525E+00                           | 2.834E-02                           | 1.553E+00                       | 1.169E+00                          | 8.983E-03          | 9.382E-01                      |
| 2.5000        | 1.535E+00                           | 3.667E-02                           | 1.572E+00                       | 1.490E+00                          | 1.134E-02          | 1.178E+00                      |
| 3.0000        | 1.546E+00                           | 4.544E-02                           | 1.592E+00                       | 1.806E+00                          | 1.377E-02          | 1.390E+00                      |
| 3.5000        | 1.558E+00                           | 5.456E-02                           | 1.612E+00                       | 2.118E+00                          | 1.626E-02          | 1.578E+00                      |
| 4.0000        | 1.569E+00                           | 6.399E-02                           | 1.633E+00                       | 2.426E+00                          | 1.879E-02          | 1.748E+00                      |
| 4.5000        | 1.579E+00                           | 7.367E-02                           | 1.653E+00                       | 2.730E+00                          | 2.136E-02          | 1.902E+00                      |
| 5.0000        | 1.589E+00                           | 8.357E-02                           | 1.672E+00                       | 3.031E+00                          | 2.395E-02          | 2.043E+00                      |
| 5.5000        | 1.598E+00                           | 9.367E-02                           | 1.692E+00                       | 3.328E+00                          | 2.656E-02          | 2.173E+00                      |
| 6.0000        | 1.606E+00                           | 1.040E-01                           | 1.710E+00                       | 3.622E+00                          | 2.919E-02          | 2.294E+00                      |
| 7.0000        | 1.621E+00                           | 1.250E-01                           | 1.746E+00                       | 4.201E+00                          | 3.447E-02          | 2.512E+00                      |
| 8.0000        | 1.635E+00                           | 1.466E-01                           | 1.781E+00                       | 4.768E+00                          | 3.978E-02          | 2.706E+00                      |
| 9.0000        | 1.646E+00                           | 1.686E-01                           | 1.815E+00                       | 5.324E+00                          | 4.509E-02          | 2.880E+00                      |
| 10.0000       | 1.657E+00                           | 1.910E-01                           | 1.848E+00                       | 5.870E+00                          | 5.040E-02          | 3.039E+00                      |
| 12.5000       | 1.679E+00                           | 2.483E-01                           | 1.927E+00                       | 7.194E+00                          | 6.355E-02          | 3.385E+00                      |
| 15.0000       | 1.697E+00                           | 3.071E-01                           | 2.004E+00                       | 8.466E+00                          | 7.643E-02          | 3.677E+00                      |
| 17.5000       | 1.712E+00                           | 3.672E-01                           | 2.079E+00                       | 9.691E+00                          | 8.913E-02          | 3.930E+00                      |
| 20.0000       | 1.724E+00                           | 4.281E-01                           | 2.152E+00                       | 1.087E+01                          | 1.015E-01          | 4.155E+00                      |
| 25.0000       | 1.745E+00                           | 5.521E-01                           | 2.297E+00                       | 1.312E+01                          | 1.252E-01          | 4.541E+00                      |
| 30.0000       | 1.761E+00                           | 6.781E-01                           | 2.439E+00                       | 1.523E+01                          | 1.476E-01          | 4.866E+00                      |
| 35.0000       | 1.774E+00                           | 8.056E-01                           | 2.579E+00                       | 1.723E+01                          | 1.687E-01          | 5.146E+00                      |
| 40.0000       | 1.785E+00                           | 9.344E-01                           | 2.719E+00                       | 1.911E+01                          | 1.886E-01          | 5.394E+00                      |
| 45.0000       | 1.795E+00                           | 1.064E+00                           | 2.859E+00                       | 2.091E+01                          | 2.075E-01          | 5.614E+00                      |
| 50.0000       | 1.803E+00                           | 1.195E+00                           | 2.998E+00                       | 2.262E+01                          | 2.253E-01          | 5.814E+00                      |
| 55.0000       | 1.811E+00                           | 1.326E+00                           | 3.137E+00                       | 2.425E+01                          | 2.421E-01          | 5.996E+00                      |
| 60.0000       | 1.818E+00                           | 1.458E+00                           | 3.276E+00                       | 2.580E+01                          | 2.581E-01          | 6.163E+00                      |
| 70.0000       | 1.830E+00                           | 1.724E+00                           | 3.554E+00                       | 2.874E+01                          | 2.878E-01          | 6.461E+00                      |
| 80.0000       | 1.840E+00                           | 1.991E+00                           | 3.831E+00                       | 3.144E+01                          | 3.147E-01          | 6.721E+00                      |
| 90.0000       | 1.849E+00                           | 2.260E+00                           | 4.109E+00                       | 3.396E+01                          | 3.392E-01          | 6.952E+00                      |



## APPENDIX D.3. (Continued)

| Photon Energy (MeV) | Air        |                 |                 | Water      |                 |                 | ICRU Compact Bone |                 |                 | ICRU Striated Muscle |                 |                 |
|---------------------|------------|-----------------|-----------------|------------|-----------------|-----------------|-------------------|-----------------|-----------------|----------------------|-----------------|-----------------|
|                     | $\mu/\rho$ | $\mu_{tr}/\rho$ | $\mu_{en}/\rho$ | $\mu/\rho$ | $\mu_{tr}/\rho$ | $\mu_{en}/\rho$ | $\mu/\rho$        | $\mu_{tr}/\rho$ | $\mu_{en}/\rho$ | $\mu/\rho$           | $\mu_{tr}/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 5.04       | 4.61            | 4.61            | 5.21       | 4.79            | 4.79            | 20.3              | 19.2            | 19.2            | 5.30                 | 4.87            | 4.87            |
| 0.015               | 1.56       | 1.27            | 1.27            | 1.60       | 1.28            | 1.28            | 6.32              | 5.84            | 5.84            | 1.64                 | 1.32            | 1.32            |
| 0.02                | 0.758      | 0.511           | 0.511           | 0.778      | 0.512           | 0.512           | 2.79              | 2.46            | 2.46            | 0.796                | 0.533           | 0.533           |
| 0.03                | 0.350      | 0.148           | 0.148           | 0.371      | 0.149           | 0.149           | 0.962             | 0.720           | 0.720           | 0.375                | 0.154           | 0.154           |
| 0.04                | 0.248      | 0.0668          | 0.0668          | 0.267      | 0.0677          | 0.0677          | 0.511             | 0.304           | 0.304           | 0.267                | 0.0701          | 0.0701          |
| 0.05                | 0.206      | 0.0406          | 0.0406          | 0.225      | 0.0418          | 0.0418          | 0.346             | 0.161           | 0.161           | 0.224                | 0.0431          | 0.0431          |
| 0.06                | 0.187      | 0.0305          | 0.0305          | 0.205      | 0.0320          | 0.0320          | 0.273             | 0.0998          | 0.0998          | 0.204                | 0.0328          | 0.0328          |
| 0.08                | 0.167      | 0.0243          | 0.0243          | 0.185      | 0.0262          | 0.0262          | 0.209             | 0.0537          | 0.0537          | 0.183                | 0.0264          | 0.0264          |
| 0.10                | 0.155      | 0.0234          | 0.0234          | 0.171      | 0.0256          | 0.0256          | 0.181             | 0.0387          | 0.0387          | 0.170                | 0.0256          | 0.0256          |
| 0.15                | 0.136      | 0.0250          | 0.0250          | 0.151      | 0.0277          | 0.0277          | 0.150             | 0.0305          | 0.0305          | 0.150                | 0.0275          | 0.0275          |
| 0.2                 | 0.124      | 0.0268          | 0.0268          | 0.137      | 0.0297          | 0.0297          | 0.133             | 0.0301          | 0.0301          | 0.136                | 0.0294          | 0.0294          |
| 0.3                 | 0.107      | 0.0287          | 0.0287          | 0.119      | 0.0319          | 0.0319          | 0.114             | 0.0310          | 0.0310          | 0.118                | 0.0317          | 0.0317          |
| 0.4                 | 0.0954     | 0.0295          | 0.0295          | 0.106      | 0.0328          | 0.0328          | 0.102             | 0.0315          | 0.0315          | 0.105                | 0.0325          | 0.0325          |
| 0.5                 | 0.0868     | 0.0297          | 0.0296          | 0.0966     | 0.0330          | 0.0330          | 0.0926            | 0.0317          | 0.0317          | 0.0958               | 0.0328          | 0.0328          |
| 0.6                 | 0.0804     | 0.0296          | 0.0295          | 0.0894     | 0.0329          | 0.0329          | 0.0856            | 0.0315          | 0.0314          | 0.0886               | 0.0326          | 0.0325          |
| 0.8                 | 0.0706     | 0.0289          | 0.0289          | 0.0785     | 0.0321          | 0.0321          | 0.0751            | 0.0307          | 0.0306          | 0.0778               | 0.0318          | 0.0318          |
| 1.0                 | 0.0635     | 0.0280          | 0.0278          | 0.0706     | 0.0311          | 0.0309          | 0.0675            | 0.0297          | 0.0295          | 0.0699               | 0.0308          | 0.0306          |
| 1.5                 | 0.0517     | 0.0256          | 0.0254          | 0.0575     | 0.0284          | 0.0282          | 0.0549            | 0.0272          | 0.0270          | 0.0570               | 0.0282          | 0.0280          |
| 2                   | 0.0444     | 0.0236          | 0.0234          | 0.0493     | 0.0262          | 0.0260          | 0.0472            | 0.0251          | 0.0249          | 0.0489               | 0.0259          | 0.0257          |
| 3                   | 0.0358     | 0.0207          | 0.0205          | 0.0396     | 0.0229          | 0.0227          | 0.0382            | 0.0221          | 0.0219          | 0.0392               | 0.0227          | 0.0225          |
| 4                   | 0.0308     | 0.0189          | 0.0186          | 0.0340     | 0.0209          | 0.0206          | 0.0331            | 0.0204          | 0.0200          | 0.0337               | 0.0207          | 0.0204          |
| 5                   | 0.0276     | 0.0178          | 0.0174          | 0.0303     | 0.0195          | 0.0191          | 0.0297            | 0.0192          | 0.0187          | 0.0300               | 0.0193          | 0.0189          |
| 6                   | 0.0252     | 0.0168          | 0.0164          | 0.0277     | 0.0185          | 0.0180          | 0.0274            | 0.0184          | 0.0178          | 0.0274               | 0.0183          | 0.0178          |
| 8                   | 0.0223     | 0.0157          | 0.0152          | 0.0243     | 0.0170          | 0.0166          | 0.0244            | 0.0173          | 0.0167          | 0.0240               | 0.0169          | 0.0164          |
| 10                  | 0.0205     | 0.0151          | 0.0145          | 0.0222     | 0.0162          | 0.0157          | 0.0226            | 0.0168          | 0.0159          | 0.0219               | 0.0160          | 0.0155          |

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