



## Potty Training for Your Geiger Counter

by ullix, May 2017

Pardon the [wordplay](#), I couldn't resist. This article is about the use of natural **Potassium** <sup>1)</sup> to give your Geiger counter a little bit of a training workout when you get tired of measuring just the background. Potassium is omnipresent on the earth, essential for all life, may already be available in or around your home, and has a little bit of natural radioactivity – though well below any danger zones.

I will show how to best use it, taking advantage of today's Geiger counter technology and software.

### What is Potassium?

[Potassium](#) is a chemical element, its symbol is **K** (for Kalium), its atomic number is  $z = 19$ , and its atomic weight is 39.1. It belongs to the group of alkali metals. Other members of this group are e.g. Lithium, the key ingredient of modern, rechargeable batteries, and Sodium, well known for its use as table salt, and its salty presence in the oceans, both times in the chemical form of Sodium Chloride, chemical formula NaCl.

Potassium is an essential ingredient in all forms of life - human, animal, plants, insects, worms, fungi, bacteria – no life without it! We humans get our Potassium from the food we eat.

Of interest to the Geiger counter users is the fact that it comes in three different isotopes of which one is radioactive. Isotopes are atoms which have the same atomic number – here  $z = 19$ , i.e. there are 19 protons in the nucleus, surrounded by 19 electrons in the atomic shell – but have different numbers of neutrons (20, 21, and 22) in the nucleus, which form atoms of the atomic weight  $19 + 20 = 39$ , 40, and 41. The mix of the three results in the overall atomic weight of 39.1. The isotopes are written as e.g.  $^{40}\text{K}$ , or here as K40 for ease of writing. K39 and K41 are stable, but [K40 is unstable, or radioactive](#).

K40 is present in the natural mix of K in tiny amounts of 0.012%. It decays very slowly with a half life of about 1000 million years, so its presence will barely change for as long as mankind may exist. And when we look back to about 4000 million years ago, or about 4 half-lives of K40, it would thus have been present ~16 times higher, near 0.2%, when first life on earth came into existence.

Due to K40's long half life and its low presence in the K mix, the radioactivity of natural Potassium is very low. Yet it can be measured with – in today's standards – simple technology, like Geiger counters. Their price is about on-par with a smartphone of the lower-cost variety!

However, some understanding of the physics of radioactivity is really helpful for a meaningful use of Geiger counters and software to extract information.

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1 The name is derived from [pot ash](#), referring to the method of washing out plant ashes in large iron [potties](#), uuh, pots. The residue after evaporation is the pot ash, containing K in the form of potassium carbonate ( $\text{K}_2\text{CO}_3$ ).

## Question:

### If K is radioactive, should I not be changing my diet to avoid its intake?

Let's ignore the underlying question whether there is even a problem with very low levels of radiation (google for LNT, Linear No Threshold, theories, for this much debated topic), or perhaps an advantage, because there isn't anything you can do about it.

Your body needs a certain amount of potassium, and it very eagerly keeps this constant. If you only eat food with a low amount of K, then your body extracts from that low amount until it has enough. On the other hand, if you eat food with a high amount of K, your body will get rid of the surplus until it is back to its normal.

If you do manage to get your K down, it is probably because you are on certain medication, had too much alcohol, or suffer from other out-of-order things. You may have to be rushed to the hospital! The doctor will probably diagnose [Hypokalemia](#) and give you an injection to bring K back to the levels where it should be!

Life has evolved on this basis since 4000 million years. So, don't bother, your body knows better.

K40 decays by two radioactive processes: the dominant one (~90%) is by emitting an electron with an energy of up to 1.33 MeV<sup>2</sup>). This is called beta radiation. The other one (~10%) is by emitting a photon of 1.460 MeV, called gamma radiation. Both energies are in the [higher end of the range of energies for emissions from nuclear decay](#). And, by the way, the gamma line is perfect for calibrating and tuning a high resolution gamma detector; in my work I once simply put a brick near my detector, and enjoyed a good gamma source!

## Do Geiger Counters see K40 Radiation?

Yes, most see both the beta and the gamma radiation. But: the energy of the gamma rays is high enough to penetrate matter; it easily enters a Geiger tube – but just as easily passes it without triggering a count. The beta radiation on the other hand, i.e. the beta particle (an electron), has a very good chance of triggering a count, once it is inside the tube. Unfortunately it is easily absorbed in matter. Even the plastic case of the Geiger counter may be enough to stop the beta, and so it will never get a chance to enter the tube, and you never get a count!

The design of the counter, its tube, and its housing will determine how sensitive it is to beta and gamma. But the Geiger counter cannot discriminate between beta and gamma and tell you what's hit him. [This is a consequence of the design](#), benefiting sensitivity, but so you just get “a count”.

## In what form do I need K40?

Potassium as a pure metal is highly chemically reactive and may burn in contact with air. With respect to other alkali metals just think of Li-batteries of smartphones, laptops and electric cars, which did burst into flames! But you can use chemical substances which contain potassium in their formula, as shown in the table, and are completely benign and already in use in and around our homes.

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<sup>2</sup> MeV is Mega-Electron-Volt, or 1 million eV. The unit eV is the kinetic energy an electron achieves by acceleration in an electric field of 1 Volt, and is an appropriate unit in the world of atoms and electrons. Medical X-rays range from 30 to 100 keV (1 keV = 1 kilo-eV = 1000 eV); visible light has energies of about 2 eV (red) to 3 eV (blue); UV-light from 3-5 eV, and the microwaves from a microwave oven or a Bluetooth mouse are 10µeV (0.00001 eV). The [GMC-300 series counters are specified](#) as being sensitive to energies from 30 keV to 3.5 MeV.

**Note:** I want to emphasize again that you can measure Potassium radioactivity not because it is radioactive at a high perhaps even dangerous level – it is not – but because even today’s low cost Geiger counters available to the ordinary consumer have such a **high sensitivity!**

Name	Type	Chemical formula	Molar Mass	K [% weight]	Density (g/cm <sup>3</sup> )	K [g/cm <sup>2</sup> ] at 1 cm thickness
Potassium	Pure metal	K	39	100%	0.9	0.9
Potassium Oxide	Oxide	K <sub>2</sub> O	94	83%	2.3	1.9
Potassium Chloride	Salt	KCl	75	52%	2.0	1.0
Potassium Carbonate	Salt	K <sub>2</sub> CO <sub>3</sub>	138	57%	2.4	1.4
Potassium Sulfate	Salt	K <sub>2</sub> SO <sub>4</sub>	174	44%	2.7	1.2

The compounds have only between 44% and 83% K in their molecule, compared to pure metal, but they also have higher density. The last column gives an idea of the amount of K you can get close to the counter tube; think of “shrink-wrapping” the Geiger counter with a 1 cm thick layer of those compounds. As you see, one could actually get more K closer to the counter with the compounds than with the metal (but metal would not work, as it would burn away in your hand!).

Unfortunately this is not quite true, because the compounds are not coming in solid sheets, but as some sort of powder, and the powder density will be lower than the solid density. But it is close. Overall the oxide would be best, the salts are about equal.

## Where can I buy that stuff?

The compounds may be available in local pharmacies, or online with chemical suppliers, and even ebay and Amazon.

I have also seen it advertised in US Health food stores, KCl sometimes being marketed as an essential ingredient “for a salt free diet”. Gosh, no, this **is a salt!** But it may work with your counter. Make sure it is the pure material, and not supplemented with some other filler. Enjoy yourself by asking the sales staff about radioactivity in their products; I can see the headline: “Radioactivity Found in Health Food Store Supplement” ;-)).

Do get only dry products, not solutions - the amount of K in solution is too low, and a liquid is too messy to use.

I was able to purchase KCl and K<sub>2</sub>CO<sub>3</sub> in “food grade” (yes, it is also used in food preparation!) quality from Amazon, [e.g. this one](#). It looks like salt crystals look, not distinguishable from your plain table salt. A total of ~1 pound will suffice, but more gives more flexibility. Price likely in the order of \$5 ... \$10 for a pound; getting the cheapest stuff is ok.

The fact that K is essential for all life, including plant life, and its original way of manufacturing (see footnote 1 on page 1) suggests another way: Potassium is a component in almost all garden fertilizers. Look in your local garden center and study the N-P-K (Nitrogen, Phosphorus, Kalium = Potassium) labels. All components are needed for fertilization, but here you care only about K. It

will be present in concentrations of nominal 5 ... 50% - although it is oftentimes difficult to see what the actual compound is, as the amount of K may be specified as the amount of  $K_2O$  would have been, had the K been provided as  $K_2O$ , but actually is provided as  $K_2CO_3$  or  $K_2SO_4$  or else. Take the stuff with the highest K number; but it should be at least 20%! Price likely in the order of \$3 ... \$6 per kilogram for 3 – 5 kg packs.

Unless you have access to a chemical lab, you can't be sure what it really is. Just looking at it does not help. If it is not spelled out on the data sheet, you won't know. And even a data sheet may not help, as [in this example from a large German garden store](#): the application note says “50 % wasserlösliches Kaliumoxid” (50% water-soluble  $K_2O$ ), while the safety data sheet says “7778-80-5 Kaliumsulfat” ( $K_2SO_4$ , no concentration given). It probably is 50%  $K_2SO_4$  without even a pinch of  $K_2O$ ; it might basically be the same as the product described next.



Fig. 1 Patentkali®

In the EU you find a type of fertilizer named “Patentkali®” (see fig. 1), labeled as “30%  $K_2O$  (plus Magnesium and Sulfur)”, [like this one](#). In the EU it qualifies for “organic farming”. It actually is 50.5%  $K_2SO_4$  ([English data sheet](#)), not  $K_2O$ , but anyway, it works, as you will see below.

With such Patentkali you'd expect roughly half the count rate as with pure KCl (compare with data in above table).

## Experimental Setup

I have a [GQ GMC-300E+](#) Geiger counter available to me, and I use my own program GeigerLog to interact with the Geiger counter, take logs, do graphs, review quality of measurement, and analyze statistics.

The program is open source and available here: <https://sourceforge.net/projects/geigerlog/>. I used version 0.9.04 currently in development (soon to be published also on SourceForge).

As 90% of the  $K40$  radiation is beta, you surely want to measure the betas, or you'd get only 10% of the possible count rate when you can detect only the gammas. The next problem is, however, that the plastic case of your Geiger counter absorbs much of the betas!

Therefore I removed the backplate (~2.5mm plastic) of the counter.

**Caution:** There is high-voltage at the tube, some 400V! And although the potential current is low, better not touch it! Furthermore, the tube is sensitive to dirt, in particular finger prints. Don't touch it or put on gloves before you do.

Then I put the open counter in a plastic bag (to keep any dirt away from tube and electronics). Some strange results later I noticed that the counter was light-sensitive, and many of the counts measured were due to daylight! This is intensely discussed in the GQ forum as topic “Counter counts mostly daylight, less radioactivity” ([http://www.gqelectronicsllc.com/forum/topic.asp?TOPIC\\_ID=4540](http://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=4540)).



There is no explanation yet why seemingly identical tubes behave differently, but it appears that some tubes are light sensitive, while others are not.



*Fig. 2 Geiger counter with backplate removed and put into a plastic bag*

As a work-around I am now putting counter and else into a light-tight dark box. All measurements shown here were made this way.

## Experimental Results - A

I had the following Potassium containing test samples available:

- KCl, pure, food grade, in crystalline form (Amazon)
- $K_2CO_3$ , pure, food grade, as tiny beads, under 1 mm in diameter (Amazon)
- Patentkali®, as described in text (Garden Supply)
- Fertilizer of unknown type (Garden Supply)
- Banana Chips, dried, coarsely crushed, composed of 55% banana, plus coconut oil and sugar (Grocery)

The outcome of the measurements is shown in fig. 3. All measurements were done in CPM-mode (Counts Per Minute), **not** CPS-mode (Counts Per Second), to which the counter may have been set by default! The reason will become clear in the chapter on statistics on page 8.

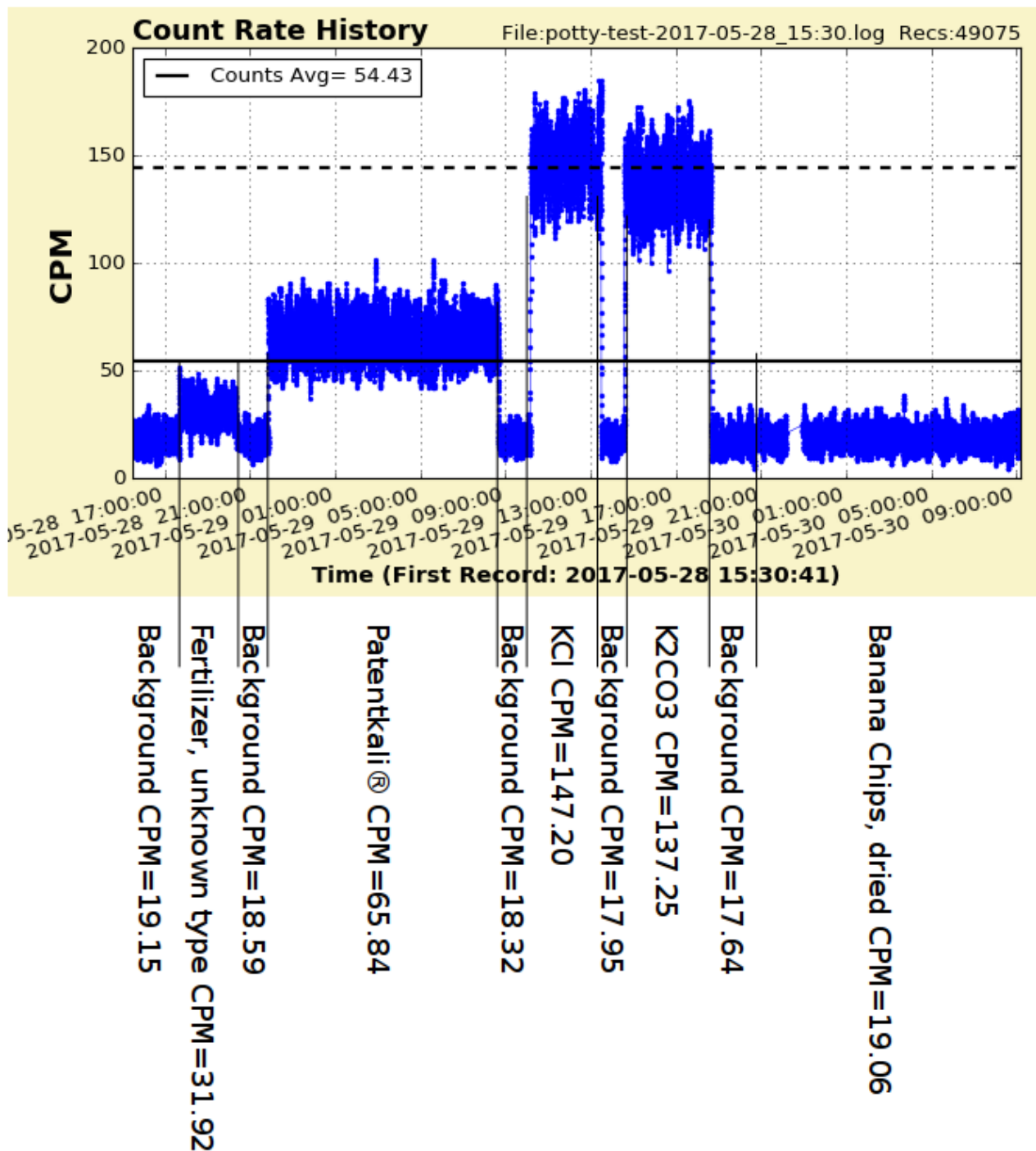


Fig. 3 Count Rate Measurement with Potassium Samples

Before a sample was measured, the background count rate was established. This count rate has steadily declined from early to late from CPM=19.15 to 18.59, 18.32, 17.95, and 17.64, however, while there may be a real trend, for now I consider it as within statistical uncertainty.

The highest count rate was found with KCl (CPM=147, more than 8 times the background), followed by K<sub>2</sub>CO<sub>3</sub> (CPM=137), the Patentkali® (CPM=66, ~4 times the background), and the unknown fertilizer (CPM=32), obviously having less K than Patentkali, but still being clearly above background.

I added the banana chips because of the discussion on the [banana equivalent dose](#), comparing a radioactive dose to the amount of bananas you would have to eat in order to get this dose. Well, the count rate was higher than the previous background number, but lower than the highest background number. So, not convincing; at best a hint that there might be some Potassium at work.

When you are measuring dose rates close to background, nothing is easy.

In the meantime I found out that [other food might be a better source for Potassium](#) (and hence for K40). Will be an experiment at some other time.

## Experimental Results – B

Just to complement the results, fig. 4 shows what you get when the backplate of the counter is **NOT** removed; the case remains closed, and hence the case already absorbs a good part of the betas.

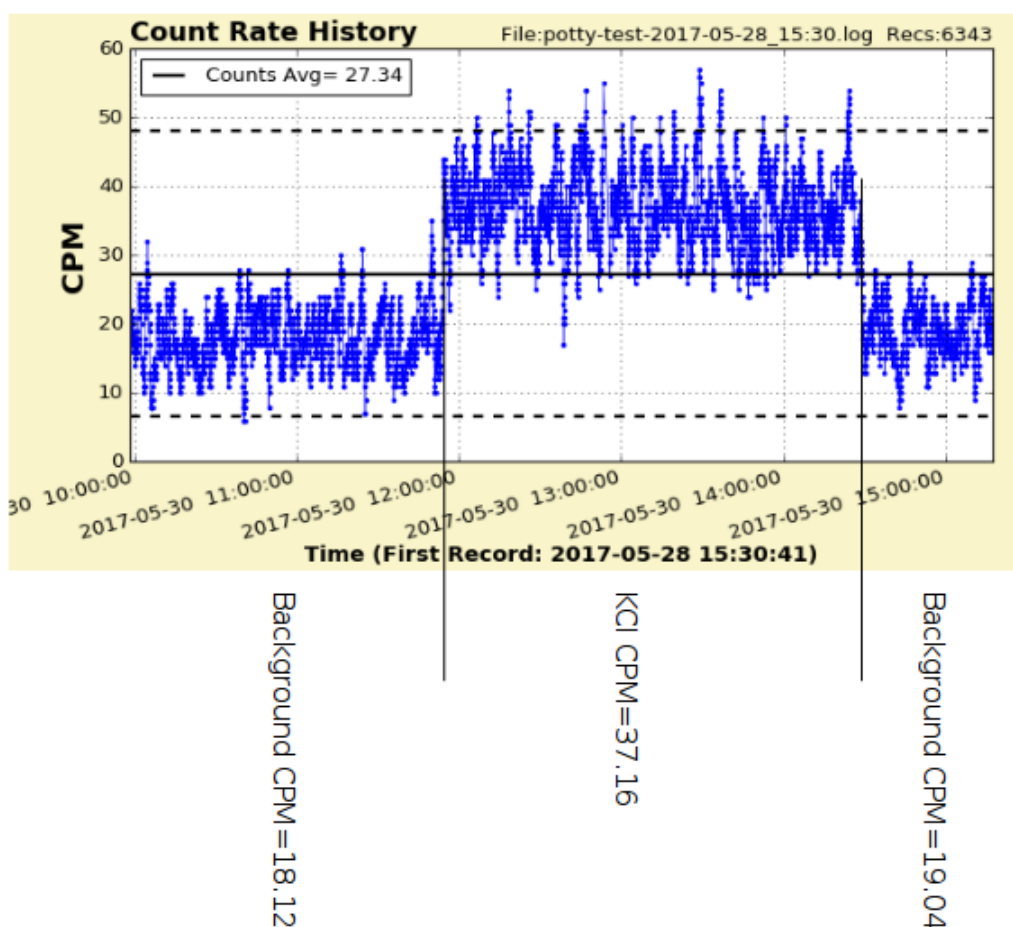


Fig. 4 Count Rate with KCl with the Backplate of the counter **NOT** removed

While the background is the same as before, KCl increases the count rate only 2 fold compared to the previous 8 fold when the backplate had been removed! Whatever the background radiation might be (cosmic rays, earth originating rays, or simply electronic noise of the Geiger counter having nothing to do with radiation) it surely does **not** look like there is a contribution from beta rays to the background.

## Statistics

When you measure the background you may be seeing an average count rate of CPM=20 (rounded), like in fig. 5 (left). While the average remains close to 20, the individual measurements fluctuate quite significantly, like here from a low of 7 to a high of 32, but the counts near 20 are coming more frequently.

Let's see how often each count value comes up by creating bins from 0 to 35 and adding 1 to each bin for each occurrence of that count rate. This can be plotted as a [histogram](#) like in fig. 5 (right).

**Note:** the plot “Count Rate Histogram with Poisson Fit” is available in GeigerLog 0.9.04 and later.

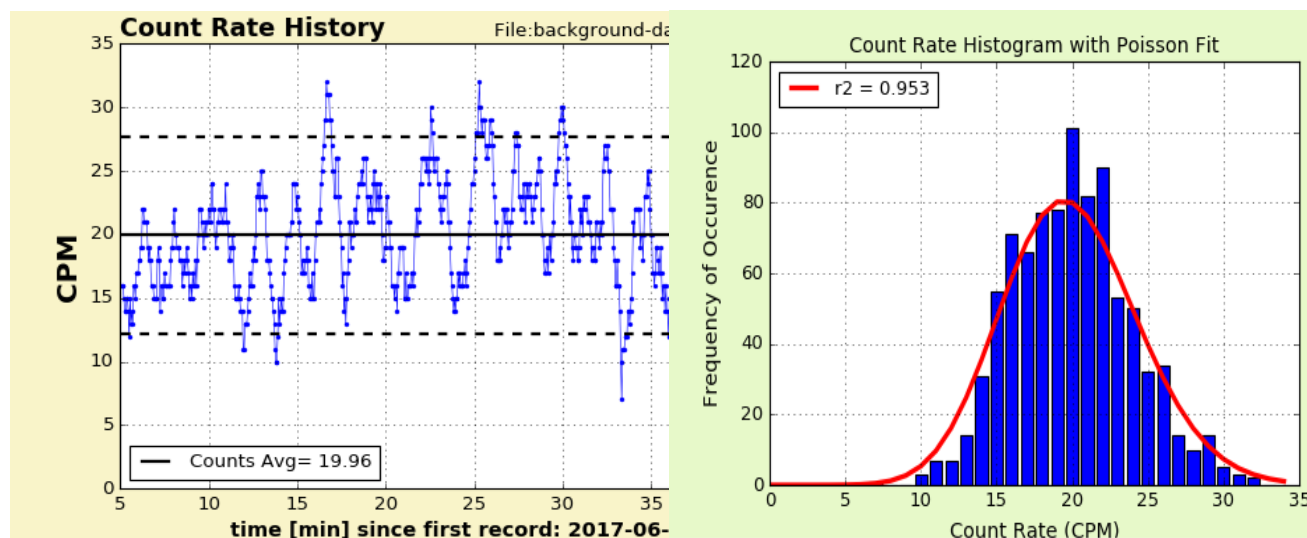


Fig. 5 Background measurement in CPM mode and Histogram of Count rates

The blue bars form a distribution with most weight near 20 but clearly having some “width”. This width is generally quantified as [Standard Deviation](#), abbreviated Std.Dev., which is calculated by GeigerLog as equal to 4 in this example. The dataset is then characterized as Average  $\pm$  Std.Dev., or here CPM= 20  $\pm$  4 for the data in fig. 5. We know that within the range from 1 Std.Dev. to the left of the average up to 1 Std.Dev. to the right, we find about 2/3rd (more precise: 68.2%) of all data. Here in the bins from 16 ... 24 we find ~600 of all 900 data points.

Actually, this is not quite correct (though still helpful, as you will see later). It would be correct, if the data points had a [Normal Distribution](#), but they do have a [Poisson Distribution](#). Let's unravel this. First, a “Normal Distribution” is the same as a “Gaussian Distribution”; those names are used in science and technology. Yet another name for the same thing is “Bell Curve”, mostly used in the social sciences. Such a distribution is fully determined by 2 parameters: the Average and the Std.Dev.. For a fit to your data the height of the curve is a 3<sup>rd</sup> parameter, which accounts for your total number of data points. In a truly “Normal” distribution, the total counts would be equal to 1 – hence the word “Normal”!

In fig. 5 (right) you see a red curve fitted to the blue-bar data, which clearly has bell-like shape. But it is a curve for a Poisson Distribution, not for a Normal Distribution. What then is the difference?



Poisson statistics can be derived from first principles for the chances of occurrence of individual events and is applicable to a variety of things, like

- car crashes on an intersection
- number of people in a pizza parlor
- number of genetic defects in a population
- number of whales sightings in a given area
- and of course the decay of a radioactive substance, and therefore the occurrence of counts in a Geiger counter

and many more.

In all cases you can't have negative values - there can't be "minus 3" people going for pizza, and you can't measure negative counts!

But a Normal Distribution is defined from minus infinity to plus infinity, while a [Poisson Distribution](#) necessarily only from zero to plus infinity. A Normal Distribution fails to explain certain experiments (example below), and even when the chance of occurrence of a "-3" event may be extremely small, it is conceptually false to allow it at all. Poisson takes care of that.

Fortunately, with increasing average, the Poisson curve becomes indistinguishable from the Normal curve, which can be shown mathematically, and which you had already noticed in fig. 5.

But when the count rate is low, it does matter! In fig. 6 you see what happens when the count rate is very low, as in a CPS measurement of background. The setup is identical to the one used for the data in fig. 5, only now we use CPS instead of CPM.

You get this garden-fence type graph, since most of the time CPS=0, and the connecting blue line goes from 0 to 1 and back to 0, only occasionally going up to 2, or 3 or the maximum here of 4. The histogram is shown in the right part of fig. 6. Almost  $\frac{3}{4}$  of the data are zero, and the fitted Poisson curve no longer looks like bell-shaped! And it is also not a "half-bell", as Poisson is simply not existing to the left of zero! In this case a Normal Distribution cannot be used!

As a rule of thumb: for any rate under 10 you are in Poisson country; for rates above 10, a Normal Distribution mostly works just as well. And therefor, **in this latter case**, what I said above about 2/3rd of the data within  $\pm$  Std.Dev. can be taken as approximately valid also when you deal with Poisson Distributions.

The red-yellowish wiggly line in fig. 6 (left) is the Moving Average over 1 minute. This is calculated by replacing every data point with the average of points from 30 seconds to the left up to 30 seconds to the right. Since this averages over 60 seconds = 1minute, it should mimic a CPM measurement, and indeed it does (compare left sides of fig. 5 and 6, consider the different scale of the graphs, CPS~0.6 equals CPM=35!).

Notice that the Moving Average has no data in the first (and last, not shown) 30 sec, which is a necessary consequence of the averaging method over 60 seconds; here it equals 30 data points as a cycle of 1 second was used!

A Poisson Distribution is fully determined by only 1 parameter: the Average. Of course, like for the Normal Distribution, an additional parameter is needed to fit to your total number of data points.

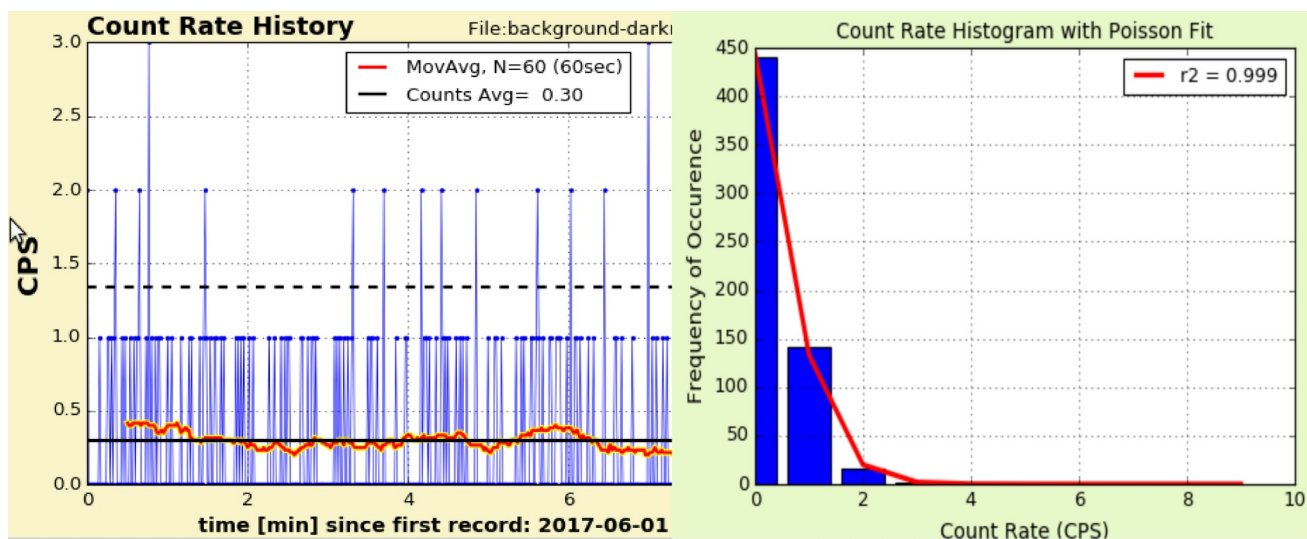


Fig. 6 Background measurement in CPS mode and Histogram of Count rates

This single-parameter determination of a Poisson distribution results from these statistical properties :

1. **Average = Variance**, and since Variance = square of (Standard Deviation), it follows:
2. **Standard Deviation = Square Root of Average**

The 2<sup>nd</sup> property may be the most helpful, because the important Std.Dev. follows directly from the average: Consider a background measurement with an average of CPM=20. The Std.Dev. is  $\sqrt{20} = 4.5$ , or relative to the average 23% ( $4.5/20 \times 100 = 23\%$ ). Try it out: Apply the Square Root rule to data from fig. 5 – it is close but not exact; it is closer with more data collected over a longer period, like in fig. 7.

When measured as CPS, the same CPM=20 will become  $\text{CPS} = 20/60 = 0.33$ . And  $\sqrt{0.33} = 0.6$ , or 200% of average ( $0.6/0.33 \times 100 = 200\%$ ), i.e. ~10 times more scatter relative to the average!

This is why CPS measurements of background gives you a garden fence of data, which most of the times is not really helpful. This raises the question: When can I / should I do CPS instead of CPM?

It depends on how smooth you want your data. If you want no more than 10% scatter in your data, you need an average of 100, because  $\sqrt{100} = 10$ ; relative to 100 this is 10%. This applies to both CPS and CPM. But  $\text{CPS} = 100$  ( $\text{CPM} = 6000$ ) equals 39  $\mu\text{Sv/h}$  – you are getting into danger territory!

Therefore another rule of thumb: as long as you are not intentionally dealing with radioactivity too “hot” for comfort, and want longterm trends, you never measure in CPS mode, only in CPM mode!

## Goodness of Fit and Quality Control

The statistical parameter R-squared ( $r^2$  or  $r^2$  for short) gives an indication of how good the data can be approximated by a Poisson curve. The best possible value is  $r^2 = 1.0$ . A very decent fit is 0.9 and above. It may be less and the data still be ok, but then at least have a second look at the time course of the data to be sure that nothing strange has happened during the measurement.

If  $r^2$  is low, something is wrong, and really wrong if negative (yes, can happen, despite the square!). This should be part of your quality control of any experiment!

## 95% Confidence Interval

Oftentimes the “95% Confidence Interval” is given in statistics. Just as you can say that within  $\pm$ Std.Dev. you have 2/3rd of all data, you can determine the range which would encompass 95% of the data. This is simply  $\sim 2x$  (more precise: 1.96x) the Std.Dev.. Of course, valid only if the underlying distribution is a Normal Distribution, but with the rule of thumb from above, this is reasonably well fulfilled with our Poisson distributions with an average  $>10$ .

GeigerLog draws the upper and lower 95% limits in the graph as horizontal dashed lines, see e.g. fig. 5 (left). In fig. 6 (left) you see only a single dashed line, as the lower one would be in negative territory; so here even the upper 95% limit may be incorrect, as the average is well under 10. However, the  $r^2 = 0.999$  suggests that all is in excellent agreement with a Poisson Distribution.

Could a 95% true limit for Poisson be calculated: yes, but for a lot of programming and little gain.

## Experimental Results – C

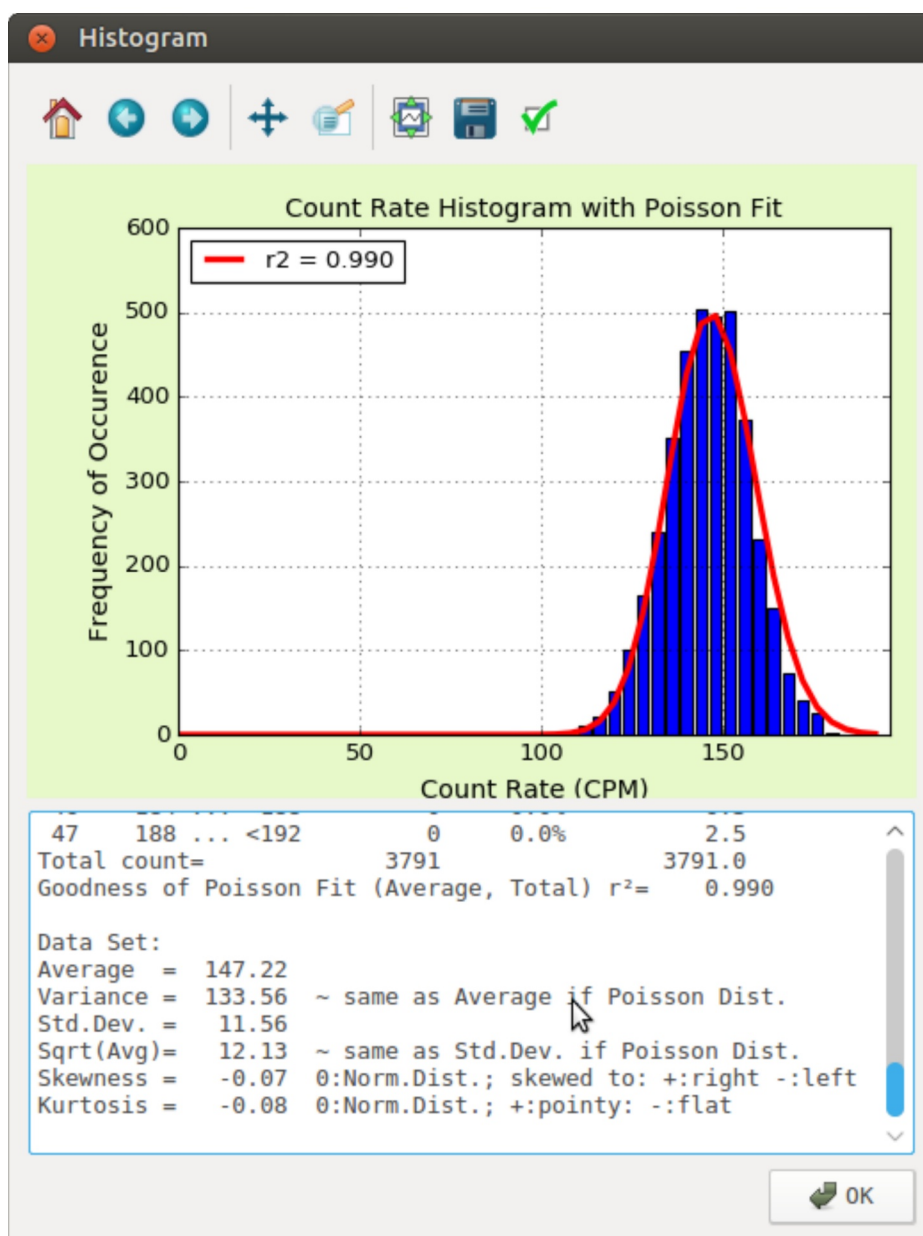


Fig. 7 Count Rate Histograms for the KCl experiment with Poisson Fit

With that introduction to statistics relevant to Geiger counters, I can now show the statistics data for one of the above Kalium runs. With  $r^2 = 0.990$  it is as good as it gets.

Skewness and Kurtosis are additional statistical properties. For a Normal Distribution you'd get a zero for both.

A Poisson distribution should be skewed to the right (resulting from not having negative values; compare red line Poisson fit in fig. 5 and 6), indicated by a positive skewness.

Kurtosis indicates the pointedness of the distribution; a positive value indicates a more pointy, a negative one a more flat distribution. Expect values near zero.

## Further Experiments

These initial results for the impact of some benign materials on the count rate suggests some advanced experiments. It could even be executed in the science class of schools if you could create a containment for the counter which permits direct access to the tube with no plastic in front of it, **but protects from touching the high voltage pins!**

### One possible setup could be:

Put the potassium sample on a table and position the open case counter above it, the tube facing the sample, but leave 1 cm vertical space between them.

Make sure your tube is not light sensitive, or put it all in a light tight box!

- In the space slide an increasing number of sheets of material, like paper, glass, aluminum, steel, lead, water (an ice sheet?), other, and measure the count rate. Measure long enough to get a reliable value.
- Try to find a way to discriminate between betas and gammas. (Hint: plot count rate versus thickness of material, and interpret the curve)
- Think of the impact which [Bremsstrahlung](#) (see Appendix) may have on your results!
- Can the results be explained with the theory outlined in the Appendix?
- Change the height of your vertical space and see how count rate changes with distance between sample and counter to test the  $1/r^2$  law.

## Appendix – Range of Electrons in Matter and some History

Unsurprisingly, the 2<sup>nd</sup> World War had created great interest in radioactivity, and much of the basic knowledge had **not** been available back then.

In 1952, Katz and Penfold published their work on the range of beta rays in matter (see References). Their work got copy&pasted into a secret US Navy report, which had been unclassified recently, and is now publicly available, while the original work of Katz and Penfold is still behind a pay-wall, still protected from being viewed by the people, who had once paid for this work!

In their work they have derived an empirical relationship for the range of beta-rays (aka electrons) in matter. This range is largely determined by the electron density of the matter, i.e. those electrons in the electron shell around the atoms of that matter.

With Range R in [mg/cm<sup>2</sup>] and electron energy E in [MeV], the relationship is:  
ln(E) is the natural logarithm of E

$$R = 412 * E^{(1.265 - 0.0954 \ln(E))}$$

With K40 the maximum beta energy is E = 1.33 MeV, therefore:

$$R = 412 * 1.33^{(1.265 - 0.094 \ln(1.33))} = 412 * 1.33^{(1.2382)} = 586.5 \text{ mg/cm}^2$$

It is easy to do this calculation today with almost any cheap calculator, but in the 1950s you probably used a slide ruler if not logarithmic tables. Any idea what effort this took? So the Navy might have been glad that Katz and Penfold had also provided the graph shown in fig. 7 and copied it into their report, too. Out of historical interest I have drawn the coordinates for 1.33 MeV electrons with red lines into the graph; my readout on the vertical axis would be 560 instead of the calculated 586.5. But let's not make a mistake: we don't know which is the "correct" number; 560 might be better than 586.5, we simply don't know! The numerical formula is no more than an approximation.

Note that the formula does **not** depend on atomic number or atomic weight. So, the metal lead is not per se better than paper. However, lead has more electrons per volume of mass and hence is more efficient for a given thickness to stop electrons. This is captured in the areal density [mg/cm<sup>2</sup>], which we need to translate into thickness for a given experiment.

Let's define T [mm] as the thickness needed to stop our betas, when we use material of the density D [g/cm<sup>3</sup>] and with that we calculate the data in the table:

$$T = R / D / 100$$

Material	Density D [g/cm <sup>3</sup> ]	Thickness T [mm]
Copy paper 75 g/m <sup>2</sup>	0.75	7.8 (~80 sheets)
Glass	2.53	2.3
Aluminum	2.70	2.2
Steel	7.75	0.8
Lead	11.3	0.5



Keep in mind that this approach attempts to capture also the last and fastest beta; you may not be able to measure anything for the last 30% or so of the thickness, because you will be too close to background!

If your interest is shielding from beta radiation, you might be thinking that lead is best. But this comes with a disadvantage: yes, lead can stop the electrons very easily, but big nuclei – such as lead – also result in “[Bremsstrahlung](#)”, which is X-ray / Gamma radiation. You end up with no electrons, but a lot more of other unwanted radiation, for which you need additional adsorbing material.

## Questions:

### What is the difference between X-rays and Gamma rays?

When you ask a physicist the spontaneous answer is: None. Gammas and X-rays are both electromagnetic waves (and can also be considered as photons). But so are other radiations like UV light, visible light, micro waves from a microwave oven or your blue tooth mouse, radio waves. The difference is that their energies are vastly different, see footnote 2 on page 2.

X-rays and Gamma rays are typically differentiated by their origin: X-rays as originating e.g. from medical equipment, and Gammas from something having to do with nuclear, like nuclear lab, particle accelerator, nuclear reactor and cosmic radiation.

One tends to associate Gammas with higher energy than x-rays, though there is overlap through arbitrariness in the energy ranges. It is thus not false to describe the output from a medial X-ray machine as Gammas, but it is unusual wording.

### What is Bremsstrahlung?

This is a German word, literally translated as “Braking Radiation”. If an electron is stopped or deflected in an electric or magnetic field, then it is losing energy and this energy is set free as X-rays / Gamma rays.

In an X-ray tube this happens because electrons coming from the cathode are being accelerated by the positive voltage at the anode towards the anode, and then are being stopped by the atoms forming the anode. Most of the electrons are simply stopped and release their energy by heating the anode, just as an ordinary electric current does. But some stoppage of the electrons results in Bremsstrahlung. High atomic numbers for the metals of the anode are preferred, because more Bremsstrahlung is created. But the anode must also be able to withstand high temperature, which is why tungsten (Wolfram) is used as anode material, and not lead with its low melting point.

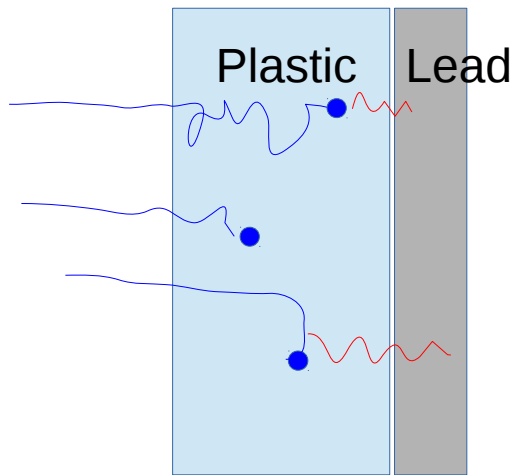
In a particle accelerator, such as a synchrotron, the electrons are forced to fly on a circular course by big magnets, and so are emitting Bremsstrahlung by this permanent deflection.

In a way it is like a car braking, or taking a sharp turn at high speed – its energy is released in part as heating of the brake pads and the tires, and in a smaller part as the audible “sound-rays” of shrieking tires.

The maximum energy of Bremsstrahlung in an X-ray tube is determined by the maximum voltage at the tube: if the X-ray machine can do 50 000 V, then the highest X-ray energy is 50 keV.

The old color-TV tubes are – construction-wise – close to an X-ray tube, and in fact their voltage of ~27 kV resulted in X-rays just strong enough to pass the thick front-glass of the tube. (X-rays from the ~18 kV voltage of the old Black&White TVs were not strong enough to make it through the glass of their tubes). The glass formula was then modified by adding more lead, in order to dampen the amount of X-rays emitted. “Don’t sit close to the tube” was another advice given at the time to minimize X-ray exposure.

If originating from a synchrotron, the Bremsstrahlung can go much higher, up to 1000 MeV.



*Fig 6 Scheme for multi layer absorber for Beta rays (blue are betas, red are x-rays)*

As a consequence of the occurrence of Bremsstrahlung, the sole use of lead or other high atomic number material is **NOT** advised if you want to **shield from beta rays**. It is instead preferred to first use a layer of low atomic weight to minimize Bremsstrahlung in intensity and energy – by using mostly plastic – followed a layer of X-ray absorbing material, mostly thin layers of lead, as schematically shown in fig. 6.

Unfortunately, a Geiger counter can't distinguish between X-rays and betas, so when you get some seemingly strange results from a beta source, think of whether this could be due to Bremsstrahlung.

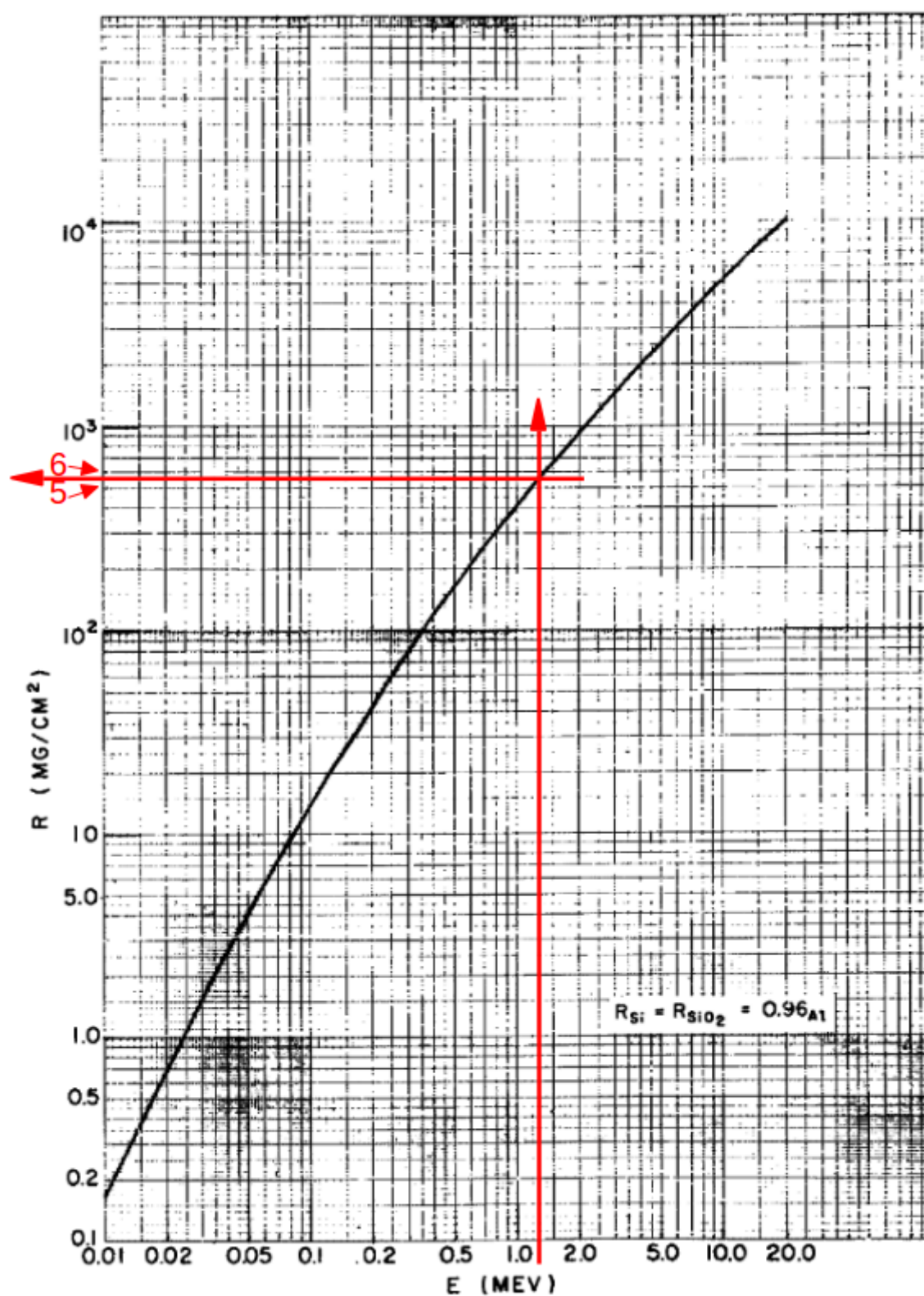


Fig. 5 - Range-energy relationship for electrons in aluminum (from Ref. 9)

Fig. 7 Range Graph from the US Naval report

## References

**Range-Energy Relations for Electrons and the Determination of Beta-Ray End-Point Energies by Absorption**, L. Katz and A. S. Penfold, Rev. Mod. Phys. 24, 28 – Published 1 January 1952

<https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.24.28> (behind pay wall)

### Abstract

It is shown that for aluminum absorbers, a single range-energy equation  $R = 412 E_0^{1.265 - 0.0954 \ln E_0}$  (mg/cm<sup>2</sup>) will fit the most reliable published values of practical ranges of monoenergetic electrons and the maximum ranges of nuclear beta-rays in the energy region  $0.01 < E_0 < 2.5$  MeV. The average deviation of 59 monoenergetic measurements from this equation is +0.08 percent in energy, and -0.05 percent in energy for 35 beta-ray measurements. The mean deviation is 4.1 percent in each case. There are few ranges for energies above 2.5 MeV. All the higher energy values found in the literature and four new measurements on monoenergetic electrons are presented and are shown to be consistent with the range-energy equation  $R = 530 E_0 - 106$  (mg/cm<sup>2</sup>) for  $E_0 > 2.5$  MeV. It is shown that the curve  $(dE_0/dR)$  is nearly parallel to the theoretical curve for the rate of energy loss by ionization in the region between 0.01 and 20 MeV and is about 25 percent larger. The reason for this discrepancy is not known. All the methods commonly used to determine the ranges of beta-rays from absorption curves are discussed and a new method developed by the authors is presented.

**Range - Energy Relations For Proton's And Electrons In Al, Si, And SiO<sub>2</sub>**, V. J. Linnenbom, Radiation Effects Branch, Radiation Division, NRL Report 5828

Unclassified Naval Research Report from 1962, <http://www.dtic.mil/dtic/tr/fulltext/u2/285855.pdf>

Excerpt on Electrons:

### Electrons

For reasons previously given, range-energy relationships for electrons are best obtained experimentally. Katz and Penfold (9) have summarized very ably the work in this field up to 1951. Based on all available data, both on monoenergetic electrons and  $\beta$ -rays, they arrived at the following empirical relationships between the range in Al expressed in mg/cm<sup>2</sup> and the electron energy expressed in Mev:

$$R = 412 E^n, \quad \text{for} \quad 0.01 \text{ Mev} < E < 3 \text{ Mev} \quad (9)$$

where  $n = 1.265 - 0.0954 \ln E$ , and

$$R = 530 E - 106, \quad \text{for} \quad 3 \text{ Mev} < E < 20 \text{ Mev}. \quad (10)$$

The range-energy relationship given by these functions is plotted in Fig. 5, which is the same as Fig. 2 in Katz and Penfold.