# Internal Bremsstrahlung: a process to be considered for a realistic study of exposure to high-energy beta emitters


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## Aim of the study

Internal Bremsstrahlung (IB) is a process accompanying β-decay and resulting in the emission of photons with a continuous energy spectrum [1, 2].

IB is usually neglected when estimating absorbed dose from exposure to β emitters. However, for a set of high energy radionuclides IB emission intensity could significantly contribute to the total absorbed dose to the extremities of operators handling real sources [3].

In this study we made radiometric measurements using $^{90}Y$ and $^{32}P$ sources and compared them with Monte Carlo (MC) simulations in order to demonstrate the need to include IB emission in MC estimations.

Since IB spectrum can be modelled in different ways, the comparison provided indications on the most appropriate modelling of IB photon spectral distribution.

In β-decay, probability ≠ 0 that a photon is emitted together with the β particle and the neutrino/antineutrino.
Photons are characterized by a continuous energy spectrum and are generated by the interaction between the β particle and the emitting nucleus. The process is called ***Internal (or Inner) Bremsstrahlung, IB***.

In 1936, Knipp and Uhlenbeck [1], and, independently, Bloch [2] suggested a theory of IB (KUB theory) for allowed transitions, neglecting the Coulomb effects.

Probability, S(k), that a β particle emits a photon with energy between k and k+dk (allowed transitions):

$$S(k)\,\mathrm{d}k = \int_{1+w}^{W_0} N(W)\,\mathrm{d}W\,\Phi(W,k)\,\mathrm{d}k \qquad (1)$$

*β spectrum* ← $N(W)\,\mathrm{d}W$

Probability that a beta particle created at the nucleus with an energy W will emit a photon of energy k:

$$\Phi(W,w) = \frac{\alpha p'}{\pi p w}\left[\frac{W^2 + W'^2}{W p'}\ln(W + p') - 2\right] \qquad (2)$$

KUB theory was successively extended to forbidden transitions and modified in order to include Coulomb effects (Lewis and Ford 1957 [4], Felsner 1963 [5], Ford and Martin 1969 [6], etc).
Many experimental studies are available in literature but some discrepancies exist between results.

Walrand et al 2018 Phys. Med. Biol. 63 075016
"The origin and reduction of spurious extrahepatic counts observed in 90Y non-TOF PET imaging post radioembolization” [7]

*“ … This study investigates whether these two effects could be at the origin of two unexplained observations in $^{90}$Y imaging by PET: the increasing tails in the radial profile of true coincidences, and the presence of spurious extrahepatic counts post radioembolization in non-TOF PET and their absence in TOF PET. …*
*… Internal bremsstrahlung and long energy resolution tails inclusion in MC simulations quantitatively predict the increasing tails in the radial profile. In addition, internal bremsstrahlung explains the discrepancy previously observed in bremsstrahlung SPECT between the measure of the $^{90}$Y bremsstrahlung spectrum and its simulation with Gate-Geant4. …”*

**Something is missing in in MC simulation!**

Italiano et al, Phys. Med. 76:159-165

"Enhancement of radiation exposure risk from β-emitter radionuclides due to Internal Bremsstrahlung effect: A Monte Carlo study of $^{90}$Y case case" [3]

**Question: does the IB contribute to the absorbed dose to the extremities of a worker handling β emitting nuclides?**

$^{90}$Y source (end-point of β spectrum: 2.2 MeV)

MC simulations with GAMOS including IB photons for estimating: absorbed dose (skin and deep) in some irradiation scenarios (point source, plexiglass vial and glass vial).

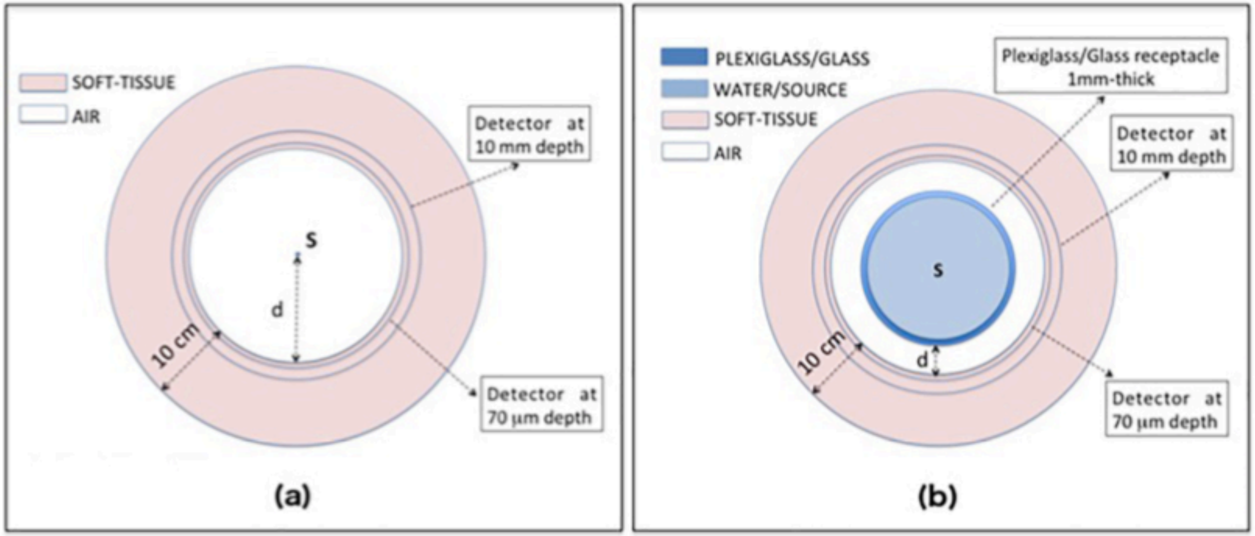



**Fig. 3.** Sketch of the adopted geometries: (a) Point-like source with d = 10, 30, 50, 100 cm and (b) cylindrical source (both plexiglass and Pyrex glass vials) with d = 0, 10, 30, 50, 100 cm.



How to include IB photons in MC calculations?

Experimental measurements of IB spectrum for $^{90}Y$ are available in literature <u>but some discrepancies exist</u>!

Two experimental data sets were selected.

The function proposed by Walrand et al (2018) [7]

$$B(E) = a\left(e^{-bE^{\beta}-cE^{\gamma}} - e^{-bE_{max}^{\beta}-cE_{max}^{\gamma}}\right) \quad (3)$$

(where $a$, $b$, $c$, $\beta$ and $\gamma$ are fit parameters while $E_{max}$ is the end-point energy of the β spectrum) was used to fit the experimental data sets.

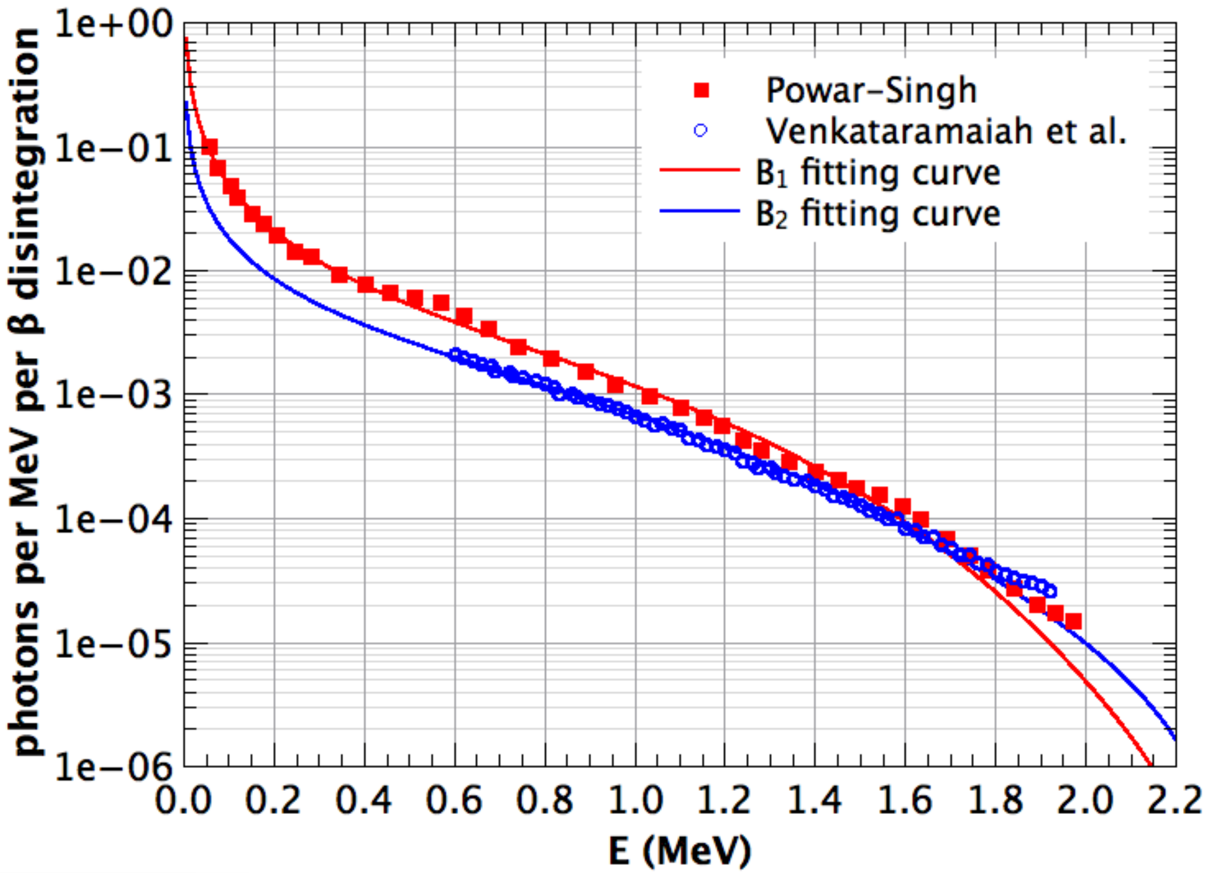
Two hypothesis for IB photon spectral distribution were obtained:

Powar and Singh (1975) [8] data + Felsner theory [5] → fitting function **B1**

Venkataramaiah (1980) [9] data + Ford and Martin theory [6] → fitting function **B2**

**Table 1.** Fit parameters for the functions $B_1$ and $B_2$.

| Fitting curve | a | b | $\beta$ | c | $\gamma$ | $\chi^2$ / doF |
|---|---|---|---|---|---|---|
| $B_1$ | 25.9 | 9.64E+00 ±6.45E-02 | 1.88E-01 ±3.06E-03 | 3.68E-01 ±1.02E-01 | 3.60E+00 ±6.21E-01 | 5.56E-05 |
| $B_2$ | 25.9 | 1.00E+01 ±2.12E-02 | 1.41E-01 ±7.05E-04 | 4.94E-01 ±3.03E-02 | 2.84E+00 ±1.30E-01 | 6.25E-06 |




B1 and B2 functions were used to generate histograms representing the IB energy spectrum.

Photons were generated in the source volume and the energy spectra, expressed as a constant-bin histogram, were set in a user-defined file read by GAMOS.

MC simulations were run without and with including IB photons.

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# RESULTS

Skin dose (@70 μm depth in soft tissue) – IB photon contribution < 1%

IB photon emission is neglectable when estimating skin dose!

**. . . BUT . . .**



# Deep dose (@10 mm depth in soft tissue) – relevant IB photon contribution

## IB is not neglectable when estimating deep dose!

Absorbed 'deep' dose values resulting from MC simulations. The distance, *d*, from the source is in *cm* while absorbed dose values are in *mSv/MBq-h*.

| $d$ | $D_{IB}^{B1}$ | $D_{IB}^{B2}$ | $D_{\beta+EB}$ | $D_{TOT}^{B1}$ | $D_{TOT}^{B2}$ | $\chi(\%) D_{TOT}^{B1} vs D_{\beta+EB}$ | $\chi(\%) D_{TOT}^{B2} vs D_{\beta+EB}$ |
|---|---|---|---|---|---|---|---|
| Point-like Source | | | | | | | |
| 10 | 5.34E-05 | 2.36E-05 | 5.28E-04 | 5.81E-04 | 5.52E-04 | 10.1 | 4.5 |
| 30 | 7.27E-06 | 3.27E-06 | 4.39E-05 | 5.12E-05 | 4.72E-05 | 16.6 | 7.4 |
| 50 | 2.77E-06 | 1.23E-06 | 1.25E-05 | 1.53E-05 | 1.37E-05 | 22.1 | 9.8 |
| 100 | 7.20E-07 | 3.20E-07 | 2.11E-06 | 2.83E-06 | 2.43E-06 | 34.1 | 15.2 |
| Cylindrical Vial (Plexiglass) | | | | | | | |
| 0 | 1.45E-03 | 6.66E-04 | 8.17E-01 | 8.19E-01 | 8.18E-01 | 0.2 | 0.1 |
| 10 | 4.94E-05 | 2.23E-05 | 1.02E-04 | 1.51E-04 | 1.24E-04 | 48.5 | 21.9 |
| 30 | 6.82E-06 | 3.07E-06 | 1.43E-05 | 2.12E-05 | 1.74E-05 | 47.6 | 21.4 |
| 50 | 2.60E-06 | 1.17E-06 | 5.15E-06 | 7.75E-06 | 6.32E-06 | 50.3 | 22.7 |
| 100 | 6.76E-07 | 3.05E-07 | 1.42E-06 | 2.10E-06 | 1.73E-06 | 47.5 | 21.4 |
| Cylindrical Vial (Pyrex Glass) | | | | | | | |
| 0 | 4.25E-04 | 2.05E-04 | 4.53E-02 | 4.57E-02 | 4.55E-02 | 0.9 | 0.5 |
| 10 | 4.38E-05 | 2.03E-05 | 7.27E-05 | 1.17E-04 | 9.30E-05 | 60.2 | 27.9 |
| 30 | 6.08E-06 | 2.81E-06 | 1.07E-05 | 1.68E-05 | 1.35E-05 | 56.9 | 26.3 |
| 50 | 2.32E-06 | 1.07E-06 | 4.71E-06 | 7.04E-06 | 5.78E-06 | 49.3 | 22.7 |
| 100 | 6.08E-07 | 2.80E-07 | 1.16E-06 | 1.76E-06 | 1.44E-06 | 52.6 | 24.3 |

Assuming B1 as IB photon spectral distribution, dose increments up to 60% are estimated

Assuming B2 as IB photon spectral distribution, dose increments up to 28% are estimated

**Open questions:**

**1. Which hypotesis is the correct one?**

**2. IB emission is really such a relevant process to be necessarily included in MC simulation?**

# Materials and Methods

*Experimental setup*

For each isotope, a standardized liquid solution provided by the *Institute of Radiation Physics* (IRA), Lausanne, was used to fill a vial with about 1 g of solution. The vials were accurately weighed before and after filling, therefore the mass of each vial was precisely determined, with an uncertainty of 1% or less; activities were consequently calculated from the certified activity concentration of the standardized solution.

Radiometric measurements were carried out using liquid, pure $^{90}$Y source contained in pyrex-glass vials, filled with about 1g of solution. Exposure was measured with the dose calibrator Veenstra model VDC-405, by Comecer.

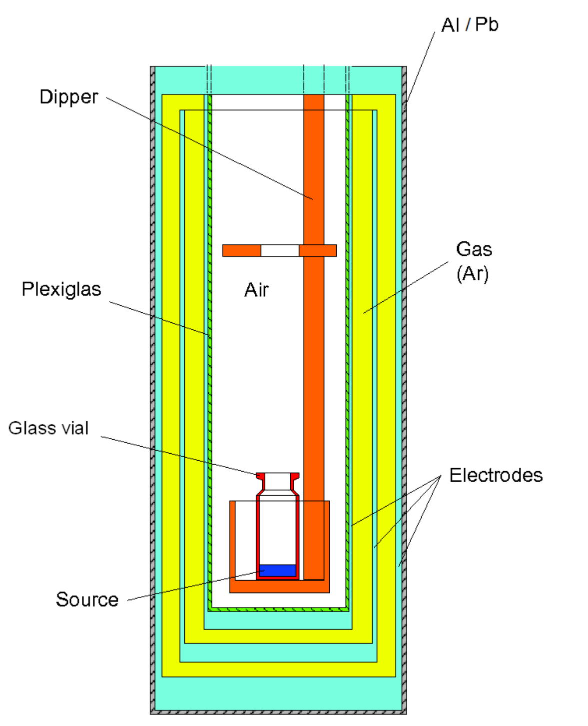



Figure 2. Schematic view of the Veenstra model VDC-405 dose calibrator.

$^{90}$Y is pure beta emitters; the beta spectrum end-point energy is 2.2 MeV. Aiming to enhance the evidence of IB contribution, experimental data were acquired in two configurations: without and with a plastic shield surrounding the vial.

*Monte Carlo simulation*

The experimental setup was carefully reproduced in GAMOS, a user-friendly interface of GEANT4.

No variance reduction techniques were used.

$10^8$ histories were run. Statistical uncertainties <1%.

MC simulation validation: measurements and simulations were carried out also for a set of gamma emitting radionuclides: $^{57}Co$, $^{133}Ba$, $^{137}Cs$ and $^{60}Co$.

MC simulations were carried out without and with IB emission.

To account for IB process, photons were generated in the source volume and the energy spectra, expressed as a constant-bin histogram, were set in a user-defined file read by GAMOS.

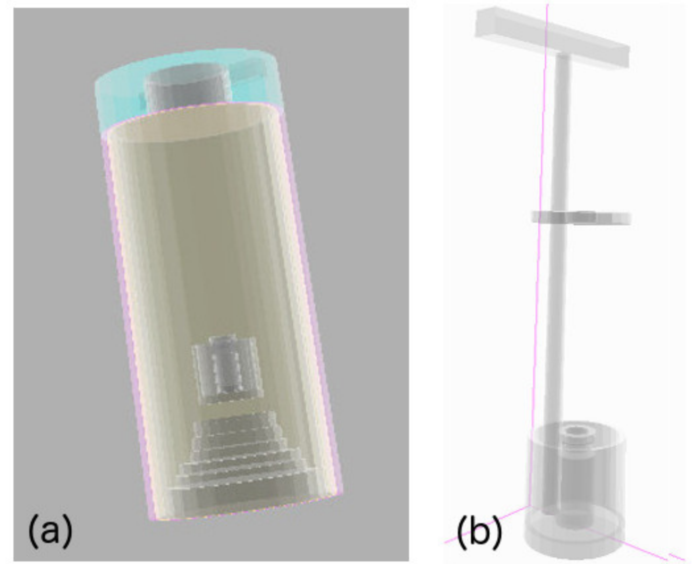



Figure 3**:** (a) 3D layout of the geometry reproduced in MC simulations; (b) detail of the vial holder inside the ionization chamber.

The IB energy spectra for $^{90}Y$ were modelled according to our previous studies [3].

# Results ($^{90}Y$)

A fair agreement (within 6%) was found between MC estimates and measurements for $^{57}Co$, $^{133}Ba$, $^{137}Cs$ and $^{60}Co$.

For $^{90}Y$, when ***neglecting IB emission in MC simulation***, theoretical calculations underestimate the electric current signal in VEENSTRA calibrator by up to -14%.

| Source | $I_{EXP}$ (pA/MBq) | $I_{MC}$ (pA/MBq) | ε (%) |
|---|---|---|---|
| $^{90}Y$ | 0.198 ± 0.001 | 0.174 ± 0.002 | -12.1 |
| $^{90}Y$ (24h) | 0.198 ± 0.001 | 0.174 ± 0.002 | -12.1 |
| $^{90}Y$ shielded | 0.192 ± 0.001 | 0.166 ± 0.002 | -13.5 |
| $^{90}Y$ shielded (24h) | 0.193 ± 0.001 | 0.166 ± 0.002 | -14.0 |

Conversely, by ***Including IB emission in MC simulation***, a good agreement is found when the function B2 is used to generate the IB photon spectral distribution.

| | $I_{EXP}$ (pA/MBq) | $I_{MC(B1)}$ (pA/MBq) | ε(B1) (%) | $I_{MC(B2)}$ (pA/MBq) | ε(B2) (%) |
|---|---|---|---|---|---|
| $^{90}Y$ | 0.198 ± 0.001 | 0.234 ± 0.002 | +18.2 | 0.198 ± 0.002 | 0.0 |
| $^{90}Y$ (24h) | 0.198 ± 0.001 | 0.234 ± 0.002 | +18.2 | 0.198 ± 0.002 | 0.0 |
| $^{90}Y$ with shielding | 0.192 ± 0.001 | 0.224 ± 0.002 | +16.7 | 0.189 ± 0.002 | -1.6 |
| $^{90}Y$ with shielding (24h) | 0.193 ± 0.001 | 0.224 ± 0.002 | +16.1 | 0.189 ± 0.002 | -2.1 |

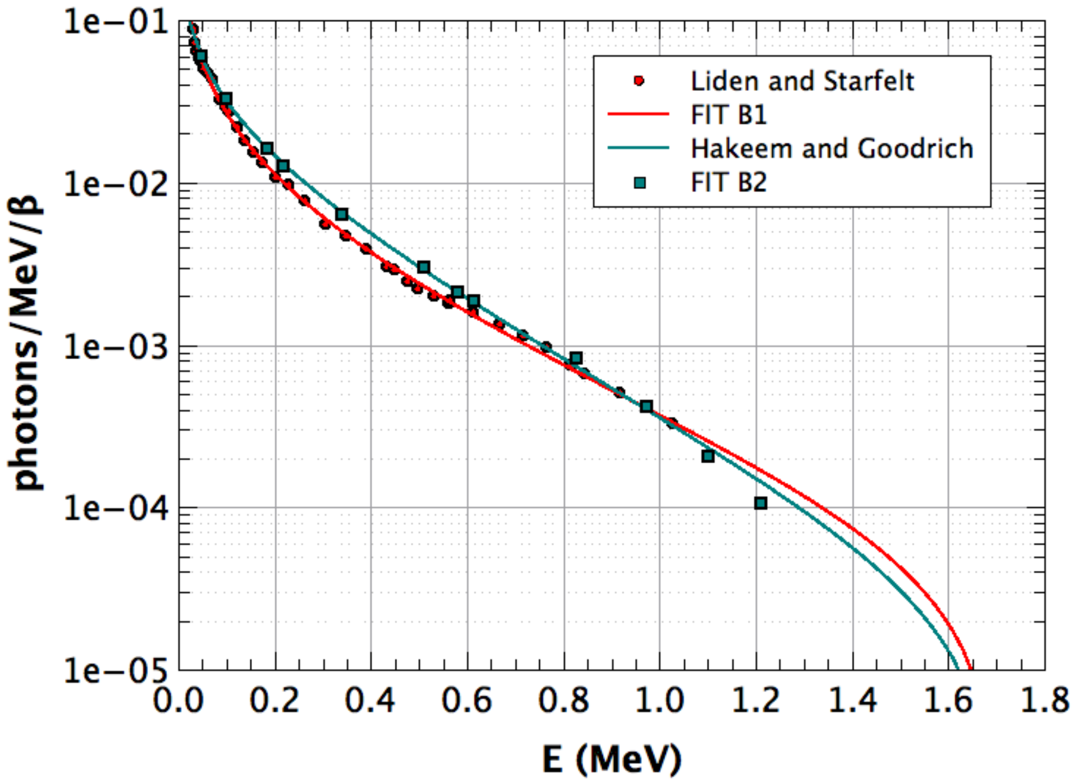
# What about $^{32}P$?

A similar study was carried out for $^{32}P$, a high-energy β emitter (end-point energy of about 1.7 MeV).

Also in this case, experimental data available in literature show discrepancies when comparing each other.

Two set of data [10, 11] were selected and fitted following the same procedure used for $^{90}Y$.

$^{32}P$ liquid sources were prepared and measured with the VEENSTRA activity calibrator.




Two configurations were consdiered: without and with a plexiglass shielding set around the vial containing the liquid source.

MC simulations were run without and with IB photons.

# Results ($^{32}P$)

***Neglecting IB photons in MC simulation*** a disagreement up to -16.5% is observed when comparing measurements with MC estimations.

| Source | $I_{EXP}$ (pA/MBq) | $I_{MC}$ (pA/MBq) | ε (%) |
|---|---|---|---|
| $^{32}P$ | 0.1256 ± 0.0005 | 0.1061 ± 0.001 | -15.5 |
| $^{32}P$ (shielded) | 0.1219 ± 0.0005 | 0.1018 ± 0.002 | -16.5 |

Conversely, ***taking into account IB photon emission in MC simulation***, a fair agreement is found.

| Source | $I_{EXP}$ (pA/MBq) | $I_{MC}$ (pA/MBq) with IB emission | ε (%) |
|---|---|---|---|
| $^{32}P$ | 0.1256 ± 0.0005 | 0.1306 ± 0.0011 | +4.0 |
| $^{32}P$ (shielded) | 0.1219 ± 0.0005 | 0.1256 ± 0.0010 | +3.0 |

**Results here presented were obtained using the experimental data from Liden & Starfelt.*
**Auditore L, Juget F, Pistone D, Nedjadi Y, Amato E, Italiano A. Internal Bremsstrahlung emission during $^{32}P$ decay. Submitted for publication.*

# Conclusions

This study indicates that:

1. IB emission should be considered when performing MC simulations for estimating the exposure to beta emitters such as $^{90}Y$ and $^{32}P$.

2. IB photon emission accompanying β-decay can induce a relevant contribution in radiation protection estimations. For $^{90}Y$, using the IB spectral distribution model here presented, we estimated an increase of the absorbed dose to the extremities of workers handling $^{90}Y$ sources up to about 28% [3].

3. The dose to extremities calculated for $^{32}P$ should be revised in the light of the results here presented.
    a. *Delacroix D, Guerre JP, Leblanc P, Hickman C. Radionuclide and radiation protection data handbook. Radiat Prot Dosim 2002;98:1–168.*
    b. *Amato E, Italiano A, Auditore L, Baldari S. Radiation protection from external exposure to radionuclides: A Monte Carlo data handbook. Phys Med 2018;46:160-7.*

4. The extension of theoretical and experimental studies to other β decaying radionuclides is in our opinion, worth of consideration.

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# Thank you for your attention!