

Technical note 2: gamma conversion process

Zhuxin LI, Claire MICHELET, Sébastien INCERTI

CENBG, February 10, 2020

Introduction

This technical note explains the implementation of EPICS2017 database for gamma conversion process, which includes the following parts:

- description of Livermore cross section data format implemented in Geant4 (version 10.6, before march 30th, 2020) for gamma conversion process (section 1)
- format of original EPICS2017 data for gamma conversion process (sections 2 and 3)
- description of EPICS2017 cross section data format implemented in Geant4 10.7 and later for gamma conversion process (section 4)
- cross section data difference between EPICS2017 and Livermore (section 5)
- implemented model classes using EPICS2017 database (section 6)

1. Livermore model for gamma conversion

1.1. G4LivermoreGammaConversionModel model class

For the gamma conversion process in Geant4, the **G4LivermoreGammaConversionModel** class performs the following tasks:

- read the tabulated cross section data from Geant4 data library
- compute the interpolated cross section for the energy value of the incident gamma
- generate the final state (electron + positron).

At this stage, gamma conversion into e-e+ pair is considered according to two processes: pair production (“pure pair”) and triplet production. The gamma energy threshold is 1.022 MeV for pair production and 2.044 MeV for triplet production. The corresponding cross section is zero below this threshold, that’s to say respectively for $E \leq 1.022$ MeV for pair production and $E \leq 2.044$ MeV for triplet production. The maximum energy available in the tabulated values is 100 GeV.

The way these two processes are included in this class is *via* the cross section data file: **the tabulated total cross section is actually the sum of the cross section data for pair production and triplet production.**

1.2. Location of cross section data files

For the previous version (version 10.6, before march 30th, 2020), the Livermore total cross section (pair + triplet) data files that the class reads are contained in the directory:

\$G4LEDATA/livermore/pair

Cross section data files for pair production are saved in the directory:

\$G4LEDATA/livermore/pairdata

Cross section data files for triplet production are saved in the directory:

\$G4LEDATA/livermore/tripdata

1.3. Format

Total cross section, pair production and triplet production cross section data files have the same format. They are composed of **two header lines** and **a series of cross section data (energy-cross section data lines)**.

The file name is:

- For pair production: ***pp-pair-cs-Z.dat*** (“pp” is for “pair production”)
- For triplet production: ***pp-trip-cs-Z.dat***
- For total gamma conversion: ***pp-cs-Z.dat***

where Z is the atomic number of the element.

Fig. 1 presents an example of a part of total cross section data file *pp-cs-1.dat* for Hydrogen.

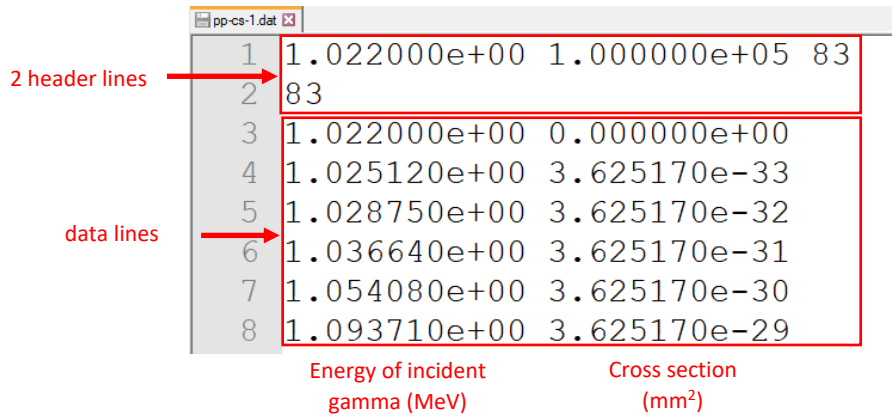


Fig. 1. Example of the beginning of the data file for Hydrogen for Livermore

1.3.1. Information in the header lines

The 3 figures (Fig. 1) in the first header line indicate the lowest and highest energy values in the table (in **MeV**), and the number of energy-cross section points.

For pair production and total cross section files: the lowest and highest energy values are always 1.022000e+00 and 1.000000e+05 MeV.

For triplet production cross section files: the lowest and highest energy values are always 2.044000e+00 and 1.000000e+05 MeV.

The figure in the second header line repeats the number of energy-cross section points.

1.3.2. Information in the data lines

As illustrated in Fig. 1, the first column contains the energy values in **MeV**, with **7 significant digits** (which is different from EPICS2017 Data, namely **EPDL2017.ALL**, with **10 significant digits**), from the lowest to highest energy value given in the first header line. The second column contains the corresponding cross section data in **mm²** with **7 significant digits**.

1.4. Interpolation method to obtain total cross section data files

As mentioned above, total cross section data files come from the sum of the cross section data of pair production and triplet production. The total cross section data have **the same energy bins as pair production**. However, since the energy intervals and the lowest energy value are different in pair production data and triplet data, some energy points are missing in the triplet data.

Thus, for the energy points **existing both in pair production data and in triplet production data**, we use the following formula:

$$\sigma_{total} = \sigma_{pair} + \sigma_{triplet} \tag{1.1}$$

For the energy points that **do not exist in triplet data**, linear interpolation [1] was made on triplet data to get the same energy point as in pair production.

$$\sigma_{total} = \sigma_{pair} + \sigma_{interpolated\ triplet} \tag{1.2}$$

2. Format of pair production data in EPICS2017

In *EPDL2017.ALL*, as introduced in Technical note 1, we can simply locate the data lines relevant to the pure nuclear gamma conversion process, by choosing **74** for the reaction descriptor in the second header line (Fig. 2, line 2). In fact, three types of data relevant to pure nuclear gamma conversion (“pure pair”) process are given for each element:

- 1) the cross section (Fig. 2);
- 2) the average energy of the secondary positron (Fig. 3);
- 3) the average energy of the secondary electron (Fig. 4).

Fig. 2-4 present an example of the **data** tables relevant to the pair production process for Hydrogen. Some of the parameters in the header lines are identical in these three tables (see Technical note 1):

The first header line specifies: Z = 1, A = 000, Yi = 7 (incident particle = photon) (Fig. 2, in red).

The second header line specifies: C =74 (reaction descriptor: pair production) (Fig. 2, in red).

We are only interested here in the cross section data (and not in the energy of electron and positron) for the purpose of updating the Geant4 database. Nevertheless, we will still present all the available information.

2.1. Pair production cross section

Fig. 2 presents an example of a part of **cross section data table relevant to the pair production** process for Hydrogen.

In this example (Fig. 2, in blue):

- In the first header line: Yo = 0, means that no information is given about the secondary particles.
- In the second header line: I = 0, means that the data lines below are the cross section data

2 header lines →	1000	7	0	1.00797	1807172	2	0.0	0.0	0.0
	74	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
data lines →	1.022000000E+00	0.000000000E+00							
	1.025120000E+00	3.625200000E-11							
	1.025233250E+00	3.895700000E-11							
	1.025342980E+00	4.176900000E-11							

Energy of incident gamma (MeV) Cross section (barn)

Fig. 2. Example of cross section data table relevant to the pair production process for Hydrogen in EPDL2017.ALL

2.2. Average energy of the secondary positron

Fig. 3 presents an example of **average energy of the secondary positron** for Hydrogen.

In this example (Fig. 3, in blue):

- In the first header line: Yo = 8, means that secondary particles are positrons.
- In the second header line: I = 10, means that the data lines indicate the average energy of secondary particles, namely positrons in this case.

1000	7	8	1.00797	1807172	2	0.0	0.0	0.0
74	10	0	0.0	0.0	0.0	0.0	0.0	0.0
			1.022000000E+00	0.000000000E+00				
			1.000000000E+05	4.999949000E+04				

Energy of incident gamma (MeV) Energy of secondary positron (MeV)

Fig. 3. Example of average energy table of the secondary positron for Hydrogen in EPDL2017.ALL

2.3. Average energy of the secondary electron

Fig. 4 presents an example of average energy of the secondary electron for Hydrogen.

In this example,

- In the first header line: $Y_0 = 9$, means that secondary particles are electrons.
- $I = 10$, means that the data lines indicate the average energy of secondary particles, namely electrons in this case.

1000	7	9	1.00797	1807172	2	0.0	0.0	0.0
74	10	0	0.0	0.0	0.0	0.0	0.0	0.0
			1.022000000E+00	0.000000000E+00				
			1.000000000E+05	4.999949000E+04				

Energy of incident gamma (MeV) Energy of secondary electron (MeV)

Fig. 4. Example of average energy of the secondary electron for Hydrogen in file EPDL2017.ALL

2.4. Units

Energy used in EPDL2017.ALL is in MeV.

Cross section is in barns.

3. Format of triplet production data in EPICS2017

In EPDL2017.ALL, as introduced in Technical note 1, we can simply locate the data lines relevant to the triplet production, by choosing 75 for the reaction descriptor in the second header line (Fig. 5, line 2). In fact, three types of data relevant to the triplet production process are given for each element:

- 1) the cross section (Fig. 5);
- 2) the average energy of the secondary positron (Fig. 6);
- 3) the average energy of the secondary electron (Fig. 7).

Fig. 5-7 present an example of the data tables relevant to the triplet production process for Hydrogen. Some of the parameters in the header lines are identical in these three tables (see Technical note 1):

The first header line specifies: $Z = 1$, $A = 000$, $Y_i = 7$ (incident particle = photon) (Fig. 5, in red).

The second header line specifies: $C = 75$ (reaction descriptor: triplet production) (Fig. 5, in red).

We are only interested here in the cross section data for triplet production, for the purpose of updating the new Geant4 database. Nevertheless, we will present all the available information.

3.1. Triplet production cross section

Fig. 5 presents an example of a part of **cross section data table relevant to the triplet production** process for Hydrogen.

In this example (Fig. 5, in blue):

- In the first header line: $Y_0 = 0$, means that no information is given about the secondary particles.
- In the second header line: $I = 0$, means that the data lines indicate the cross section

2 header lines →	1000	7	0	1.00797	1807172	2	0.0	0.0	0.0
	75	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
data lines →	2.044000000E+00 0.000000000E+00 2.085810000E+00 1.004230000E-08 2.087368080E+00 1.079150000E-08								
	Energy of incident gamma (MeV)				Cross section (barn)				

Fig. 5. Example of cross section data table relevant to the triplet production process for Hydrogen in EPDL2017.ALL

3.2. Average energy of the secondary positron

Fig. 6 presents an example of **average energy of the secondary positron** for Hydrogen.

In this example (Fig. 6, in blue):

- In the first header line: $Y_0 = 8$, means secondary particles are positrons.
- In the second header line: $I = 10$, means that the data lines indicate the average energy of secondary particles, namely positrons in this case.

2 header lines →	1000	7	8	1.00797	1807172	2	0.0	0.0	0.0
	75	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
data lines →	2.044000000E+00 5.110000000E-01 1.000000000E+05 4.999949000E+04								
	Energy of incident gamma (MeV)				Energy of secondary positron (MeV)				

Fig. 6. Example of average energy table of the secondary positron for Hydrogen in EPDL2017.ALL

3.3. Average energy of the secondary electron

Fig. 7 presents an example of **average energy of the secondary electron** for Hydrogen.

In this example (Fig. 7, in blue):

- In the first header line: $Y_0 = 9$, means secondary particles are electrons.
- $I = 10$, means that the data lines indicate the average energy of secondary particles, namely electrons in this case.

2 header lines →	1000	7	9	1.00797	1807172	2	0.0	0.0	0.0
data lines →	75	10	0	0.0	0.0	0.0	0.0	0.0	0.0
	2.044000000E+00	5.110000000E-01							
	1.000000000E+05	4.999949000E+04							1

Energy of incident gamma (MeV) Energy of secondary electron (MeV)

Fig. 7. Example of average energy of the secondary electron for Hydrogen in file EPDL2017.ALL

3.4. Units

Energy is in **MeV**.

Cross section is in **barns**.

4. Implementation of total cross section

4.1. generate_pp_cs.c macro

generate_pp_cs.c is a ROOT macro, which is used to generate the total cross section data files from *EPDL2017.ALL* for elements (Z:1-100), these files have been included in the *\$G4LEDATA/epics2017* Geant4 data library (*version 10.6, modification on march 30th, 2020, emlowen-V10-06-00*). It is composed of 2 functions: *extract_pair_trip_cs()* and *create_pp_cs()*.

4.1.1. extract_pair_trip_cs() function

This function extracts respectively the cross section data of *pair production* and *triplet production* for 100 elements from *EPDL2017.All*.

As explained in section 2, pair production cross section data are defined by the header line:

```
74 0 0 0.0 0.0 0.0 0.0 0.0
```

Similarly, triplet production data are defined by the header line:

```
75 0 0 0.0 0.0 0.0 0.0 0.0
```

This function produces respectively 100 cross section data files (one file for one element), saved in two different directories called:

- For pair production: *epics2017/pairdata*
- For triplet production: *epics2017/tripdata*

The file names are:

- For pair production: *pp-pair-cs-Z.dat*
- For triplet production: *pp-trip-cs-Z.dat*

where Z is the atomic number of the element.

The units for energy and cross section in the generated data files are in **MeV** and in **mm²**.

4.1.2. create_pp_cs() function

The *create_pp_cs()* function generates two types of data on the basis of generated data for pair production and triplet production explained above:

- total cross section data, written in the files: *epics2017/pair/pp-cs-Z.dat*

- interpolated triplet productio data, written in the files: *epics2017/triplInterp/pp-triplInterp-cs-Z.dat*

where Z is the atomic number of the element.

To sum up, the *pair* directory contains the total cross section data files, obtained on the basis of the generated data files for pair production (in *pairedata*) and triplet production (in *tripdata*) explained above by using the interpolation method in section 1.4.

Using this interpolation method, intermediate files are created (in *triplInterp*) to effectively keep the interpolated triplet data points, and use them to produce the total cross section data file. The interpolated triplet data files are used to obtain the plots in the following section 5.4.

Besides, the *create_pp_cs()* function also generates an output file *out.txt*. For each element it keeps three values:

- the number of energy-cross section points for pair production (*pairedata/pp-pair-cs-Z.dat* files), in the energy interval $1.022 - 10^5$ MeV
- the number of energy-cross section points for triplet production after interpolation (*triplInterp/pp-triplInterp-cs-Z.dat* files), in the energy interval $2.044 - 10^5$ MeV
- the number of points in triplet data for which an interpolation calculation was actually required.

4.1.3. Command

To use the *generate_pp_cs.c* macro, firstly you should place this macro and the *EPDL2017.ALL* file in the same directory. Then, type the following command in the Terminal:

```
root generate_pp_cs.c
```

Note that this macro might also be used to regenerate Livermore data files if it reads EPDL2014.DAT.

4.2. Format

The format of the implemented total cross section data files obtained from *EPDL2017.ALL* follows the format of Geant4 Livermore data files contained in the directory *\$G4LEDATA/epics2017/pair*.

It is composed of **2 header lines** followed by **a series of physical data lines** with 2 columns (energy in **MeV** and cross section in **mm²**). The cross section, originally given in **barns** in *EPDL2017.ALL*, is converted to **mm²**, which is the default unit for pair production process in Geant4. A major difference compared to Livermore data is the number of significant digits. **We kept 10 significant digits for physical data lines** (whereas there are only 7 significant digits for Livermore). (*However, we noticed that not all the significant digits are actually used for pair production and triplet cross section data in EPDL2017.ALL*).

The format of the total cross section data files is illustrated in Fig. 8.

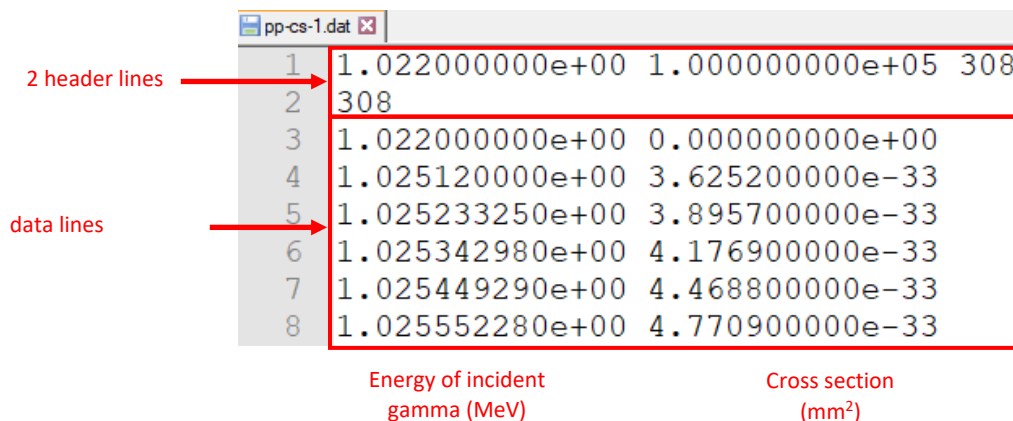


Fig. 8. Example of a part of total cross section data file for Hydrogen for EPICS2017

4.2.1. Information in the header lines

Just as the data files of Livermore, the three figures in the first header line indicate the lowest and highest energy values in the table (in **MeV**), and the number of data points. The figure in the second header line repeats the number of data points, it is **the same as the number of points in pair production data file**.

4.2.2. Information in the data lines

As illustrated in Fig. 8, the first column contains the energy values of the incident gamma in **MeV** with **10 significant digits**, from the lowest to highest energy value given in the first header line. The second column contains the corresponding cross section data in **mm²** with **10 significant digits**.

5. Comparison of cross section data

Before implementing the new database in Geant4, we have compared pair production triplet production and total cross section data between EPICS2017 and Livermore using different ROOT macros.

5.1. Pair production

5.1.1. plot_pair.c macro

The *plot_pair.c* ROOT macro plots the following figures for pair production cross section data. There is one figure per element.

- cross section data of EPICS2017 (Z: 1-100) (example in Fig. 9, for Hydrogen)
- cross section data of Livermore (Z: 1-100) (example in Fig. 10, for Hydrogen)
- comparison of cross section data between EPICS2017 and Livermore (example in Fig. 11, for Hydrogen)

The generated figures are saved in the corresponding directories:

- *plots/pair/epics2017*
- *plots/pair/livermore*
- *plots/pair/comparison*

To use the *plot_pair.c* macro, you should put it in the same directory as the *epics2017* and *livermore* are, so that it can read the files contained in their *pairedata* sub-directory (see section 4.1). The *plots/pair* directories above are automatically generated when the macro runs, by the command:

```
root plot_pair.c
```

The figure presenting the comparison of pair production cross section data between EPICS2017 and Livermore is composed of three graphs:

1. Comparison of pair production cross section between EPICS2017 and Livermore
2. Relative difference (%) of cross section for EPICS2017 compared to Livermore:

$$RD = \frac{CS_{EPICS2017} - CS_{Livermore}}{CS_{Livermore}} \times 100\%$$

where $CS_{EPICS2017}$ and $CS_{Livermore}$ are the cross section of a given energy for EPICS2017 and Livermore

3. A zoom of the relative difference focused on the low energy region. The energy interval for the plot is chosen according to the points where the relative difference is not equal to 0. If the difference is 0 for all points, then the energy interval is set 1-3 MeV by default.

The figures below (Fig. 9-11) display examples for Hydrogen.

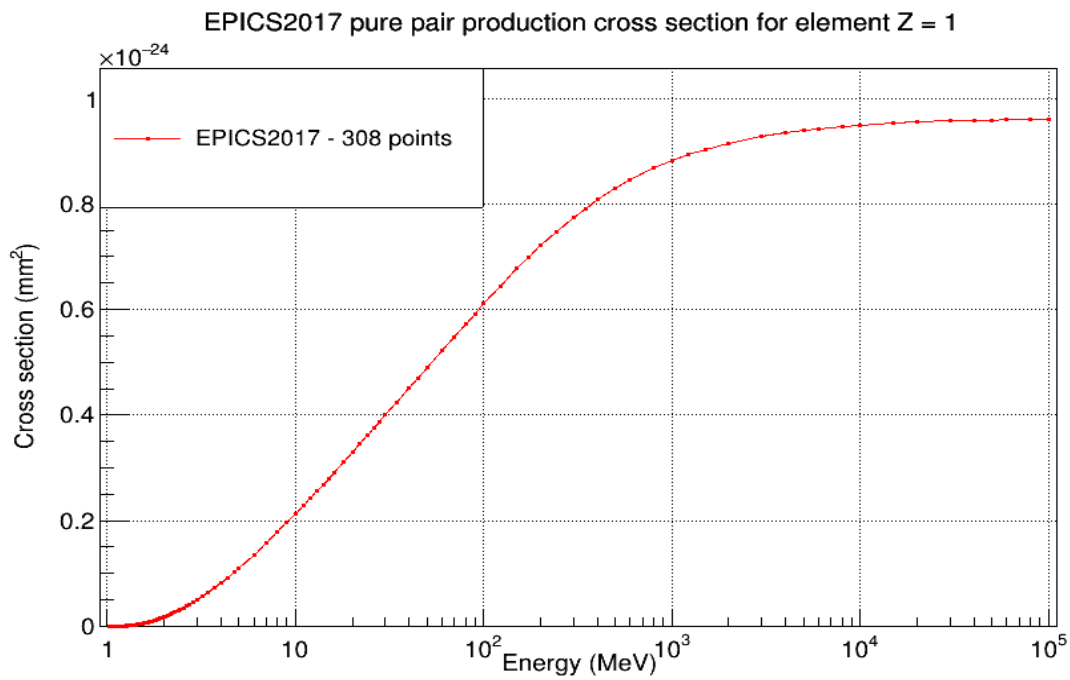


Fig. 9. An example of cross section data for pair production (“pure pair”) for EPICS2017 for Hydrogen

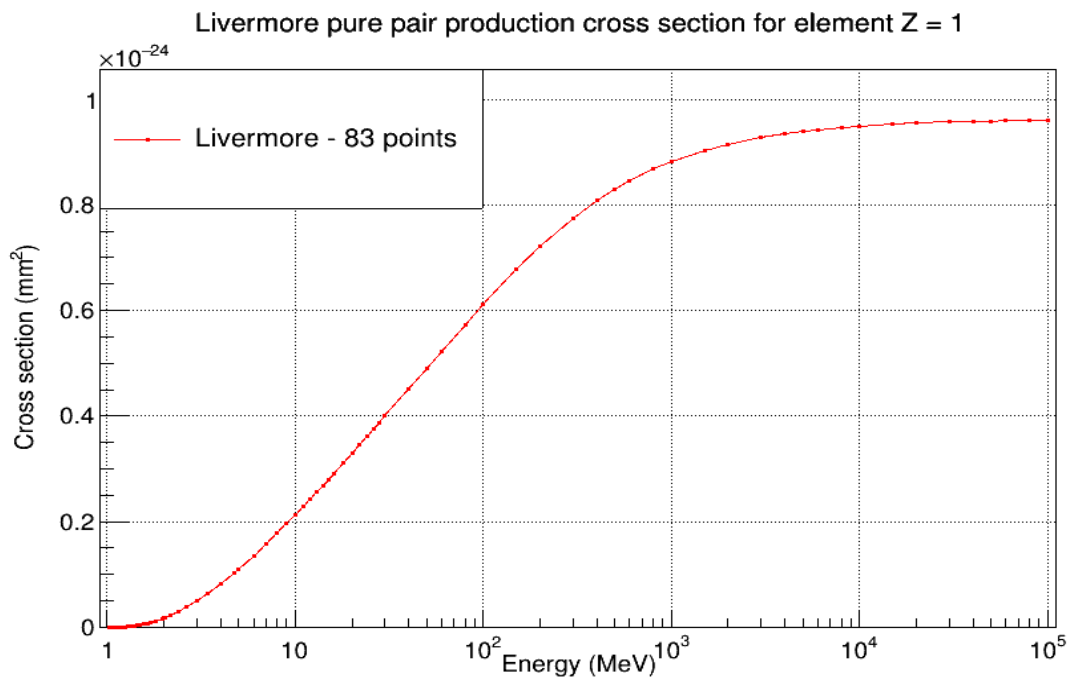


Fig. 10. An example of cross section data for pair production (“pure pair”) for Livermore for Hydrogen

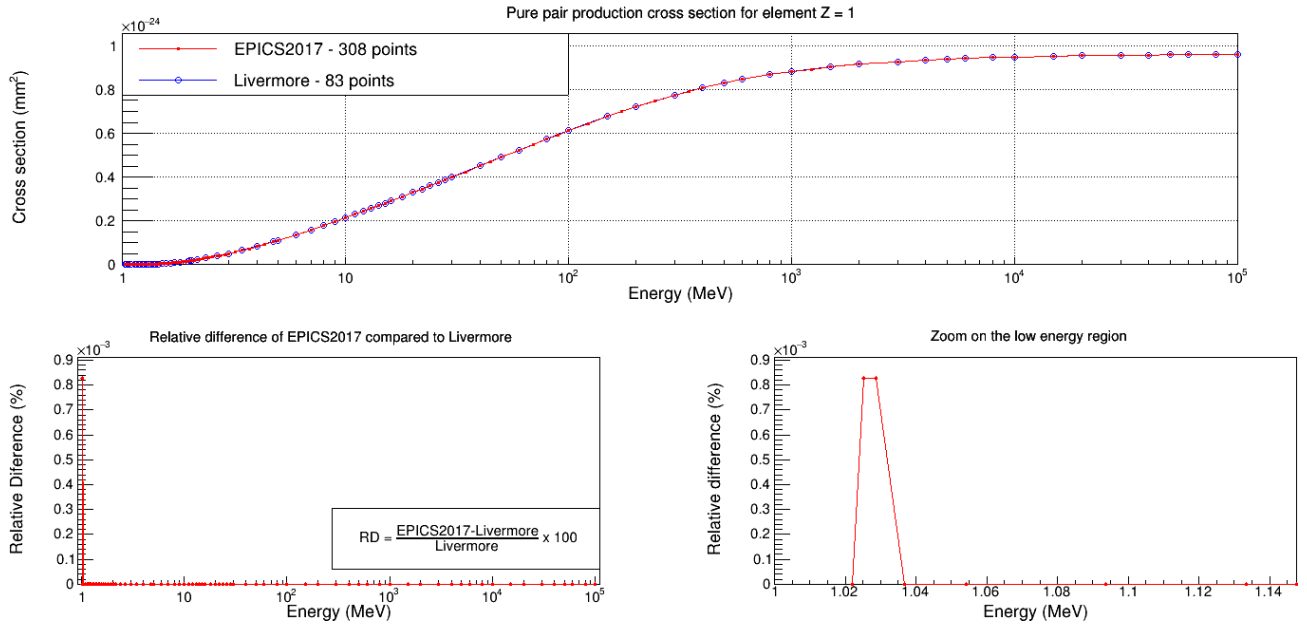


Fig. 11. An example of comparison of cross section data for pair production (“pure pair”) between EPICS2017 and Livermore for Hydrogen

5.1.2. Discussion

1. Number of points

For each element, EPICS2017 contains more energy-cross section points than Livermore does. For example, Hydrogen has 308 points for EPICS2017 (Fig. 9) while only 83 for Livermore (Fig. 10). Besides, all the points of Livermore are included in EPICS2017, so that we can compare the 83 points with the same energy (Fig. 11, bottom left graph).

2. Rounding errors

From the relative comparison graphs (for instance, Fig. 11, bottom graph), we observe that some points display differences between the two databases. These differences are actually negligible (relative difference < 10⁻⁵). They come from the way of rounding of the cross section values. For instance, for Hydrogen, two different points are perceived (as shown Fig. 11 bottom right). This small difference is only due to different rounding (and different number of significant digits) between EPICS2017 and Livermore (Table 1).

Table 1: An example of difference of pair production cross section values between EPIC2017 and Livermore for Hydrogen (for the two different points shown in Fig. 11, bottom graphs)

Energy (MeV)	Cross section of EPICS2017 (mm ²)	Cross section of Livermore (mm ²)
1.02512	3.625200000e-33	3.625170e-33
1.02875	3.625200000e-32	3.625170e-32

5.2. Triplet production

5.2.1. plot_trip.c macro

The *plot_trip.c* ROOT macro plots the figures of triplet production cross section data. There is one figure per element.

- cross section data of EPICS2017 (Z: 1-100) (example in Fig. 12, for Gadolinium)

- cross section data of Livermore (Z: 1-99) (example in Fig. 13, for Gadolinium)
- comparison of cross section data between Livermore and EPICS2017 (Z: 1-99) (example in Fig. 14, for Gadolinium)

The generated figures are saved in the corresponding directories:

- **plots/trip/epics2017**
- **plots/trip/livermore**
- **plots/trip/comparison**

To use the **plot_trip.c** macro, you should put it in the same location as the **epics2017** and **livermore** are, so that it can read the files contained in their **tripdata** sub-directory (see section 4.1). The **plots/trip** directories above are automatically generated when the macro runs, by the command:

```
root plot_trip.c
```

The figure presenting the comparison of triplet production cross section data between EPICS2017 and Livermore is composed of three graphs:

1. Comparison of triplet production cross section between EPICS2017 and Livermore
2. Relative difference (%) of triplet cross section for EPICS2017 compared to Livermore:

$$RD = \frac{CS_{EPICS2017} - CS_{Livermore}}{CS_{Livermore}} \times 100\%$$

where $CS_{EPICS2017}$ and $CS_{Livermore}$ are the cross section of a given energy for EPICS2017 and Livermore

3. A zoom of the relative difference focused on the low energy region. The energy interval for the plot is chosen according to the points where the relative difference is not equal to 0. If the difference is 0 for all points, then the energy interval is set 1-3 MeV by default.

The figures below (Fig. 12-14) display examples for Gadolinium (Z=64).

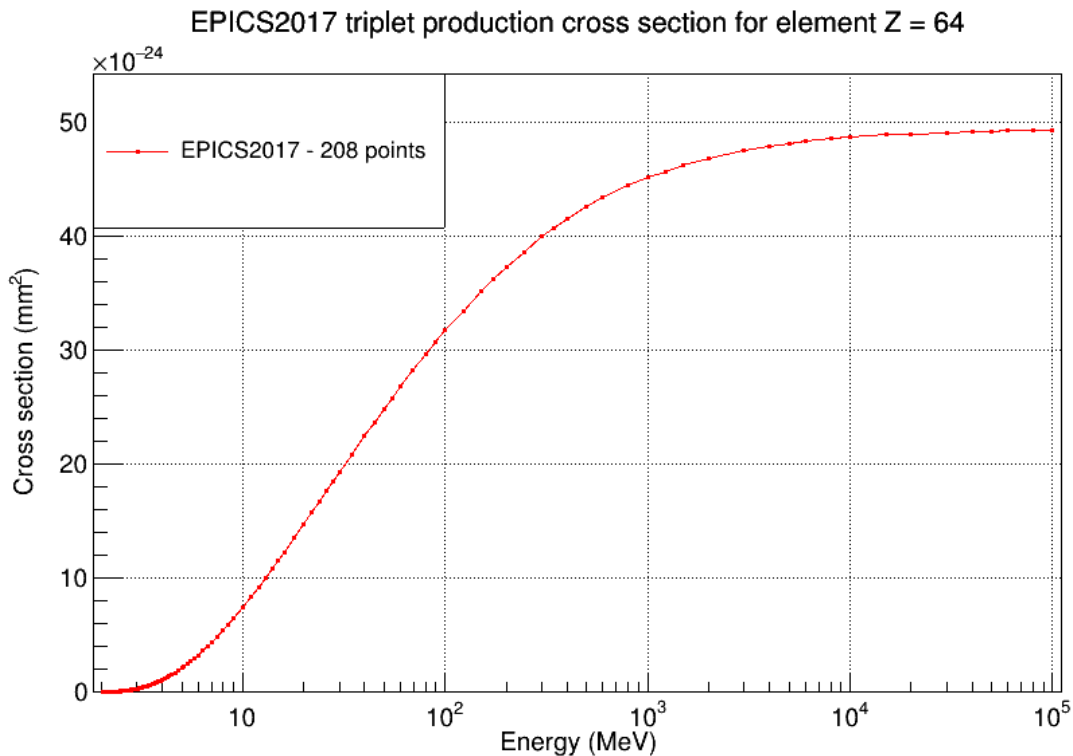


Fig. 12. An example of cross section data for triplet production for EPICS2017 for Gadolinium

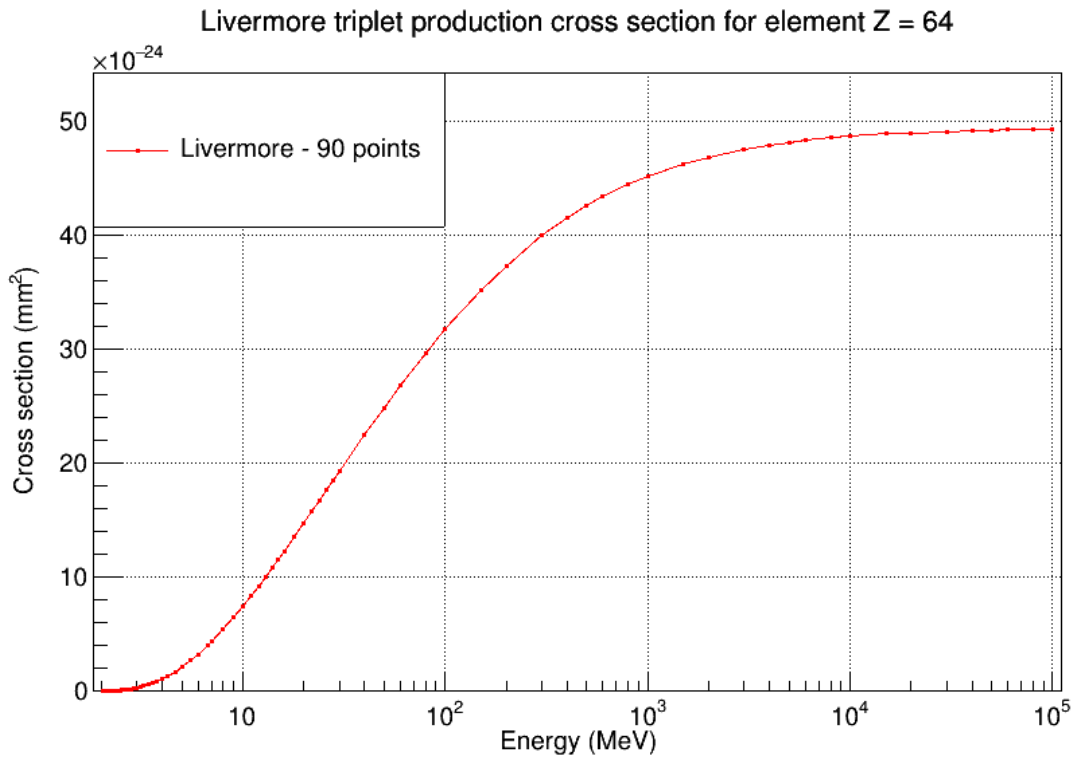


Fig. 13. An example of cross section data for triplet production for Livermore for Gadolinium

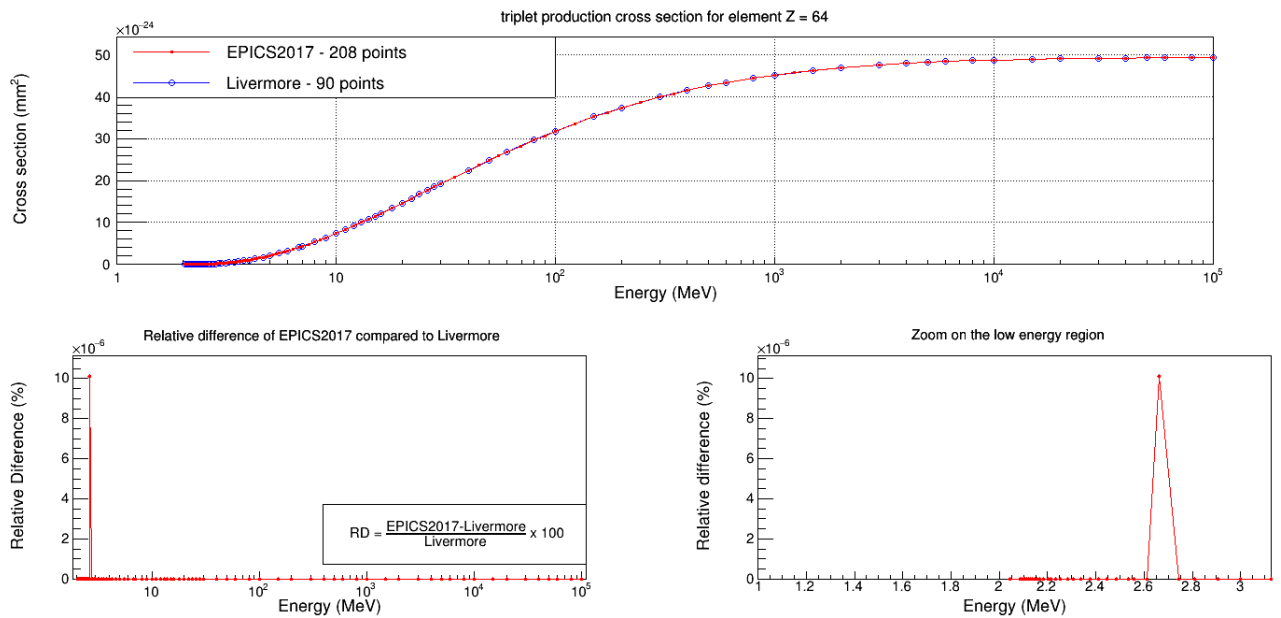


Fig. 14. An example of comparison of cross section data for triplet production between EPICS2017 and Livermore for Gadolinium

5.2.2. Discussion

1. Number of points

As already mentioned for pair production, for each element, EPICS2017 contains more energy-cross section points than Livermore. For example, Gadolinium has 208 points for EPICS2017 (Fig. 12) while

only 90 for Livermore (Fig. 13). Besides, all the points of Livermore are included in EPICS2017, so that we can compare the 90 points with the same energy (Fig. 14, bottom left graph).

2. Rounding errors

For all elements except Gadolinium, no difference was found for triplet production data between the two models. The difference occurring for Gadolinium is very small (relative difference $<10^{-6}$) and comes from the rounding errors as well (one different point, as shown in Fig. 14 bottom and in Table 2).

Table 2. Cross section of two databases for Gadolinium (for the point different in Livermore and in EPICS2017)

Energy (MeV)	Cross section of EPICS2017 (mm ²)	Cross section of Livermore (mm ²)
2.6604	9.886900000e-26	9.886899e-26

5.3. Total cross section

5.3.1. plot_total.c macro

The *plot_total.c* ROOT macro plots the figures of gamma conversion cross section data. There is one figure per element.

- cross section data of EPICS2017 (Z: 1-100) (example in Fig. 15, for Hydrogen)
- cross section data of Livermore (Z: 1-99) (example in Fig. 16, for Hydrogen)
- comparison of cross section data between Livermore and EPICS2017 (Z: 1-99) (example in Fig. 17, for Hydrogen)

The generated figures are saved in the corresponding directories:

- *plots/total/epics2017*
- *plots/total/Livermore*
- *plots/total/comparison*

To use the *plot_total.c* macro, you should put it in the same directory as the *epics2017* and *livermore* are, so that it can read the files contained in their *pair* sub-directory (see section 4.1). The *plots/total* directories above are automatically generated when the macro runs, by the command:

```
root plot_total.c
```

The figure presenting the comparison of gamma conversion cross section data between EPICS2017 and Livermore is composed of three graphs:

1. Comparison of gamma conversion cross section between EPICS2017 and Livermore
2. Relative difference (%) of gamma conversion cross section for EPICS2017 compared to Livermore

$$RD = \frac{CS_{EPICS2017} - CS_{Livermore}}{CS_{Livermore}} \times 100\%$$

where $CS_{EPICS2017}$ and $CS_{Livermore}$ are the cross section of a given energy for EPICS2017 and Livermore

3. A zoom of the relative difference focused on the low energy region. The energy interval for the plot is chosen according to the points where the relative difference is not equal to 0. If the difference is 0 for all points, then the energy interval is set 1-3 MeV by default.

The figures below (Fig. 15-17) display examples for Hydrogen.

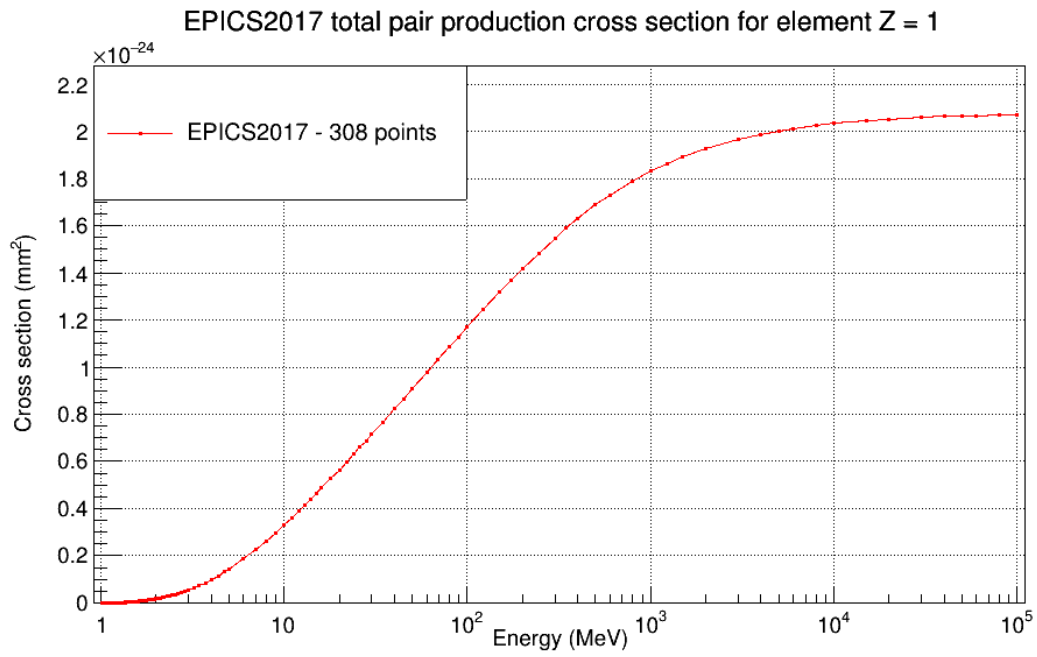


Fig. 15. An example of cross section data for gamma conversion for EPICS2017 for Hydrogen

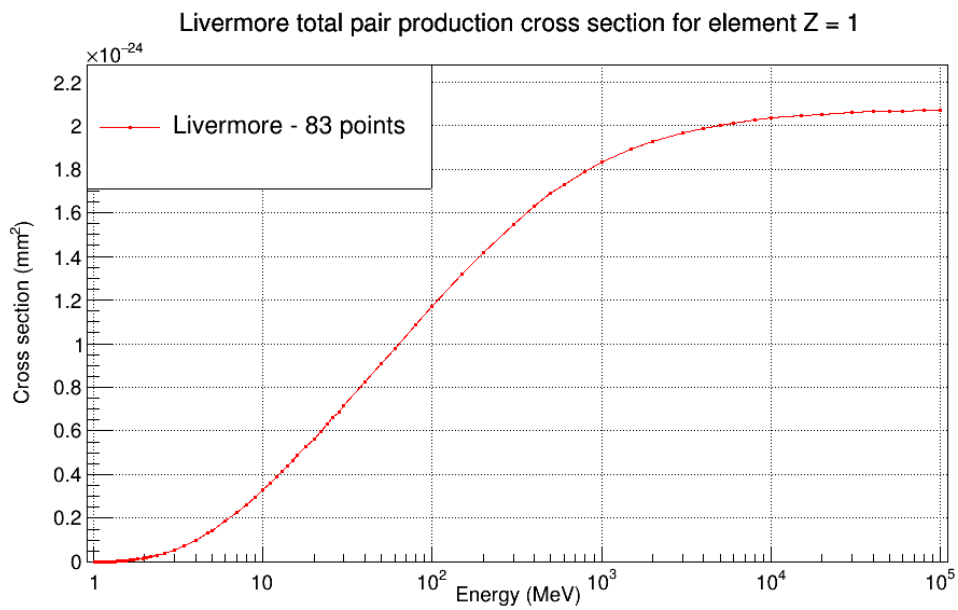


Fig. 16. An example of cross section data for gamma conversion for Livermore for Hydrogen

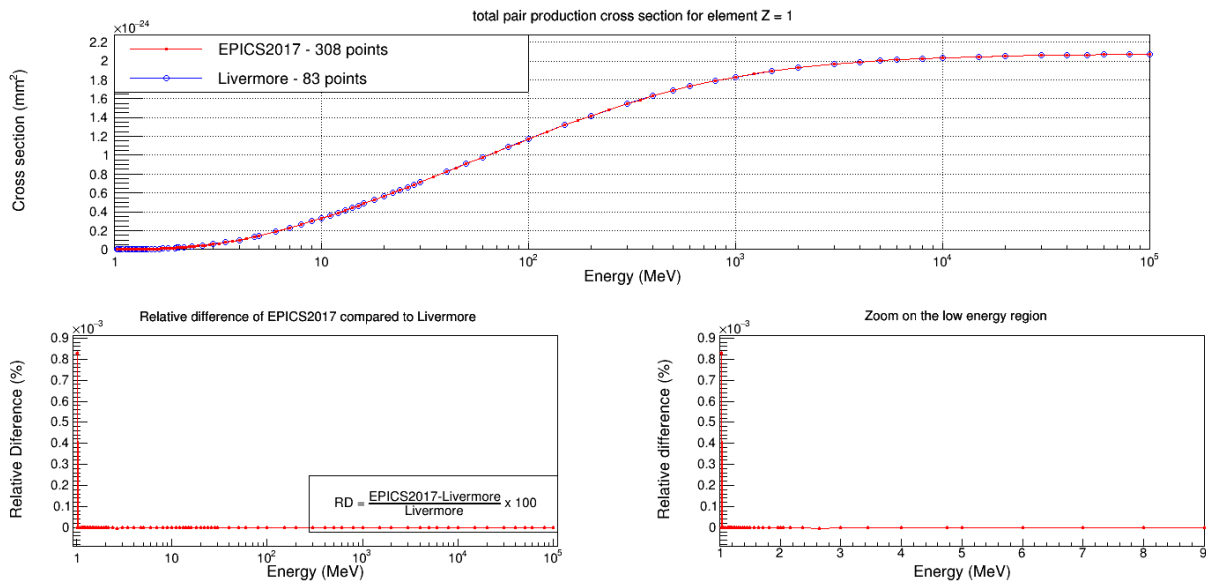


Fig. 17. An example of comparison of cross section data for gamma conversion between EPICS2017 and Livermore for Hydrogen

5.3.2. Discussion

1. Number of points

As explained previously in section 1.4, gamma conversion data have the same number of points as pair production, for each element. EPICS2017 contains more energy-cross section points than Livermore. For example, Hydrogen has 308 points for EPICS2017 (Fig. 15) while only 83 for Livermore (Fig. 16). Besides, all the points of Livermore are included in EPICS2017, so that we can compare the 83 points with the same energy (Fig. 17, bottom left graph).

2. Differences

The differences for gamma conversion between EPICS2017 and Livermore are very small (relative difference $<10^{-5}$). They come from three reasons:

- rounding errors for pair production cross section (as explained in section 5.1.2)
- rounding errors for triplet production cross section (as explained in section 5.2.2, given that only Gadolinium shows a difference)
- interpolation differences for triplet data, there are more points in EPICS2017, the energy intervals are thus smaller. The interpolation method has been explained in section 1.4.

5.4. General comparison for EPICS2017

For the new database EPICS2017, we are also interested in the ratio of triplet production over total pair cross section when a pair production interaction occurs. This ratio will be useful for the further development of models in Geant4.

For each element, the `plot_comparison.c` macro plots one figure comparing pair (“pure pair”), triplet and total production cross section data of EPICS2017. It is composed of two graphs:

- EPICS2017 pair production, triplet, interpolated triplet and gamma conversion cross section
- the ratio of triplet production over total production cross section

The generated figures are saved in the directory: `plots/epics2017`

To use the `plot_comparison.c` macro, you should put it in the same directory as the `epics2017` directory, so that it can read the files contained in all its sub-directories (see section 4.1). The `plots/epics2017` directory above is automatically generated when the macro runs, by the command:

```
root plot_comparison.c
```

Fig. 18 shows an example of comparison for Hydrogen.

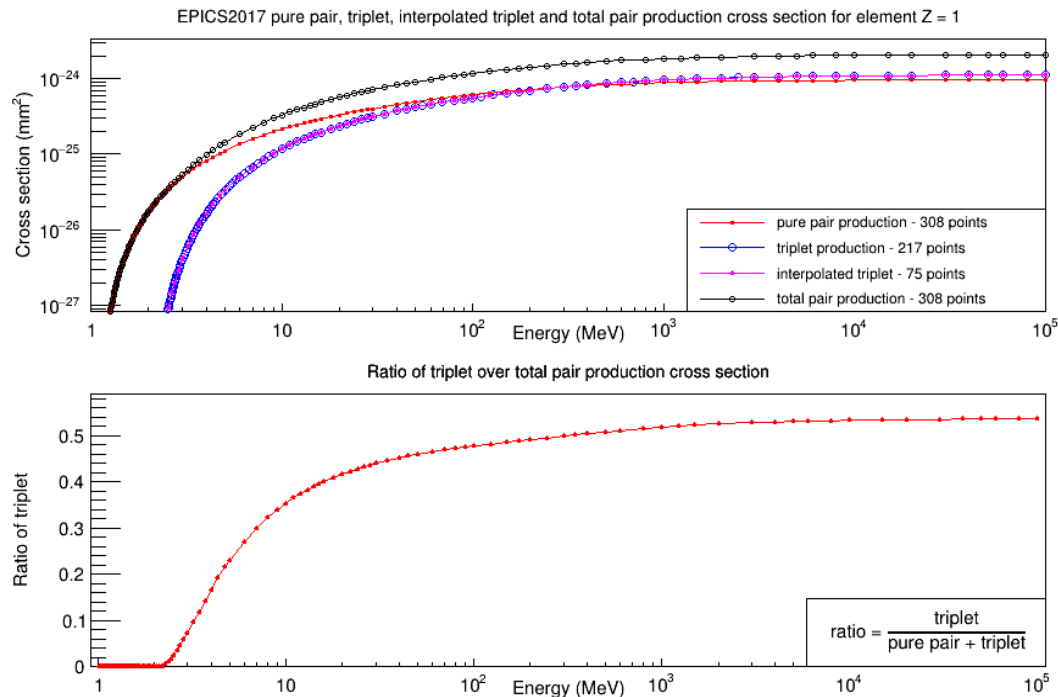


Fig. 18. An example of comparison of data for EPICS2017 for Hydrogen

6. Model classes using EPICS2017 database

The current *G4LivermoreGammaConversionModel* used in Geant4 (*version 10.6, before march 30th, 2020*) was modified by using EPICS2017 database instead of Livermore database. Besides, another model class, which also uses EPICS2017 was generated for pair production process in Geant4:

- *G4LivermoreGammaConversionModel*, which used to use Livermore database, now uses EPICS2017 database.
- *G4LivermoreGammaConversion5DModel*, which is a new model class using EPICS2017 database.

6.1. G4LivermoreGammaConversionModel

The previous *G4LivermoreGammaConversionModel* was derived from the base class *G4VEmModel* and implemented its virtual methods such as *ComputeCrossSectionPerAtom()* and *SampleSecondaries()*. *ComputeCrossSectionPerAtom()* method returns the microscopic cross section for a given photon energy by reading the tabulated database, such as EPICS2017 database. The result is used to calculate the mean free path, also called interaction length. *SampleSecondaries()* method is to sample the final state after an interaction.

However, from version 10.6 (March 30th, 2020) in agreement with Geant4 collaboration, some modifications are made based on the previous version:

- 1) The new *G4LivermoreGammaConversionModel* is derived from *G4PairProductionRelModel* (the standard model used for pair production process), instead of *G4VEmModel*
- 2) The new *G4LivermoreGammaConversionModel* class keeps its original *ComputeCrossSectionPerAtom()* overriding method, but the reading path of the cross section is now *\$G4LEDATA/epics2017*

- 3) In the new *G4LivermoreGammaConversionModel*, the *SampleSecondaries()* method does not exist anymore. In that way, *G4LivermoreGammaConversionModel* uses the *SampleSecondaries()* method inherited from *G4PairProductionRelModel*
- 4) In the *G4LivermoreGammaConversionModel.cc* code, *G4PairProductionRelModel::initialise()* is called in the *G4LivermoreGammaConversionModel::Initialise()* method

6.2. G4LivermoreGammaConversion5DModel

The *G4LivermoreGammaConversion5DModel* class is derived from *G4BetheHeitler5DModel* [2]. *G4BetheHeitler5DModel* provides a more precise *SampleSecondaries()* method, that is, the nuclear or triplet production of polarized or non-polarized photons on atomic or isolated-charge targets can be performed. Thus, *G4LivermoreGammaConversion5DModel* uses the *SampleSecondaries()* method inherited from *G4BetheHeitler5DModel* to generate the final state. Meanwhile, it keeps the same *ComputeCrossSectionPerAtom()* method as in *G4LivermoreGammaConversionModel* in order to make use of the EPICS2017 database. Similarly, *G4BetheHeitler5DModel::initialise()* is called in *G4LivermoreGammaConversion5DModel::Initialise()* method.

List of macro files

The ROOT macro files that we mentioned above are:

1. *generate_pp_cs.c*, generating data files for pair production process of EPICS2017
2. *plot_pair.c*, plotting the difference for pair production data between EPICS2017 and Livermore
3. *plot_trip.c*, plotting the difference for triplet production data between EPICS2017 and Livermore
4. *plot_total.c*, plotting the difference for total production data between EPICS2017 and Livermore
5. *plot_comparison.c*, plotting the ratio of triplet production over total pair cross section for EPICS2017

Reference

[1] Cullen DE. A Survey of Photon Cross Section Data for use in EPICS2017.

[2] Doglioni C, Ivanchenko V, Bagulya A, Bakr S, Bandieramonte M, Bernard D, et al. Geant4 electromagnetic physics progress. EPJ Web of Conferences. 2020;245.