Key Dosimetry Data – Impact of New ICRU Recommendations

Part I – Key Data for Ionizing-Radiation Dosimetry

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Brief Glimpse of the ICRU Role in International Harmonization in Ionizing Radiation

1875, Meter Convention
Establishes the CIPM (International Committee on Weights and Measures) and the laboratory BIPM (International Bureau of Weights and Measures)

1895, Röntgen discovers x rays
1898, Curie discovers radium

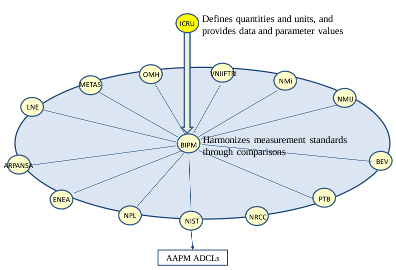
1925, ICRU is established
1928, ICRU recommends the röntgen as dosimetric unit

From recommendations of the ICRU

1958, CCRI (Consultative Committee on Ionizing Radiation) is established

CCRI(I), Section I: x- and gamma-rays and charged particles
CCRI(II), Section II: measurement of radionuclides
CCRI(III), Section III: neutron measurements

Two-Part Harmony in Ionizing Radiation



Primary Motivation for This Work

Request of the Consultative Committee on Ionizing Radiation, CCRI(I), primarily to address issues about parameters that affect air-kerma (or ionometric) standards of National Metrology Institutes.

Up till now, consensus values of parameters (that will soon be explained):

- For electrons produced by x and gamma rays, mean energy per ion pair formed in air, $W = (33.97 \pm 0.05)$ eV
- Values of graphite-to-air electron-stopping-power ratios calculated based on the recommendations of ICRU Report 37 (1984)
- However, a 1992 report of measurement result for I_{graphite} value would change stopping-power ratios, and international standards for air kerma, by more than 1 %
- Note that one actually measures the product of W/e and the graphite-to-air stopping-power ratio, so the two quantities are not independent

ICRU Report 90

KEY DATA FOR IONIZING-RADIATION DOSIMETRY: MEASUREMENT STANDARDS AND APPLICATIONS

Report Committee
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Effort Includes Advancing Relevant Past ICRU Work
(among others)

and be consistent with

Main Issues Considered by the Report Committee

Charged Particles: electrons, positrons, protons, alpha particles, carbon ions

- Mean excitation energies, I: air, graphite, liquid water
- Density effect in graphite
- Mean energy to produce an ion pair in air, W_{air}

Photons:

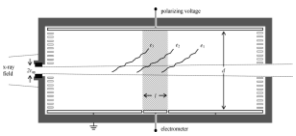
- Photon cross sections: air, graphite, liquid water
- Photon attenuation, energy-transfer, and energy-absorption coefficients

Other:

- Radiation chemical yield, G(x)

Air-Kerma Measurement Standards for Photon Beams

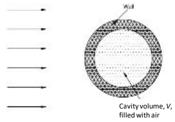
Free-air chamber to realize air kerma for x rays



Some salient points:
- Collecting volume is simply $\pi r^2 l$, even for a conical beam
- Dimension d large enough to insure secondary electrons can slow to rest
- Non-collecting volume large enough to insure charged-particle equilibrium (at least quasi)

Air-Kerma Measurement Standards for Photon Beams

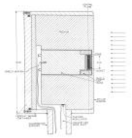
Graphite-walled air-cavity chamber to realize air kerma for γ rays

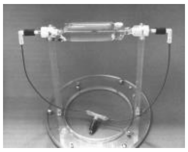


Some salient points:
- Implementation of Bragg-Gray cavity theory
- Walls thick compared to max penetration distance of secondary electrons
- Electron slowing-down spectra nearly identical in wall and in cavity air

Absorbed-Dose Measurement Standards

Graphite (left) and water (right) calorimeters





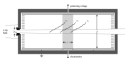
Some salient points:

- Requires knowledge of the specific heat capacity
- and the heat defect of the sensing material
- Has become the preferred standard for high-energy beams

What Are the Key Data?
Illustrative Measurement Equations

To realize x-ray air kerma with a free-air chamber

$$K_{\rm air} = (W_{\rm air}/{\rm e})\frac{q_{\rm net}}{m_{\rm air}(1-\bar{g}_{\rm air})}\prod_i k_i$$

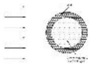


To realize gamma-ray air kerma with a graphite-walled Bragg-Gray cavity chamber

$$K_{\rm air} = (W_{\rm air}/{\rm e})\frac{q_{\rm net}}{m_{air}(1-\bar{g}_{\rm air})}s_{\rm g,air}(\mu_{\rm en}/\rho)_{\rm air,g}\prod_i k_i$$

with notation

$$s_{\rm g,air} = \frac{\overline{(S_{\rm el}/\rho)}_{\rm graphite}}{\overline{(S_{\rm el}/\rho)}_{\rm air}}$$



and

$$(\mu_{\rm en}/\rho)_{\rm air,g} = \frac{\overline{(\mu_{\rm en}/\rho)}_{\rm air}}{\overline{(\mu_{\rm en}/\rho)}_{\rm graphite}}$$

Illustrative Measurement Equations

To realize x-ray air kerma with a free-air chamber

Need value for electrons

$$K_{\rm air} = (W_{\rm air}/{\rm e})\frac{q_{\rm net}}{m_{\rm air}(1-\bar{g}_{\rm air})}\prod_i k_i$$

Need brems production cross sections

To realize gamma-ray air kerma with a graphite-walled Bragg-Gray cavity chamber

$$K_{\rm air} = (W_{\rm air}/{\rm e})\frac{q_{\rm net}}{m_{air}(1-\bar{g}_{\rm air})}s_{\rm g,air}(\mu_{\rm en}/\rho)_{\rm air,g}\prod_i k_i$$

where

$$s_{\rm g,air} = \frac{\overline{(S_{\rm el}/\rho)}_{\rm graphite}}{\overline{(S_{\rm el}/\rho)}_{\rm air}}$$

Need *I* value and density effect

and

$$(\mu_{\rm en}/\rho)_{\rm air,g} = \frac{\overline{(\mu_{\rm en}/\rho)}_{\rm air}}{\overline{(\mu_{\rm en}/\rho)}_{\rm graphite}}$$

Need best values and uncertainty of ratio

Elaboration for Measurement Equations

Photons:

$$\frac{\overline{(\mu_{\mathrm{en}}/\rho)}_{\mathrm{air}}}{\overline{(\mu_{\mathrm{en}}/\rho)}_{\mathrm{graphite}}} = \frac{\int \Phi_E E \left(\frac{\mu_{\mathrm{en}}(E)}{\rho}\right)_{\mathrm{air}} \mathrm{d}E}{\int \Phi_E E \left(\frac{\mu_{\mathrm{en}}(E)}{\rho}\right)_{\mathrm{graphite}} \mathrm{d}E}$$

incident photon fluence

electron fluence in cavity

Electrons:

$$\frac{\overline{(S/\rho)}_{\mathrm{graphite}}}{\overline{(S/\rho)}_{\mathrm{air}}} = \frac{\int_{\Delta}^{T_{\max}} \Phi_T^{\mathrm{air}} \left(\frac{S_\Delta^-(T)}{\rho}\right)_{\mathrm{graphite}} \mathrm{d}T + \Phi_T^{\mathrm{air}}(\Delta) \left(\frac{S_{\mathrm{el}}^-(\Delta)}{\rho}\right)_{\mathrm{graphite}} \Delta}{\int_{\Delta}^{T_{\max}} \Phi_T^{\mathrm{air}} \left(\frac{S_\Delta^-(T)}{\rho}\right)_{\mathrm{air}} \mathrm{d}T + \Phi_T^{\mathrm{air}}(\Delta) \left(\frac{S_{\mathrm{el}}^-(\Delta)}{\rho}\right)_{\mathrm{air}} \Delta}$$

mass electronic stopping power

where the restricted electronic stopping power (Bethe theory) is

mean excitation energy

$$\frac{1}{\rho} S_\Delta^\pm(T) = \frac{2\pi r_e^2 m_e c^2}{\beta^2} \frac{Z}{uA} \left(\ln\left[(T/I)^2 (1+\tau/2) \right] - \delta + H^\pm(\tau) \right)$$

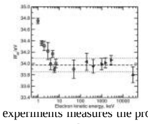
density-effect correction

Key Data for Charged Particles

- W_{air} mean energy expended by electrons in dry air per ion pair formed
- I_{air}
- I_{graphite} — mean excitation energy of the medium to calculate the electronic stopping power of charged particles
- I_{water}
- δ density-effect correction to the electronic stopping power of charged particles
- g_{air} the fraction, averaged over the distribution of the air kerma with respect to the electron energy, of the kinetic energy of electrons liberated by the photons that is lost in radiative processes (mainly bremsstrahlung) in dry air

Background: Mean Energy to Produce an Ion Pair in Air

- Since the publication of ICRU Report 31 (1979), there have been a number of reports on the determination of W_{air} for electrons and on w_{air} in nitrogen and air for protons.
- ICRU, based on an analysis of Jones (2006), recommends a value of w_{air}/e for proton therapy of (34.2 ± 0.1) J C^{-1}. The Key Data Report Committee accepts this value and focuses mainly on W_{air} for electrons.



- A collection of precision experiments measures the product $W_{\mathrm{air}} \cdot s_{\mathrm{graphite,air}}$, so the recommended values of W_{air}, I_{graphite}, and ρ_{graphite} are intertwined.

Background: Mean Excitation Energies

The mean excitation energy, *I*, is the key and non-trivial parameter in Bethe stopping-power theory, used in charged-particle transport and dosimetry.

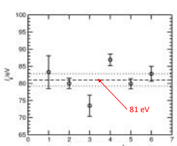
- ICRU Report 37 (1984) on e^- and e^+ stopping powers recommended $I_{graphite}$= (78.0 ± 4.3) eV, I_{air} = (85.7 ± 1.2) eV, and I_{water} = (75.0 ± 1.8) eV. These values wrere retained in ICRU Report 49 (1993) for p and α stopping powers.
- Bichsel and Hiraoka (1992), analyzing energy loss of 70 MeV protons in 21 (mostly elemental) materials relative to Al, reported $I_{graphite}$ = (86.9 ± 1.2) eV, and I_{water} = (79.7 ± 0.5) eV. Recent analyses of the dielectric-response function for liquid water recommend values of I_{water} larger than 75 eV.
- Considered by itself, such a change in the mean excitation energy for graphite can have a large effect in national air-kerma standards, ≈1.3 % for ^{60}Co, ≈1.5 % for ^{137}Cs, and ≈1.5 % for ^{192}Ir.
- As water is the universal dosimetry reference material, I_{water} is also considered - has impact in clinical dosimetry.
- ICRU Report 73 considered stopping of ions heavier than He, <u>but not in the context of Bethe theory</u>.

Mean Excitation Energies

air

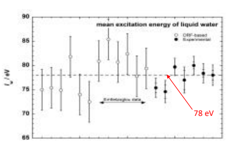
data from 1955 to 2006

Constituent	Fraction by weight	<Z/A>	Recommended I/eV	Recommended u_c/eV
N_2	0.755267	0.499761	82.3	1.22
O_2	0.231450	0.500019	95.2	1.0
Ar	0.012827	0.450586	187	3
CO_2	0.000456	0.499889	87	2
Dry air	1	0.499190	85.7	1.2



graphite

data from 1951 to 2007



water

data from 1952 to 2009

Background: Density Effect

- Graphite is not a simple homogeneous material. ICRU Report 37 (1984) recommended the use of the bulk density in the calculation of the density effect, included also results for crystallite density, but considered also treating inhomogeneous materials as a mixture.
- Applied to the case of graphite, a mixture-with-air approach gives values of the electronic stopping power that are the same to four significant figures as those for pure graphite with the crystallite density $\rho_{graphite}$ = 2.265 g/cm^3. This is consistent with the suggestion of MacPherson (1998) who found better agreement with the measured energy loss of 6 MeV to 28 MeV electrons in graphite when using the crystallite density of 2.26 g/cm^3 rather than the bulk density (≈1.7 g/cm^3) for the calculation of the density-effect correction.
- The use of the crystallite density rather than the bulk density by itself changes the graphite-to-air stopping-power ratio associated with graphite-wall air-ionization cavity chambers by ≈0.2 % for ^{60}Co, ≈0.1 % for ^{137}Cs, and ≈0.06 % for ^{192}Ir.

Background: g_{air}

- g_{air} is an average over the bremsstrahlung yield Y of secondary electrons slowing down in air
- Y is evaluated as $$Y(T_0) = \int_0^{T_0} \frac{S_{rad}(T)}{S_{el}(T) + S_{rad}(T)} \mathrm{d}T$$
- S_{rad} is the radiative stopping power, which depends on bremsstrahlung-production cross sections
- bremsstrahlung-production cross sections now adopted from work of Seltzer and Berger (1985), which is slightly different from those used in ICRU Report 37 (1984)
- final effect on g_{air} is of order 0.5 % or less, and g_{air} itself is about 0.0033 for ^{60}Co air kerma: <u>so effect on 1- g_{air} is negligible</u>

Summary of Recommendations

	Previous	This Report	Standard uncertainty	Relative standard uncertainty (%)	Relative change (%)	Comments
I_{air}	85.7 eV	85.7 eV	1.2 eV	1.40	**0**	
I_g	78 eV	81 eV	1.8 eV	2.22	**3.8**	graphite ρ = 2.265 g cm^{-3}
I_w	75 eV	78 eV	2 eV	2.56	**4.0**	
W_{air} **for electrons**	33.97 eV	33.97 eV	0.12 eV	0.35	**0**	Asymptotic value
W_{air} **for protons**	34.23 eV	34.44 eV	0.14 eV	0.4	**0.6**	Asymptotic value
W_{air} **for C ions**	34.50 eV	34.71 eV	0.52 eV	1.5	**0.6**	Asymptotic value
$G(Fe^{3+})$		1.62 µmol J^{-1}	0.008 µmol J^{-1}	~0.5		High energy electrons
h_w **(4 °C)**	0	0		0.15	**0**	Low-LET radiations

The analysis of Burns (2012) results in the best estimate of $W_{air}\, s_{g,air}$ = 33.72 eV for ^{60}Co radiation, determined with a relative standard uncertainty of 0.08 %. Adoption of this result would reduce the air-kerma determination for ^{60}Co graphite-cavity standards by about 0.7 %, due to the change in $s_{g,air}$.

Recommendations Discussion

Density Effect

For graphite use the crystallite density, $\rho_{graphite}$ = 2.265 g/cm^3

Mean Excitation Energies

<u>Air</u>

- I_{air} = (85.7 ± 1.2) eV. I_{air} unchanged but with smaller uncertainty.

<u>Graphite</u>

Reported I values range from about 71 eV to 87 eV. Recommendation is

- $I_{graphite}$ = (81.0 ± 1.8) eV. Previous was (78 ± ~4) eV

<u>Water</u>

Reported I values range from about 75 eV to 82 eV. Recommendation is

- I_{water} = (78 ± 2) eV. Previous was (75 ± 2) eV

Mean Energy to Produce an Ion Pair in Air by Electrons

- W_{air} = (33.97 ± 0.12) eV. No change in value, but now has a larger uncertainty

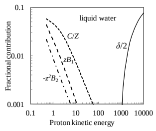
(Modified) Bethe Theory for Heavy Charged Particles

Electronic (collision) stopping power:

$$\frac{1}{\rho}S_{\mathrm{el}} = \frac{4\pi r_e^2 m_e c^2}{\beta^2}\frac{Z}{uA}z^2 B(\beta)$$

where stopping number is

$$B(\beta) = \ln\left(\frac{2m_e c^2\beta^2}{(1-\beta^2)I}\right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} + zB_1 + z^2 B_2$$



shell correction

Barkas correction

Bloch correction

Sample (Abridged) Stopping-Power/Range Tables

Electrons in liquid water, I = 78 eV

fractional change per fractional change in I

T	S_{el}/ρ	S_{rad}/ρ	S_{tot}/ρ	r_0/ρ	Y	δ	$\partial(\log\ )/\partial(\log I)$		
MeV	MeV cm² g⁻¹			g cm⁻²			S_{el}/ρ	r_0/ρ	Y
0.001	1.181E+02	2.830E-03	1.181E+02	4.235E-06	1.199E-05	0.000E+00	-0.370	0.370	0.370
0.002	7.436E+01	3.307E-03	7.436E+01	1.524E-05	2.318E-05	0.000E+00	-0.295	0.336	0.334
0.005	3.806E+01	3.737E-03	3.807E+01	7.536E-05	5.253E-05	0.000E+00	-0.232	0.270	0.267
0.010	2.239E+01	3.890E-03	2.239E+01	2.537E-04	9.476E-05	0.000E+00	-0.200	0.229	0.227
0.020	1.308E+01	3.939E-03	1.309E+01	8.632E-04	1.670E-04	0.000E+00	-0.176	0.198	0.197
0.050	6.564E+00	4.011E-03	6.568E+00	4.348E-03	3.442E-04	0.000E+00	-0.152	0.168	0.168
0.100	4.093E+00	4.211E-03	4.097E+00	1.439E-02	5.851E-04	0.000E+00	-0.139	0.151	0.151
0.200	2.779E+00	4.771E-03	2.784E+00	4.512E-02	9.831E-04	0.000E+00	-0.127	0.138	0.137
0.500	2.025E+00	7.228E-03	2.032E+00	1.774E-01	1.976E-03	0.000E+00	-0.113	0.123	0.122
1.000	1.845E+00	1.276E-02	1.858E+00	4.384E-01	3.577E-03	2.086E-01	-0.061	0.097	0.090
2.000	1.821E+00	2.666E-02	1.848E+00	9.811E-01	7.071E-03	7.703E-01	-0.036	0.068	0.055
5.000	1.891E+00	7.922E-02	1.970E+00	2.554E+00	1.910E-02	1.906E+00	-0.022	0.042	0.029
10.000	1.967E+00	1.816E-01	2.148E+00	4.980E+00	4.077E-02	2.928E+00	-0.018	0.031	0.021
20.000	2.045E+00	4.079E-01	2.453E+00	9.327E+00	8.357E-02	4.039E+00	-0.013	0.022	0.015
50.000	2.139E+00	1.145E+00	3.284E+00	1.985E+01	1.920E-01	5.665E+00	-0.005	0.014	0.007
100.000	2.202E+00	2.437E+00	4.640E+00	3.259E+01	3.190E-01	6.998E+00	-0.001	0.009	0.003
200.000	2.263E+00	5.103E+00	7.366E+00	4.955E+01	4.701E-01	8.367E+00	0.000	0.006	0.001
500.000	2.341E+00	1.323E+01	1.558E+01	7.692E+01	6.620E-01	1.019E+01	0.000	0.004	0.000
1000.000	2.401E+00	2.691E+01	2.931E+01	9.994E+01	7.764E-01	1.158E+01	0.000	0.003	0.000

Sample (Abridged) Stopping-Power/Range Tables

Protons in liquid water, I = 78 eV

fractional change per fractional change in I

T MeV	S_{el}/ρ	S_{nuc}/ρ	S_{tot}/ρ	r_0/ρ g cm⁻²	Detour factor	$\partial\log/\partial\log(I)$	
	MeV cm⁻² g⁻¹					(S_{el}/ρ)	r_0/ρ
0.2	6.585E+02	9.016E-01	6.594E+02	2.967E-04	0.9460	-0.081	0.006
0.5	4.065E+02	4.043E-01	4.069E+02	8.945E-04	0.9790	-0.394	0.220
1.0	2.574E+02	2.173E-01	2.577E+02	2.487E-03	0.9905	-0.311	0.298
2.0	1.569E+02	1.157E-01	1.570E+02	7.639E-03	0.9952	-0.256	0.283
5.0	7.842E+01	4.970E-02	7.847E+01	3.656E-02	0.9974	-0.206	0.235
10.0	4.532E+01	2.603E-02	4.535E+01	1.240E-01	0.9980	-0.179	0.203
20.0	2.589E+01	1.356E-02	2.591E+01	4.289E-01	0.9983	-0.159	0.177
50.0	1.238E+01	5.691E-03	1.238E+01	2.240E+00	0.9985	-0.140	0.152
100.0	7.250E+00	2.944E-03	7.253E+00	7.759E+00	0.9987	-0.128	0.138
200.0	4.470E+00	1.522E-03	4.471E+00	2.609E+01	0.9988	-0.119	0.127
500.0	2.731E+00	6.367E-04	2.732E+00	1.176E+02	0.9990	-0.109	0.116
1000.0	2.203E+00	3.300E-04	2.204E+00	3.268E+02	0.9992	-0.096	0.108
2000.0	2.017E+00	1.715E-04	2.017E+00	8.079E+02	0.9994	-0.052	0.084
5000.0	2.029E+00	7.251E-05	2.030E+00	2.302E+03	0.9996	-0.027	0.052
10000.0	2.124E+00	3.788E-05	2.125E+00	4.707E+03	0.9998	-0.019	0.037

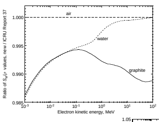
Sample (Abridged) Stopping-Power/Range Tables

Carbon ions in liquid water, I = 78 eV

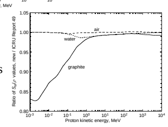
fractional change per fractional change in I

T	S_{el}/ρ	S_{nuc}/ρ	S_{tot}/ρ	r_0/ρ	$\partial(\log\ )/\partial(\log I)$		
MeV		MeV cm^2 g^{-1}		g cm^{-2}	S_{el}/ρ	r_0/ρ	
0.5	4.198E+03	1.001E+02	4.298E+03	1.911E-04	0	0	based on empirical results
1	6.116E+03	5.808E+01	6.174E+03	2.864E-04	0	0	
2	8.139E+03	3.302E+01	8.172E+03	4.238E-04	0	0	
5	8.372E+03	1.529E+01	8.387E+03	7.708E-04	0	0	
10	6.926E+03	8.428E+00	6.934E+03	1.430E-03	0	0	
20	5.284E+03	4.603E+00	5.289E+03	3.100E-03	0	0	
50	3.134E+03	2.043E+00	3.136E+03	1.072E-02	-0.179	0.048	
100	1.855E+03	1.094E+00	1.856E+03	3.222E-02	-0.188	0.147	
200	1.069E+03	5.806E-01	1.070E+03	1.063E-01	-0.165	0.165	
500	5.123E+02	2.468E-01	5.126E+02	5.438E-01	-0.143	0.153	
1000	2.984E+02	1.271E-01	2.985E+02	1.881E+00	-0.131	0.140	
2000	1.813E+02	6.474E-02	1.814E+02	6.369E+00	-0.121	0.129	
5000	1.068E+02	2.615E-02	1.068E+02	2.940E+01	-0.110	0.117	
10000	8.311E+01	1.312E-02	8.312E+01	8.401E+01	-0.102	0.110	

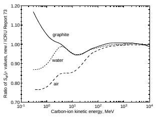
Changes in Electronic Stopping Powers



electrons

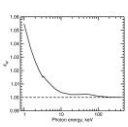


protons

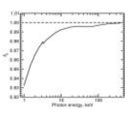


C ions

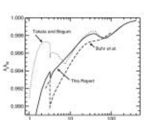
Corrections for Low-Energy X Rays



k_W corrects for rise in W_{air} at low <u>electron</u> energies



k_{ii} corrects initial ions that should not be included in air-kerma measurement

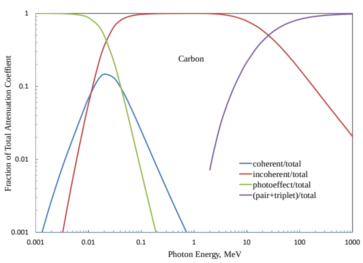


significant compensation in product of $k_{ii}\,k_W$

Background: Photon Attenuation, Energy-Transfer, and Energy-Absorption Coefficients

- Accurate photon-interaction cross sections are needed in radiation-dosimetry measurement standards and in clinical dosimetry, especially for key dosimetric materials such as water, graphite, and air
- Recommendations are needed on the uncertainty associated with the use such quantities, particularly those ratios that are important in primary measurement standards and in clinical dosimetry
- And, of course, in radiation-transport calculations

Photon-Interaction Cross Sections

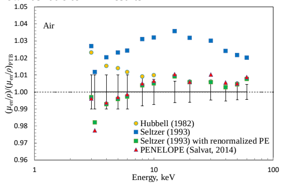


Issue for Photoeffect Cross Sections

- Cross sections are calculated using Dirac-Hartree-Fock-Slater (DHFS) wave functions for atomic bound states
- Multi-Configuration Dirac-Fock (MCDF) wave functions might yield more accurate results
- Pratt (1960) showed that well above the binding energy the photoeffect cross section is proportional to normalization of wave functions at very small radii
- Renormalization by ratio of MCDF normalization to DHFS normalization was done in Hubbell tabulations until 1986 when statistical evidence from his comparisons below 1 keV suggested that over all elements it was better to use unrenormalized cross sections (as done in XCOM)
- Seltzer (1993) thus used unrenormalized PE cross sections in evaluations of μ_{tr}/ρ and μ_{en}/ρ

Issue for Photoeffect Cross Sections

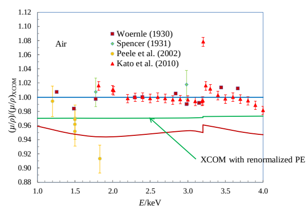
- Büermann *et al*. (2006) and Buhr *et al*. (2012) of the PTB, measured μ_{en}/ρ of air with relative standard uncertainties less than 1 % for x-ray energies from 3 keV to 60 keV using monochromatized synchrotron radiation
- Data below shown as ratio to PTB results



- So we should use renormalized PE cross sections?

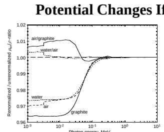
Issue for Photoeffect Cross Sections

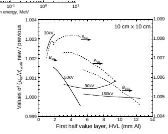
- But Kato *et al*. (2010) report attenuation-coefficients for air with relative standard uncertainties of 0.4 % measured using monochromatized synchrotron radiation

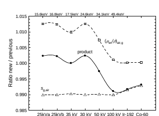


- So no clear decision

Potential Changes If Renormalization Were Adopted







Anticipated Impact of Recommendations

Measurement Standards:
The recommended changes for graphite *I* and density would result in a relative decrease of about 0.6 % – 0.7 % in international measurement standards for ^{60}Co, ^{137}Cs, and ^{192}Ir air kerma.

Estimated relative changes (%) in NIST air-kerma standards

^{60}Co	-0.66
^{137}Cs	-0.61
^{192}Ir	-0.59

Particle Therapy:
For therapy energies, the recommended change in I_{water} from 75 eV to 78 eV results in an increase in the csda range in water of:

- 0.08 mm for 20 MeV electrons
- 1.3 mm for 200 MeV protons
- 0.9 mm for 300 MeV/u C ions

Anticipated Impact of Recommendations (cont'd)

Clinical Dosimetry: Estimates of changes in determination of D_w

Quantity	Relative change (%)	
D_w for photons	-0.2	For lower-energy beam qualities
	-0.5?	For higher-energy beam qualities
D_w for electrons	-0.4	
D_w for protons and carbon ions	-0.5	

Thank You

There is of course more in the ICRU Report.