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Internal Bremsstrahlung: the missing process in beta decay Monte Carlo simulation for Dose-Point-Kernel estimation

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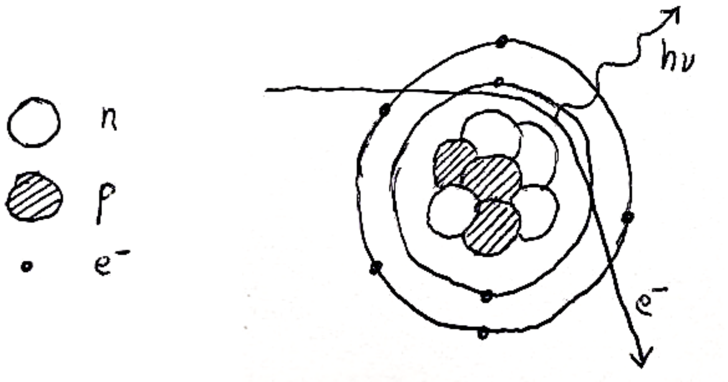
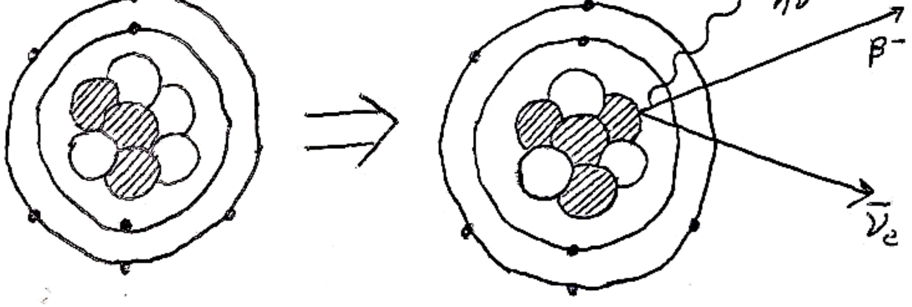
Context: Bremsstrahlungs

- External Bremsstrahlung (EB), the "well-known" Bremsstrahlung: emission of photons with continuous energy spectrum due to deceleration of a travelling charged particle by another charged particle (typically an electron by an atomic nucleus of the medium in which is travelling)
- Internal Bremsstrahlung (IB), the "unknown" Bremsstrahlung: process accompanying β-decay, consisting in emission of photons with a continuous energy spectrum from the parent nucleus, due to the interaction of the β particle with its own parent nucleus [1,2].



- Beta decay



- External Bremsstrahlung
- Internal Bremsstrahlung

Background and aim of the study

- Internal Bremsstrahlung (IB) was widely studied in the past decades: KUB theory [1, 2] + updated models [6-8] to calculate spectral distribution of IB photons, even if comparison with measurements [9, 10] not always satisfactory
- However, currently IB is usually neglected in dosimetry and radioprotection studies when estimating energy deposition due to β-decays; no Monte Carlo (MC) simulation software accounts for IB
- But is IB contribution to β-decay energy deposition effectively negligible?
- In some recent works, IB emission intensity was observed to significantly contribute to the deposited energy for some high-energy β-emitting radionuclides: ^{90}Y, ^{32}P [3-5]
- Dose-Point-Kernels (DPKs) are extensively used for the dosimetry of gamma and beta emitters, and are usually computed with MC simulations, tallying the energy deposited around a point source as a function of the radial distance R
- The aim of this study was to quantify, by means of MC simulations, the contribution of IB photons to the DPKs of ^{90}Y and ^{32}P, and revise the DPK values accordingly

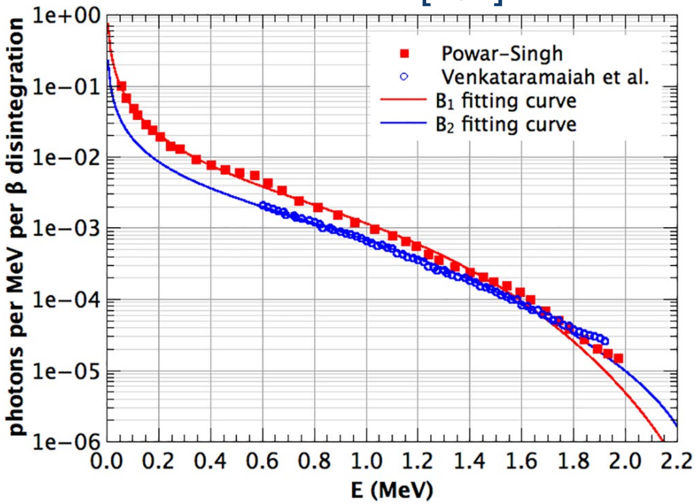
Internal Bremsstrahlung spectra modeling

- In our previous works [3-5], we adopted IB photon spectral distributions, B(E), for ^{90}Y and ^{32}P, obtained by fitting experimental data (+ theoretical models, if needed, to extrapolate at lower or higher energies) available in literature with the following function:

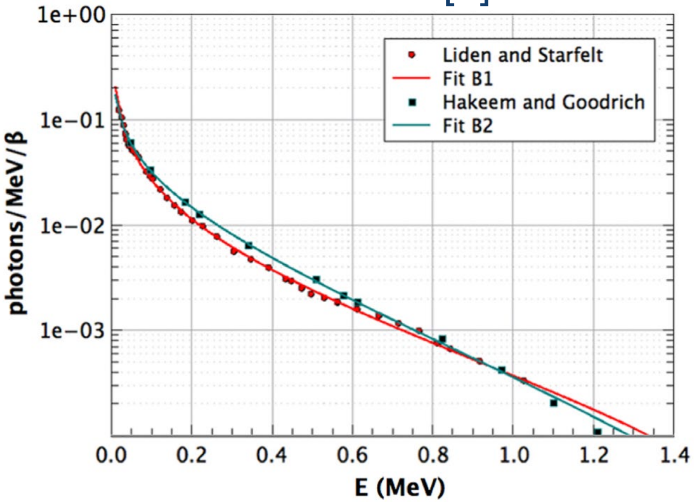
$$B(E) = a \cdot \left(e^{-bE^{\beta} - cE^{\gamma}} - e^{-bE_0^{\beta} - cE_0^{\gamma}} \right)$$

- where: $a = 25.9$; b, c, b and g fit parameters; E_0 = end-point energy of the β spectrum

- For ^{90}Y [3,4]

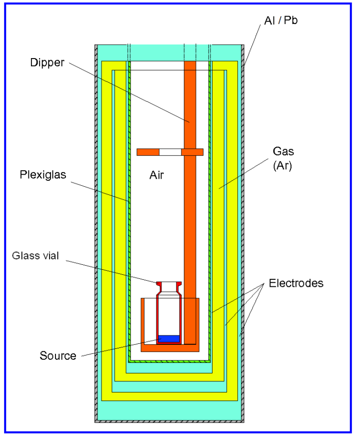


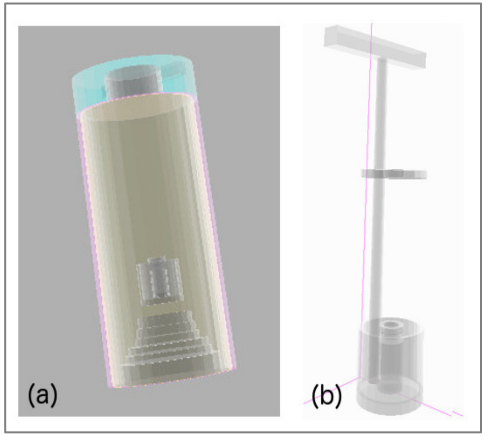
- For ^{32}P [5]



Experimental verification

- We compared experimental measurements of the signal generated in a dose calibrator (well ionization chamber for activity measurements) by a source of ^{90}Y and ^{32}P, with MC simulations including and not including respective IB spectra contribution
- **Including IB**, good agreement with exp. when using the following IB spectra modelizations: for ^{90}Y, fit of exp. data from Venkataramaiah + Ford and Martin model [4]; for ^{32}P, fit of exp. data from Liden and Starfelt [5]
- **Not including IB**, differences between exp. and MC up to -14% for ^{90}Y, up to -17% for ^{32}P → IB emission contributes up to these values to the signal in the examined setup

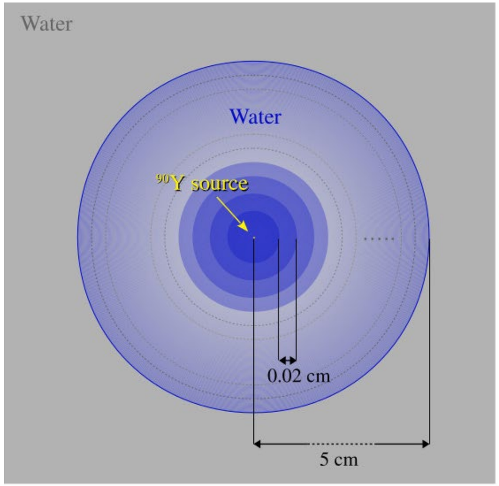


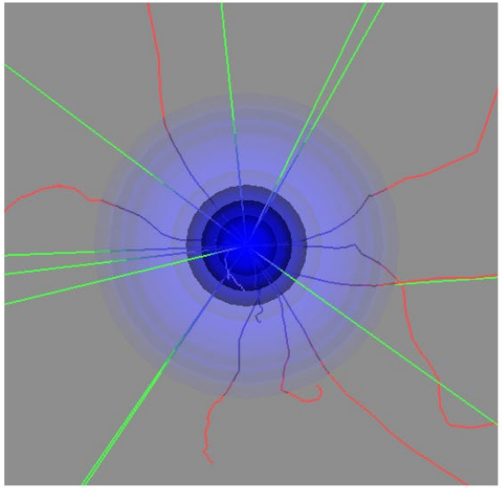


Source	I_{EXP} (pA/MBq)	IB in MC	I_{MC} (pA/MBq)	ϵ (%)
^{90}Y	0.198 ± 0.001	no	0.174 ± 0.002	-12.1
^{90}Y (shielded)	0.192 ± 0.001	no	0.166 ± 0.002	-13.5
^{90}Y	0.198 ± 0.001	yes	0.198 ± 0.002	0.0
^{90}Y (shielded)	0.192 ± 0.001	yes	0.189 ± 0.002	-1.6
^{32}P	0.1259 ± 0.0005	no	0.1057 ± 0.0010	-16.0
^{32}P (shielded)	0.1222 ± 0.0005	no	0.1013 ± 0.0010	-17.1
^{32}P	0.1259 ± 0.0005	yes	0.1302 ± 0.0010	+3.4
^{32}P (shielded)	0.1222 ± 0.0005	yes	0.1251 ± 0.0010	+2.4

Dose-Point-Kernel (DPK) estimation with GAMOS

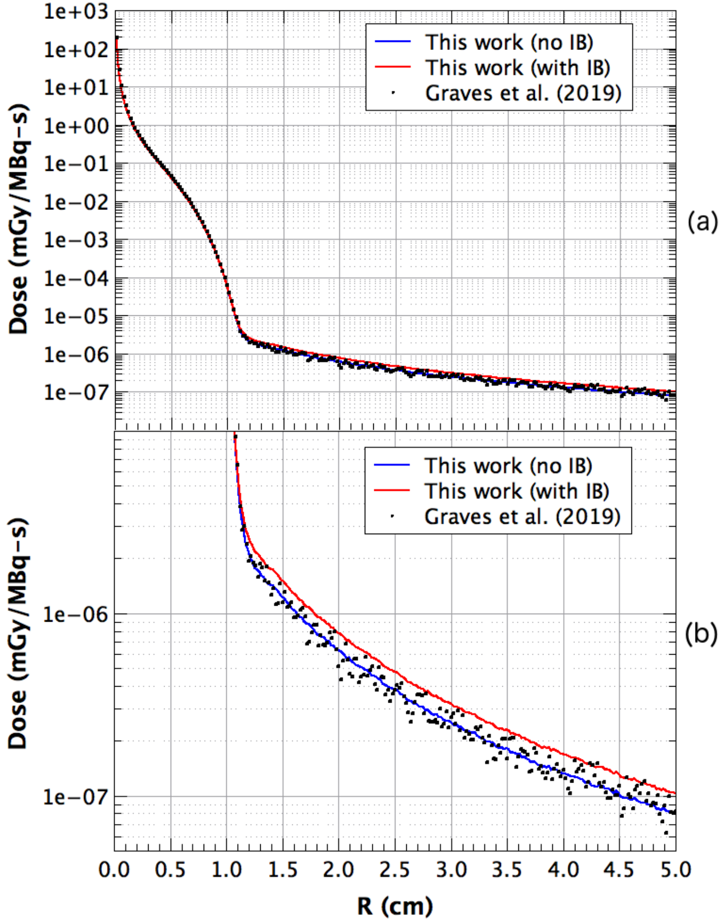
- Dose-Point-Kernel (DPK) is defined as the energy deposited all around a radioactive point source in a homogeneous medium, thus giving information on the absorbed dose as a function of the distance from the source [11-13]
- We computed DPKs for ^{90}Y and ^{32}P in water including and not including IB spectra
- MC simulations performed with GAMOS 6.2.0:
- ^{90}Y and ^{32}P decays simulated via *RadioactiveDecay* GEANT4 module (NB it dose not account for IB emission!); IB emission simulated as an additive spectrum term to the source, modelled as in our previous works
- Geometry: point source at the centre of concentric shells of water (G4_WATER; d = 1 g/cm^3); shell thickness: 0.02 cm; shells' radius: min 0 cm, max 5 cm
- Scored quantity: energy deposited in each shell
- N. of events: 10^8 events, No variance reduction techniques applied





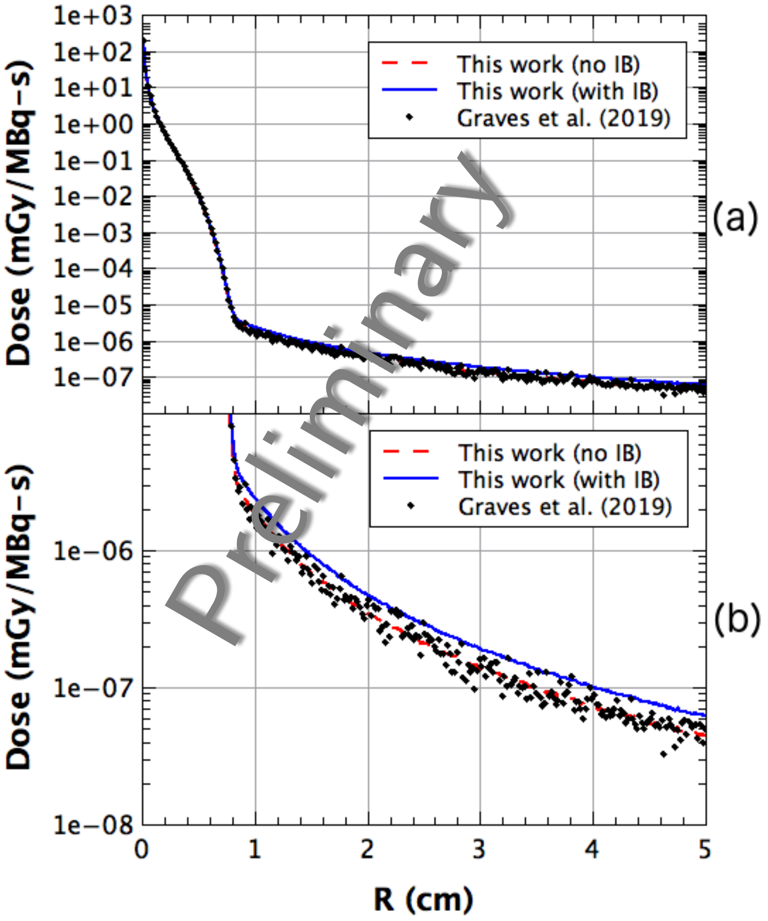
^{90}Y absorbed dose distribution

- Absorbed dose (AD) estimated as a function of the distance R from the source
- Neglecting IB emission (blue line), comparing with ^{90}Y DPK from Graves et al. (2019) [13], good agreement found, since also Graves et al. neglected IB!
- When adding IB photons to the MC simulations (red line), for distances larger than 1.2 cm, AD values are higher than the previously obtained ones
- IB source term contributes up to 30% to AD at the examined distances larger than the average range of βs from ^{90}Y.



^{32}P absorbed dose distribution

- Absorbed dose (AD) estimated as a function of the distance R from the source
- Neglecting IB emission (red line), comparing with ^{32}P DPK from Graves et al. (2019) [13], good agreement found, since also Graves et al. neglected IB!
- When adding IB photons to the MC simulations (blue line), for distances larger than 0.8 cm, AD values are higher than the previously obtained ones
- IB source term contributes up to 40% to AD at the examined distances larger than the average range of βs from ^{32}P.



^{90}Y and ^{32}P Dose-Point-Kernels

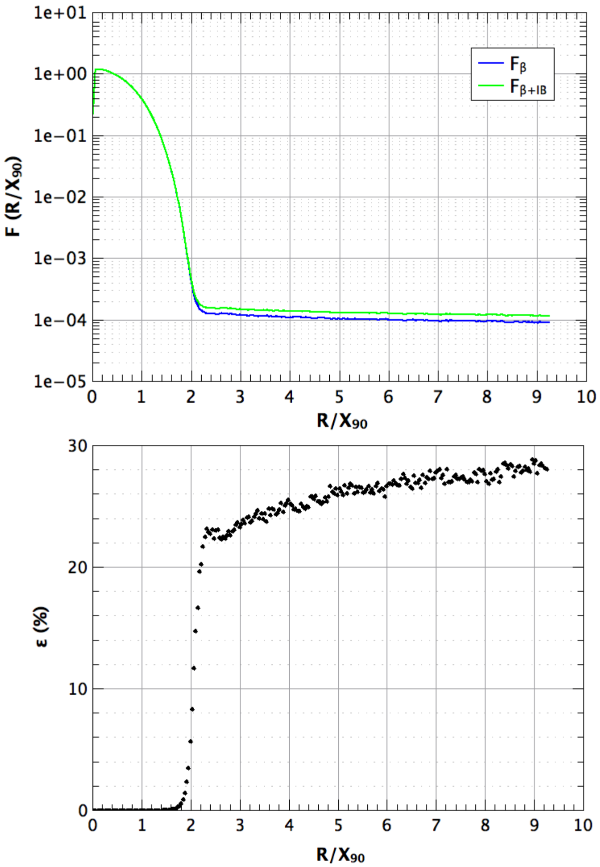
- Results confirmed also in terms of "proper" DPKs, in the conventional units as "scaled absorption function" F_β [14]

$$F_\beta(R/X_{90}) = 4\pi R^2 \rho X_{90} \phi_\beta(R)$$

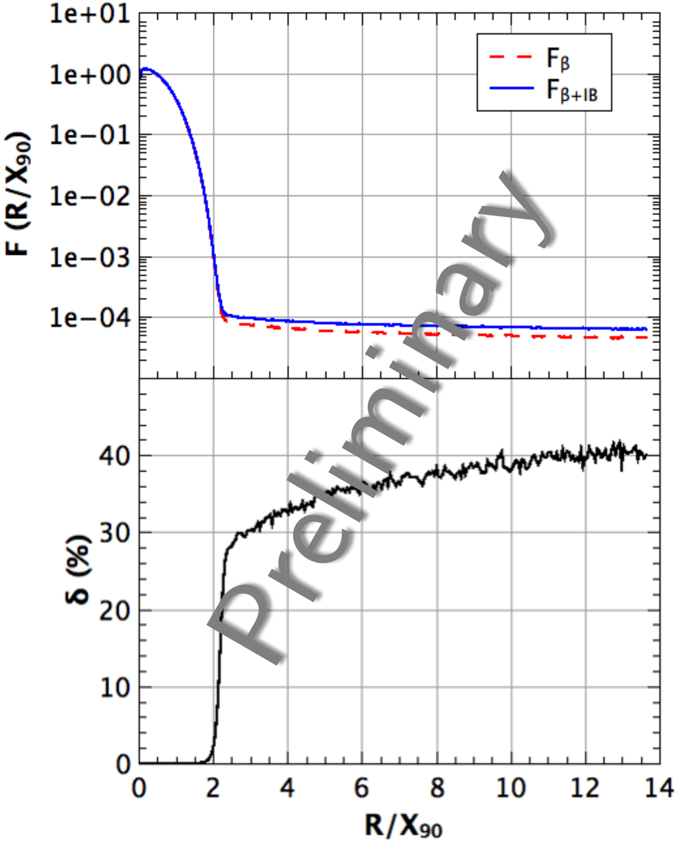
R = distance from the source
r = density of the medium
X_{90} = emitted energy 90-percentile distance
$\phi_\beta(R)$ = point isotropic specific absorbed fraction

$$\varepsilon(\%) = 100 \cdot \frac{(F_{\beta+IB}(R/X_{90}) - F_\beta(R/X_{90}))}{F_\beta(R/X_{90})}$$

- ^{90}Y



- ^{32}P



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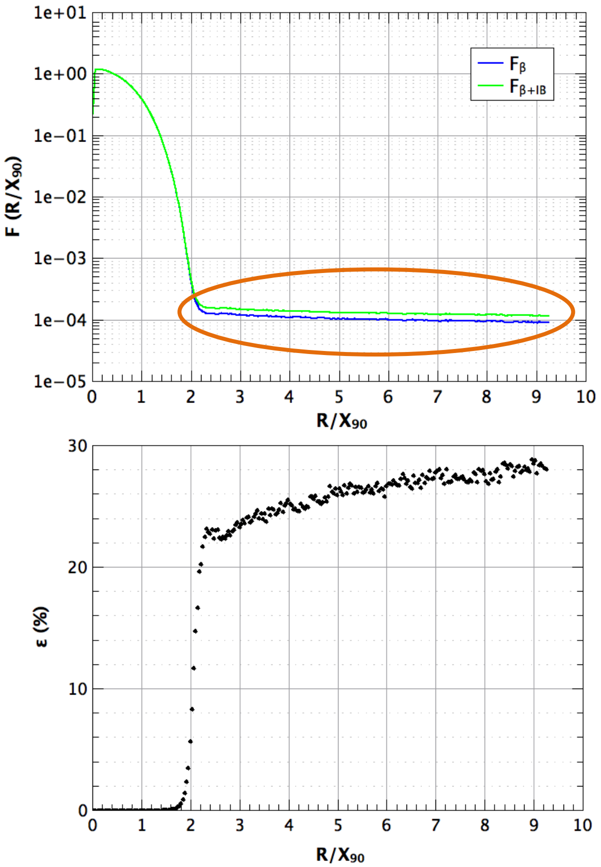
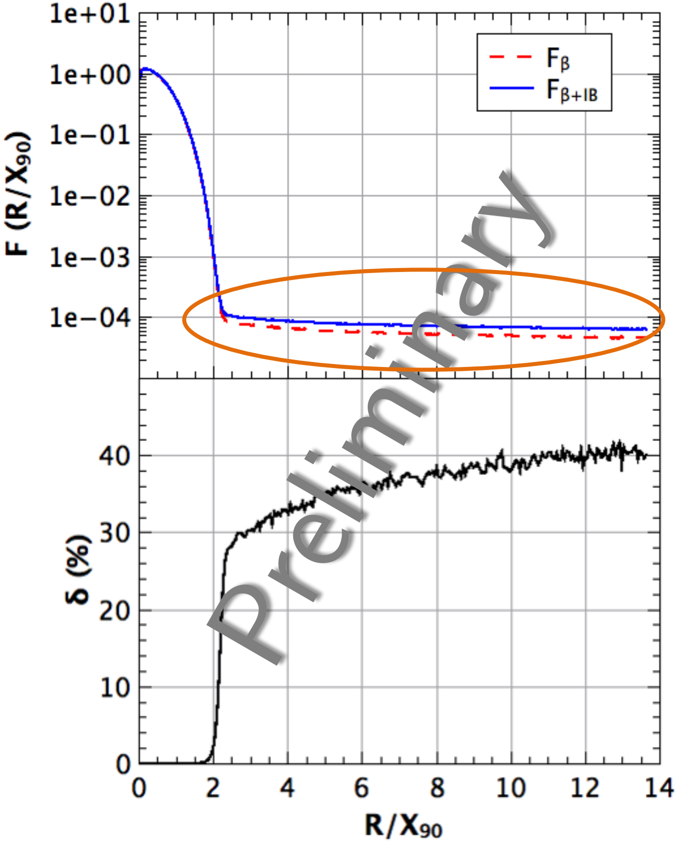
- For $R > 2X_{90}$, contribution from IB emission

- ^{90}Y



- ^{32}P



^{90}Y and ^{32}P Dose-Point-Kernels

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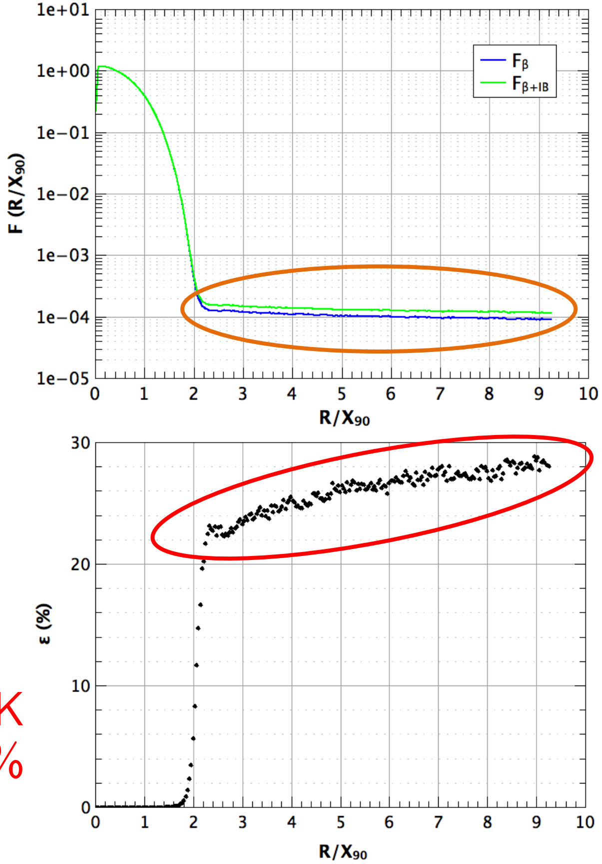
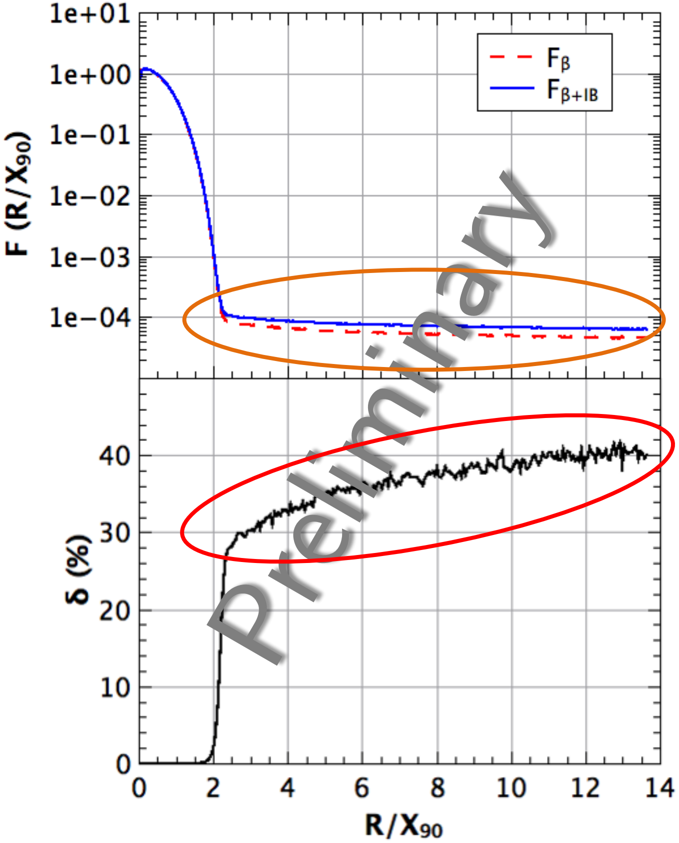
- For $R > 2X_{90}$, contribution from IB emission

- Rel. percent diff. ϵ between DPK with and without IB up to 30% for ^{90}Y and up to 40% for ^{32}P

- ^{90}Y



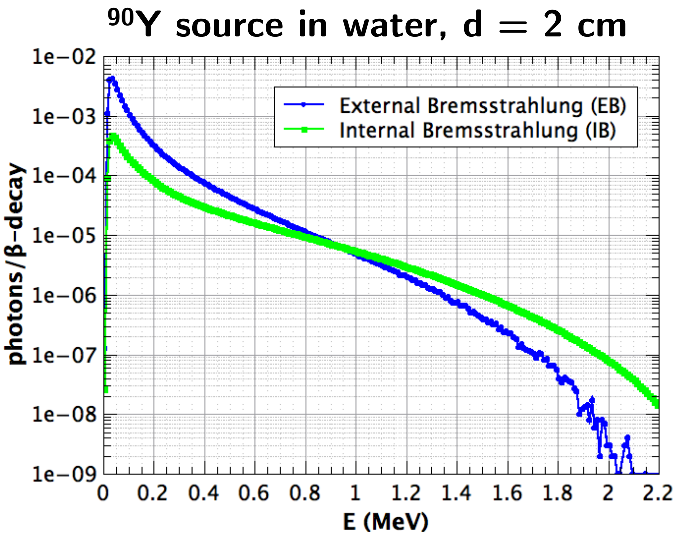
- ^{32}P

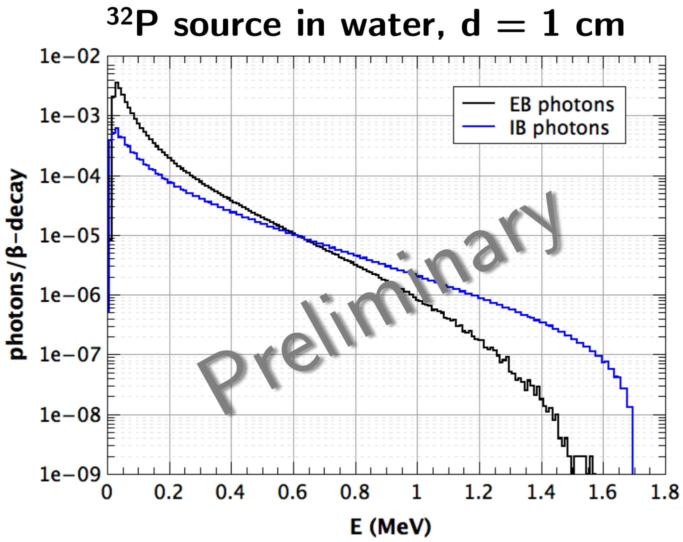


What happens beyond the average range of β particles?

- Within the average range of the β particles emitted by ^{90}Y and ^{32}P, the contribution of External Bremsstrahlung (EB) photons to the energy deposited is negligible; adding IB photons to the source term does not affect significantly this results
- However, for larger distances from the source, the energy deposition is mainly due to EB photons generated by the interaction of β particles with the surrounding medium
- When adding IB photons to the source in MC simulation, at those distances a further contribution comes from these photons

- We scored the energy spectra of EB and IB photons at distance *d* from the point source in GAMOS MC simulations
- The comparison highlights the competing contribution of EB and IB at distances larger than average β range





Conclusions

- **Internal Bremsstrahlung (IB)** is a process accompanying β-decay, usually neglected in MC simulations
- **Dose-Point-Kernels** (DPKs) are extensively used for the dosimetry of gamma and beta emitters, and currently are calculated neglecting IB
- A revision of ^{90}Y and ^{32}P DPKs, including IB spectrum in MC simulation, provides **results significantly affected by the additive IB source term**
- For distances from the source larger than the average range of β particles, the **revisited ^{90}Y DPK values are higher than the values currently used by 20-30%, while the ^{32}P DPK are higher by 30-40%**
- **The inclusion of IB process in MC simulation**, among the processes occurring during the decay of β-emitting nuclides, is **strongly advisable in order to obtain more realistic estimations**

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THANK YOU FOR YOUR ATTENTION!

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