Radioactive Neutron Sources Emission Rates

Purpose

The purpose of this procedure is to describe the setup, measurement, and reporting procedures for radioisotope neutron source calibrations with neutron emission rates ranging from 5 x 10^5 /s to 1 x 10^{10} /s.

Scope

This procedure covers the calibration of radioisotope sources of neutrons via the manganese sulfate ($MnSO_4$) bath method, in which the emission rate of the source to be calibrated is compared to the emission rate of NBS-1, the national standard Ra-Be photoneutron source. Additional details and references can be found in Refs. [1, 2, 3].

Definitions

NBS-1 The national standard Ra-Be photoneutron (γ,n) source. Its emission rate has been absolutely determined with an estimated uncertainty of ± 0.85 % (see Ref. [1]). Its neutron emission rate in October 2003 was 1.234 x 10^6 /s, and it has a half-life of 1600 years. The half-life uncertainty is 7 years, which contributes less than 0.02 % to the total relative uncertainty since the last calibration.

BIPM In addition to NBS-1, we have three calibrated neutron sources from the Bureau International des Poids et Mesures (BIPM). Their accuracy is about 1 %. They are an AmBe source (2.285 x 10^6 /s in 12/1986, half life 432 years), a Ra-Be (α,n) source (3.360 x 10^6 /s in 12/1986, half life 1600 years), and a Ra-Be photoneutron source (6.404 x 10^5 /s in 12/1969, half life 1600 years).

Equipment

Figures 1 and 2 show the manganese sulfate bath and control rooms, respectively. The equipment located in the manganese sulfate bath room (building 245, room B143) consists of:

- 1.27 m diameter bath containing $MnSO_4$ solution with a density of 1.25 kg/L
- Emerson Model C63CXJBH-5252 pump for circulating the manganese sulfate solution; SN 587010
- Teflon source holder
- stepping motor, several pulleys, and string
- D4521 Barnstead B-pure water filter system; SN 583990330636
- Anton Paar DMA 35N density meter; SN 795678

The equipment located in the control room (building 245, room B141) is:

- Central Research Laboratories remote manipulator G; SN 9362
- StepPak MCU-2 stepping motor controller; SN 0217980
- two Bicron detectors ("main" and "remote") utilizing sodium iodide crystals and photomultipliers
- stainless steel Marinelli beaker housing the "main" detector
- CAEN DT5724 4 channel 14 bit 100 MS/s digitizer SN 2-0-16
- DT5533EP 4 channel 4 kV/3 mA (4W) desktop HV power supply (USB/ethernet) configured for positive output voltage SN 222
- two A1424 Scintillation Preamplifiers SN 59 (remote detector), SN 58 (main detector); each set to 0.8 mV/pC
- DT5423 desktop power supply for A1424 preamplifiers and DT5724 digitizer SN 44

Figure 1 The manganese sulfate bath room.

Figure 2 The manganese sulfate bath control room.

Software needed to acquire data:

- Networked Windows-based computer loaded with CAEN Compass and CAEN GECO2020 General control software (HV control software); this is free software

Software needed to analyze data:

- Networked Windows-based computer loaded with Microsoft Visual Studio, Root, R, and RStudio; these packages are used to run in-house C++ code and R-scripts, and to knit in-house R-markdown files; all this software is free
- *MakeScriptBathRaw.cpp*, *CompassRyanModified.cpp*, *GetRatesModifiedRyan64.cpp*, *IntegrateHistograms64.cpp*, and *View.cpp*; these in-house C++ files assist in Compass data reduction; their purpose is described in this document; they rarely need to be modified
- *process.R, bath_ratio.R, exploring_ratio.R bath_analysis_1.Rmd, bath_analysis_2.Rmd, source_preliminary_prelim.Rmd, source_preliminary_analysis_meat.Rmd, source_report_template_prelim.Rmd, source_report_template_meat.Rmd;* these R-script and R-markdown files belong in the RStudio project directory
- *MnCorrectionsForR_Shlomi.xlsx*; this spreadsheet should be placed in directory *c:\Users\msd\documents*; it contains MCNP-based calculations of corrections for neutron losses; it is reprised in this report in Table 2; MCNP is an industry standard software used for modeling the interactions of neutrons with matter

Note: this document makes frequent reference to a directory *c:\Users\msd*, e.g., *c:\Users\msd\documents\mnbathr* is the RStudio project directory where the R-scripts and R-markdown files exist, and *c:\Users\msd\source* is the directory containing this C++ code. If someone other than *msd* is preparing this calibration, *msd* should be replaced with their username and these files should be present. A few lines in file *MakeScriptBathRaw.cpp* also need this textual replacement, after which it should be rebuilt.

Because this measurement is a relative measurement (client's source versus NBS-1), it is relatively insensitive to the environment (temperature, pressure, and humidity). A form of gain stabilization is employed to further reduce sensitivity to detector gain shifts.

Health & Safety

The calibration of neutron sources involves several different safety aspects.

1. The radiation safety aspect emphasizes the minimization of personnel exposure. The magnitude of neutron source strengths that can be safely handled at NIST is limited to 10^{10} /s, or less, so several hours of close proximity exposure would be necessary to produce a lethal dose of radiation. Our emphasis is upon obtaining as small an exposure as practical in consideration of As Low As Reasonably Achievable (ALARA) practices.
2. The other aspects are safe handling of neutron sources to prevent any damage and industrial safety practices when handling heavy shielding materials, shipping casks, and the removable parts of shipping containers.

With regard to radiation safety, Nuclear Regulatory Commission (NRC) regulations and NIST policy require that all personnel handling neutron sources be given a radiation safety and awareness training course, with a refresher course to be given every two years. Radiation safety and training services are provided by the NIST Radiation Safety Division (RSD). Safe handling of neutron sources and the industrial safety aspects are taught through an apprentice-type relationship with each new handler.

All neutron-source transfer operations at NIST are accomplished by trained professionals with the cognizance of, and frequently with the help of, RSD personnel. Temporary, in-transit, source storage is accomplished with movable water tanks and shielding barrels. Procedures are reviewed prior to each handling operation. Whole body dosimetry (TLD) and extremity dosimetry (finger rings) are worn during all source transfers, and a minimum of two authorized source users are present for a source transfer. When sources with neutron emission rates in the range 10^9 /s to 10^{10} /s are calibrated, supplemental gamma/neutron sensitive dosimeters are worn in order to document the radiation exposure received during the calibration; these transfers are carried out in close consultation with and in the presence of RSD.

Calibration Procedure

Introduction

To determine an unknown neutron emission rate, the target source is suspended at the center of a large, spherical bath of circulating manganese sulfate ($MnSO_4$) solution. As neutrons are emitted into the bath, they slow down through nuclear collisions and are captured by stable ^{55}Mn nuclei to produce radioactive ^{56}Mn. The activated solution is continuously circulated to a gamma-ray spectroscopy system containing two sodium iodide scintillation detectors. The induced activity reaches saturation after approximately 25 hours. Instead of measuring absolute activity, the facility calculates the unknown emission rate by comparing this saturated count rate directly to the saturated count rate induced by the primary national standard photoneutron source, NBS-1, under identical experimental conditions. This count rate ratio is then multiplied by the certified emission rate of NBS-1 and adjusted using calculated correction factors for instrumental effects (such as system dead time and background) and physical neutron losses (including neutron escape from the bath, self-absorption within the source, and parasitic capture by oxygen, sulfur, and the Teflon source holder).

The facility utilizes two gain-matched 2-inch by 2-inch sodium iodide (NaI) scintillation detectors housed within a lead cave to minimize background radiation fields. The main detector is positioned directly at the center of the Marinelli beaker where the activated solution circulates. As the more sensitive of the two, it is dedicated to measuring weaker neutron sources with emission rates under approximately 5×10^8 neutrons per second, including the primary national standard NBS-1. Conversely, the remote detector is mounted on its side inside an attached pipe approximately 0.5 meters from the Marinelli beaker on an adjustable positioning mechanism. Because this remote detector has a lower sensitivity—operating at a nominal response ratio of approximately 80 times less than the main detector—it is utilized to measure high-intensity sources exceeding 5×10^8 neutrons per second to expand the facility's dynamic range without risking detector saturation or excessive dead-time losses.

Preparing for a calibration

Based upon email/telephone discussions with the client, a calibration schedule is fixed, and a NIST 364 (“Radioactive Material Request”) form is filled out. Very intense sources often arrive in very heavy casks. It is essential to discuss with the client the logistics of moving the source from the delivery truck to the bath storage area. At our disposal are a forklift that can only safely be driven on the driveway (not the loading dock surface) and pallet jacks that can be used to move the source from the loading dock surface into the bath storage area.

Create a new directory on the analysis computer under a local directory, e.g., *c:\Users\msd\Documents\mnbath\Client_3*. The directory name should reflect the client’s name along with an index to ensure the name is unique (3 in this example). Certain specific files may be placed there. These include:

1. Copies of email correspondence with the client
2. Any photos documenting the calibration
3. Type-A cask certificate, sealed source certificate
4. Calibration reports, both signed and unsigned
5. Two important R-markdown files that are part of the analysis: *pre_summary.rmd* and *summary.rmd*. These allow visualization of the results at an intermediate stage and at the end of the calibration respectively.

From the bath computer, create a new data directory, e.g., *g:\shared drives\MnBathData\Client_ID,* for this calibration (this uses a Google shared drive which is automatically backed up). *Client_ID* too should have a unique name that indicates the client's name and the date, e.g., *BNL_9_2025*. This will contain the following:

1. A collection of directories containing copies of the Compass raw datasets from individual runs
2. Optionally, an inventory spreadsheet listing all the data directories along with dataset-specific comments

When each source arrives, it is carefully inspected by RSD for damage or leaks. As these sources tend to be securely encapsulated, passing examination by RSD personnel means they are very likely to work in the $MnSO_4$ bath without a problem. The sources are stored in a secure area (245/B143), which is monitored carefully by RSD. Any given source is likely to be present in storage for no more than three months.

Five separate measurements are needed to calibrate a source and establish the reliability of the results. In the order in which they should be taken, they are:

1. measurement of the background
2. measurement of NBS-1
3. measurement of the client's source
4. remeasurement of NBS-1
5. remeasurement of the background

Ideally, the initial background measurement should be carried out after the bath has been empty for at least a month. These measurements are subsequently analyzed to obtain client source strength and uncertainty. Occasionally this order is changed if, for example, there is a backlog of sources to calibrate. In this case, several sources may be measured between NBS-1 measurements.

These rate measurements are not significantly sensitive to the room or bath temperature over the range within which they normally vary.

Source manipulation for each measurement

1. Remove the neutron source from its container following the client's instructions; or, if NBS-1 is being measured, remove it from its 55-gallon drum
2. Quickly transport the source to the loading area adjacent to the bath using an appropriate grappling pole. Return to the control room.
3. Using the remote manipulator, load the Teflon source container with the source, screw the top onto the container rendering it watertight, put the source container in the bottom part of the Teflon carriage, position the carriage on the stand sitting atop the bath, grab and attach the dangling carriage top to the carriage bottom; finally, release the carriage from the stand allowing it to dangle freely over the bath.
4. Using the motor controller's up and down controls, lower the source until the black mark on the string attached to the carriage is centered on the black arrow located on the far wall. At this point, the source is centered in the bath.

In terms of maintenance, the water level in the bath should be checked periodically. The level will drop due to evaporation. The level should be kept near the lower rim of the entrance tube on top of the bath by the addition of deionized water. It is also possible to add manganese sulfate if the specific gravity of the bath liquid becomes too low. In addition, water filters are changed periodically following the manufacturer's recommendations.

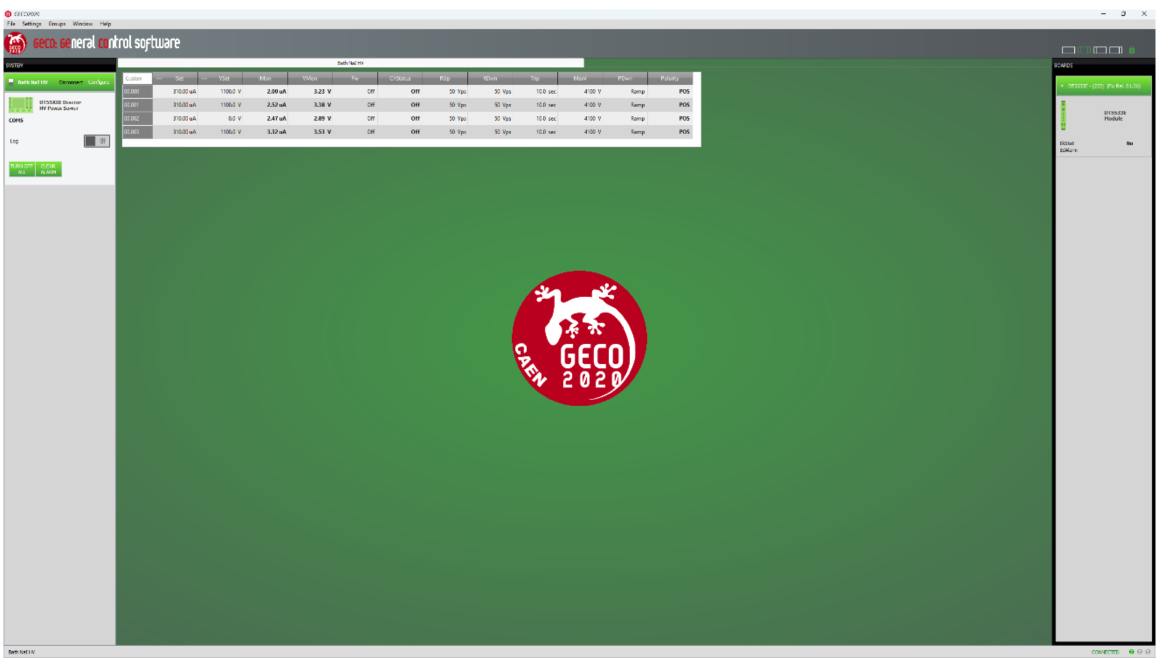

Figure 3 HV control panel for NaI detectors.

Procedure for acquisition of an individual dataset

Double-click on the CAEN GECO2020 icon on the desktop. This allows the HV to be applied to the NaI detectors (see Figure 3). The nominal operating voltage is 1100 V. There are currently three NaI detectors occupying slots 0, 1, and 3 in the application. Slots 0 and 1 correspond to the main and remote detectors respectively. The third detector is not currently involved in the calibration process. Turn on the HV and observe the voltages rise to that value (1100 V). If one of the detectors isn't going to be used, simply leave it off.

Double-click on the Compass icon on the desktop to run the Compass software. This controls the digitizer that acquires data. Documentation relevant to running Compass can be found on the local drive of the bath computer:

c:\Users\ng6daq\Desktop\CAENManuals\GD6300_Compass_QuickStart_rev19.pdf

Of particular interest is the discussion starting in section *2.11.3 DPP-PHA System Parameter Optimization*. This section explains how to tune Compass for any detector/preamplifier combination. Any time it is useful to save out a configuration for later recall, this can be accomplished with Compass' *Save Configuraton File As* command. Recall is accomplished with the *Load Configuration File* command.

Open the default project which should be *DAQOldUnit2*. On the settings tab, make sure that "Enabled" is checked (see Figure 5). Next load a configuration file; currently, the appropriate selection is *config_9_5_2025.xml*; generally, it will be the most recent file available. There are 4 detectors available to take data. Two of these, main and remote, are channels 0 and 1 respectively; channel 2 is a high purity Ge detector, and channel 3 is a third NaI detector that can operate as an external monitor. Channels 2 and 3 are not discussed in this document as they are not used in the calibration procedure (at some point, they will be incorporated into the procedure).

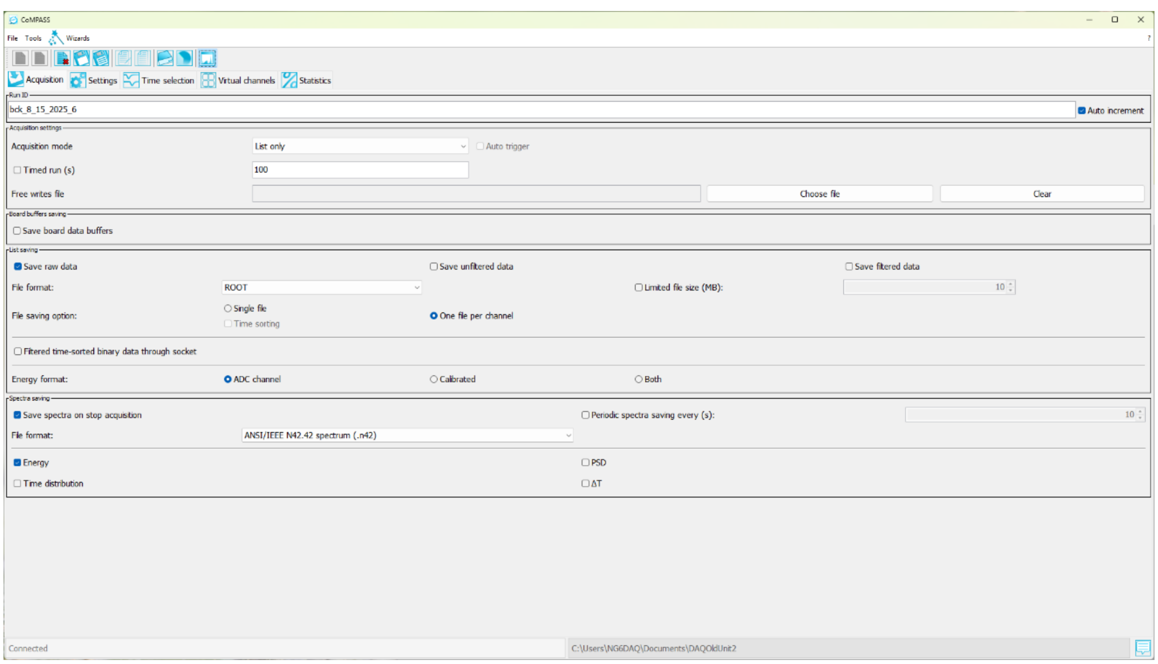

Figure 4 Compass screenshot of the Acquisition Tab. The only setting that needs to be changed is the Run ID. Notice that the run is configured to save raw data in root files.

Figure 4 shows the acquisition tab. The one setting that needs to be changed is the Run ID. Typical names are *bck_8_15_2025_5*, *qsaglobal_8_11_2025_7*, and *NBS1_7_17_2025_8*. The last digit gives the dataset number in the series; each dataset should correspond to 0.5–2 days of running. Stopping and restarting data acquisition causes this digit to automatically increase by one as well as starting acquisition of a new dataset. Individual datasets will be stored in the local directory *c:\Users\ng6daq\Documents\DAQOldUnit2\daq\Run_ID*. The current analysis software expects to find raw data in the root-format.

Figure 5 shows the Input tab under Settings (just to the right of Acquisition). Here it is important to select which detectors will be active. Typically, this will be channels 0 (main) and 1 (remote); it can include 2 and 3 if they are to be used, however they are not discussed here. If an extremely intense source (neutron emission rate > 5×10^8 neutrons per second) is being measured, then the main channel HV should be left off and channel 0 should be deselected in this tab.

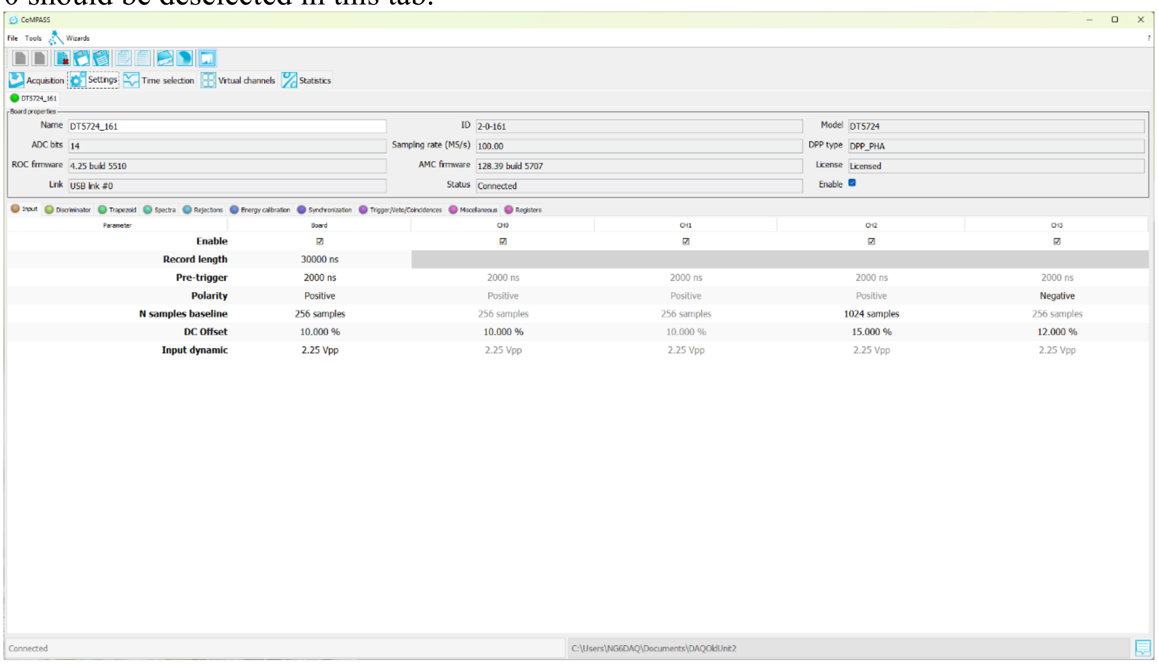

Figure 5 The Input Tab in Compass; it is critical that the *Enable* box be checked.

Begin acquisition by tapping the green arrow in the upper left corner of the Compass Plot window. It is important to be familiar with the operation of Compass as it is essential to plot active channels and input count rates and scrutinize them carefully to look for problems (a quick start section in the manual is extremely useful; additionally, the plotting interface sections of the manual should be learned). Experience shows that runs of 1–2 days duration offer the best compromise between number of files acquired and reproducibility checking. Each measurement, e.g., NBS-1, client, background, should consist of approximately five days of accumulated time. Only data taken after saturation should be analyzed to produce an emission rate (roughly 2 days after the start).

Procedure for analysis of an individual dataset

Once acquisition of a dataset is complete, copy the local data directory to the Google shared drive, e.g., from *c:\Users\ng6daq\Documents\DAQOldUnit2\daq\Run_ID* to *g:\Shared drives\MnBathData\Client_ID*. Once an individual dataset has been copied onto the shared drive, a tiny fixed batch file (*makefiles.bat*) and one or two text files (*params_ch0.txt* and *params_ch1.txt* depending on whether remote alone or main and remote are active) are placed into directory *g:\Shared drives\MnBathData\Client_ID\Run_ID\raw* where the root data file is located. The most efficient way to do this is to copy them from a previous directory and then modify them as necessary.

Table 1 describes the parameters for the critical setup files: *params_ch0.txt* and *params_ch1.txt*. Once these files are present, the command *makefiles.bat* should be executed from a command line window. *makefiles.bat* should consist of the following line:

```
c:\Users\msd\source\repos\MakeScriptBathRaw\Debug\MakeScriptBathRaw.exe 0 1
```

The final integers in this line (0 for main and 1 for remote in this case) indicate those detectors that will be active (main and remote in this case). Running it produces a collection of small files in the same directory.

Table 1 Sample input parameter file. For the first 31 items, the input is numeric, and the entry can be followed by tabs and comments if desired. The remaining items (32–43) are text-based meaning tabs and comments are not allowed. A file should be prepared for the main and remote if both detectors are being used. Items in black rarely need to be changed and can be identical for the two detectors. When a quantity is red (blue), it applies to the main (remote) detector; when a quantity is purple, it must be updated on a per dataset basis. The first six letters of the title (line 32) are the calibration ID; they will be used to filter runs to include in the emission rate calculation.

Line	Quantity	Description
1	0	Desired start time in picoseconds for general looksee at data
2	3.446e17	Desired end time in picoseconds for general looksee at data
3	3e15	Desired time binning in picoseconds for general looksee at data (3000 seconds here)

Line	Quantity	Description
4	80	Lower-level window 1 for general looksee at data
5	0	Lower-level window 2 for general looksee at data
6	16000	Lower-level window 3 for general looksee at data
7	23000	Lower-level window 4 for general looksee at data
8	16000	Upper-level window 1 for general looksee at data
9	79	Upper-level window 2 for general looksee at data
10	23000	Upper-level window 3 for general looksee at data
11	50000	Upper-level window 4 for general looksee at data
12	35e6	Experimental deadtime 1 in picoseconds for general looksee at data
13	25e6	Experimental deadtime 2 in picoseconds for general looksee at data
14	15e6	Experimental deadtime 3 in picoseconds for general looksee at data
15	5e6	Experimental deadtime 4 in picoseconds for general looksee at data

Line	Quantity	Description
16	1e6	Experimental deadtime 5 in picoseconds for general looksee at data
17	1e5	Tally saturation events in general looksee at data as long as greater than zero; has no meaning otherwise
18	0.0005	Maximum time in the Δt histogram in seconds
19	0	Start time in units of 10^{-8} seconds for critical histograms of data
20	2e14	End time in units of 10^{-8} seconds for critical histograms of data
21	15.0e2	Deadtime to use in units of 10^{-8} seconds for critical histograms of data
22	1	1: Fit to gain stabilize; 0: plot time history, don't gain stabilize; -1: fit to gain stabilize and plot; 2: plot, don't gain stabilize
23	110/93	Lower window for rate integration
24	1500/1300	Lower window for peak search and parameter estimation
25	2000/1600	Upper window for peak search and parameter estimation

Line	Quantity	Description
26	0	0: Standard time; 1: Daylight savings time
27	15000	Upper window for rate integration
28	1725/1450	Reference value for the peak channel
29	200	Number of channels to either side of the peak to be included in the fit used for gain stabilization
30	4.0/2.0	If the integrated rate is less than this value (cps), do not fit, do not gain stabilize; between this value and 2 times this value, perform a simplified fit and gain stabilize
31	1.0	Not used
32	EZAG1: EZAG_background_2_27_2024_2, main channel	Run title; the first six letters of this title are the calibration ID; they should be the same for all the datasets associated with this calibration including NBS-1, background, and client source measurements; the remaining letters should indicate which type of measurement it is; each run title should be unique
33	EZAG_background_2_27_2024_2_ch0	Prefix used for intermediate files; should closely resemble the run title (previous entry)
34	1	1 for background runs, 316 for non-background runs; this is a

Line	Quantity	Description
		an historic tag that is used for some diagnostic reports
35	F	F: it is not ^{252}Cf; T: it is ^{252}Cf; T implies there will be decay correction
36	0.001	Background (cps); this is an important parameter that should be zero or nearly zero for background runs and the measured value for non-background runs
37	17000/5000	Upper channel limit for diagnostic plotting; does not affect results
38	NULL	Source type, e.g., Cf, PuBe, AmBe, RaBe, AmB, AmF, AmLi, NBS1, SbBe, NULL (background)
39	BK_M	String that identifies source and detector (R or M), e.g., AMBE_M, AMBE_R, BIPM-1_M, BK_M, BK_R, CF_M, CF_R, NBS-1_M, NBS-1_R
40	NULL	Vendor, e.g., NULL (background), NIST, RR, FTC, PNNL, QSAGLOBAL, EZAG, BNL, QSAG
41	NULL	Serial number of source, if available (NULL for background)
42	Background run	A comment that will appear in an interim report

Line	Quantity	Description
43	0	0: don't archive, 1: archive, 2: replace in archive

One of the newly created files is called *run_auto.bat*. Its lines are repeated for each active detector (ch0 for main and ch1 for remote). These are its contents followed by their meaning.

```
1 ConvertCompass64.exe step1_ch0_temp.inp
2 ConvertCompass64.exe step1_ch1_temp.inp
3 GetRates64.exe step2_ch0_temp.inp
4 GetRates64.exe step2_ch1_temp.inp
5 IntegrateHistograms64.exe step3_ch0_temp.inp
6 IntegrateHistograms64.exe step3_ch1_temp.inp
```

Lines 1–2: These lines produce several diagnostic files and a root file that can be examined to explore the dataset in detail.
Lines 3–4: These lines produce a root file consisting of a time series of histograms; each histogram's title includes its start time and live time. This file is used to extract the deadtime-corrected rates for each bin of time in the last step.
Lines 5–6: In the last step, rates are calculated from each of the histograms contained in the root file that was produced in the second step. Item 22 in the input file controls the detailed action; if 1 or -1, each spectrum's peak is fit, and the centroid of the fit is compared with Item 28, allowing the upper and lower integration windows (Items 23 and 27) to be adjusted by that ratio, ensuring gain stabilization. Otherwise, the integration limits are exactly the numbers given in Items 23 and 27.

Execute each of these lines in turn ("*rem*" can be placed in front of all lines except one to force a single line to execute; the advantage of running them one at a time is that it makes it possible to intervene quickly if there is a problem). They should be executed from top to bottom. Once this is done, the detector-specific R-markdown files become important.

An R-markdown file is produced for each detector that is active (typically ch0 and ch1). Here is an example:

```
---
title: "EZAG1: EZ_2_13_2024_3, remote channel"
date: "2/15/2024"
output:
  html_document:
    df_print: paged
    code_folding: hide
  pdf_document: default
```

```
9  params:
10   input_file: "e:/Shared
11 drives/MnBathData/ezag_2_15_2024/EZ_2_13_2024_3/RAW/step3_c
12 h1_temp.inp"
13   spec_file: "e:/Shared
14 drives/MnBathData/ezag_2_15_2024/EZ_2_13_2024_3/RAW/CH1@DT5
15 724_161_EZ_2_13_2024_3_spectrum.txt"
16   output_prefix: "EZ_2_13_2024_3_ch1"
17   special_channel: "316"
18   californium: "T"
19   background: "1.12"
20   x_limit_spectrum: "5000"
21   source_type: "Cf" #
22 Cf,PuBe,AmBe,RaBe,AmB,AmF,AmLi,NBS1,SbBe
23   class: "CF_R" # all important main or remote indication
24   archive: !r 0 # 0: don't archive, 1: archive, 2: replace
25   vendor: "EZAG"
26   SN: "W6-960"
27 ---
28
29 ```{r}
30 main_filename <- knitr::current_input()
31 working_dir <- getwd()
32 ```
33
34 # Specific run comments
35
36 EZAG source in bath
37
38 ```{r,
39 child='c:/Users/msd/Documents/MnBathR/bath_analysis_1.Rmd'}
40 ```
41
42 ```{r,
43 child='c:/Users/msd/Documents/MnBathR/bath_analysis_2.Rmd'}
44 ```
```

Three lines can be changed in this file, after which the knit function should be applied to it in RStudio. These lines are:

Line 19: This line contains the critical background rate (cps) that should be subtracted from the rate deduced from the dataset associated with this file. This should be set to “0” for background runs. Once background runs have been undertaken, the detector-dependent background rate relevant to source-in-bath datasets becomes known and the appropriate value can be written into the appropriate R-markdown file.

Line 24: This is the archive switch. If it is “0”, the knit function can be run as often as desired, and the result will not be added to the master database. Once satisfied that the data looks good and the proper background rate has been applied, this can be switched to “1” and the file knit again. This will add the result to the master database. A third option “2” exists for when an entry has already placed in the master database for this dataset and it needs to be modified.
Line 36: This is an optional comment. It will appear in the R-markdown report generated by knitting this file.

Knitting produces a report containing several plots and tables that should be analyzed carefully to make sure everything has gone well. If both the main and remote detectors are operated, R-markdown files will be generated for each dataset, and in turn both should be knit in RStudio. The critical quantity from each report is a reference date, a decay-corrected count rate, an uncertainty on that count rate, and a collection of various run parameters. Once the background is known, it should be placed on line 19 of the R-markdown file, and the file should be knit one last time with the quantity on line 24 set to 1. This causes the result to be stored in the master database, making it available to contribute to a measured emission rate.

Procedure for extracting the emission rate

As datasets become available, an R-markdown file called *pre_summary.rmd* becomes useful. It should be placed in the same directory where the emails, photos, and certificates are stored; neither it nor the summary R-markdown file are created automatically. This is a sample file:

```
---
title: "BNLn2: BNL Cf-252 source pre-summary"
author:
  - M. Scott Dewey^[NIST, mdewey@nist.gov]
date: "7/2025"
output:
  html_document:
    df_print: paged
    code_folding: hide
    toc: true
  pdf_document: default
always_allow_html: true
params:
  Mn_corrections: "~/MnCorrectionsForR_Shlomi.xlsx"
  run_ID: "BNLn2:"
  t1: !r as.POSIXct("2025/04/14
00:00:00",tz="America/New_York")
  t2: !r as.POSIXct("2025/07/30
00:00:00",tz="America/New_York")
```

```
20 ---
21 
22 ```{r,
23 child='c:/Users/msd/Documents/MnBathr/source_preliminary_pr
24 elim.Rmd'}
25 ```
26 
27 # BNL Cf Source Measurement
28 
29 ```{r}
30 source_serial_number <- "FTC-CF-10796"
31 working_dir <- getwd()
32 ```
33 
34 ```{r,
35 child='c:/Users/msd/Documents/MnBathr/source_preliminary_an
36 alysis_meat.Rmd'}
37 ```
```

The easiest way to prepare this file is to copy a previous version from a different calibration directory into this directory, rename it if necessary, and then change lines 2, 5, 15, 16, 18, 27 and 30 with a text editor. Lines 16 and 18 specify date ranges that should be spanned for inclusion of NBS-1 and background datasets; this feature can be used to include NBS-1 and background datasets belonging to other calibration IDs. When this file is knit in RStudio, it will produce a report that can be studied to gauge progress on the available datasets. If the datasets include background runs, the last table in the report can be used to obtain background rates that can be entered into the R-markdown files for source-present-in-bath datasets. These background-adjusted source-present-in-bath R-markdown files can be re-knit with data-saving into the master database turned on. The report is also valuable in searching for problematic datasets.

Once all the datasets have been acquired, the summary R-markdown file can be knit. Here is an example of this file:

```
---
title: "BNLn2: BNL Cf-252 source summary"
author:
  - M. Scott Dewey^[NIST, mdewey@nist.gov]
date: "02/2024"
output:
  html_document:
    df_print: paged
    code_folding: hide
    toc: true
  pdf_document: default
always_allow_html: true
```

```
13 params:
14   Mn_corrections: "~/MnCorrectionsForR_Shlomi.xlsx"
15   run_ID: "BNLn2:"
16   t1: !r as.POSIXct("2025/04/14
17 00:00:00",tz="America/New_York")
18   t2: !r as.POSIXct("2025/07/30
19 00:00:00",tz="America/New_York")
20   ratio_to_use: !r 80.7
21   neutron_loss_coef: !r 0.5
22 ---
23
24 ```{r,
25 child='c:/Users/msd/Documents/MnBathr/source_report_templat
26 e_prelim.Rmd'}
27 ```
28
29 # BNL Cf Source Measurement
30
31 ```{r}
32 source_serial_number <- "FTC-CF-10796"
33 source_detector <- "R"
34 working_dir <- getwd()
35 pts_to_omit <- tribble(
36   ~source_type, ~point,
37   "Cf",1,    # still burning in
38   "NBS1", 9,  # long-term decay
39   "NBS1", 10,  # long-term decay
40   "NBS1", 11,  # long-term decay
41   "NBS1", 12  # long-term decay
42 )
43 ```
44
45 ```{r,
46 child='c:/Users/msd/Documents/MnBathr/source_report_templat
47 e_meat.Rmd'}
48 ```
```

This file should also be copied from a previous calibration directory, renamed, and then modified as needed. The same considerations as before apply to lines 2, 5, 15, 16, 18, 29, and 32 of this file; however, this file introduces a few additional lines that need to be modified in order to produce a final estimate with uncertainty of the client source's emission rate.

Line 33 assigns a value to the quantity *source_detector*; this will be either "R" if the remote detector is being used to obtain an emission rate for the client source or "M" if the main detector is being used. If "R" is entered, then line 20 becomes important;

otherwise, it is not important. This ratio (here 80.7) is the efficiency of the main detector divided by that of the remote detector. When the remote detector is used, typically because the count rate would be too high for the main detector, then the final expression for the emission rate will include this as a factor. A relative uncertainty of 0.85 % is assigned to this ratio. R-scripts *bath_ratio.R* and *exploring_ratio.R* can be used to extract this value; they extract historical ratios of measured rates with both detectors from the master database to obtain an updated value. Normally, this ratio is extremely stable with time; if it is found to vary, a manganese sulfate solution leak should be considered. With this modern acquisition system, the upper count rate limit for the main detector is higher than it was before. Therefore, there is less need to rely on the remote detector. Today, only the highest intensity sources require that the main detector be turned off. When both detectors are run, a data point for the ratio is obtained and the main value can be used to obtain the emission rate. This obviates the need to add in quadrature 0.85 % of relative uncertainty.

Lines 35-42 are optional. They are shown in this example to show how datasets already stored in the master database can be removed from consideration for the extraction of an emission rate. For each point to be removed, its source type and index into measurements of that type are specified. For example, “"NBS1", 9, # long-term decay” means remove the 9th NBS-1 point. The “#”, or comment character, can be used to add an explanation. If no points are to be removed, simply omit these lines.

Line 14 does not need to be changed, but one should be aware of it. The spreadsheet is reprised in Table 2. For any source put into the bath, there will be source spectrum-dependent neutron loss mechanisms. These arrive from fast neutron reactions, neutron leakage from the bath, and neutron reabsorption in the source. MCNP calculations have been undertaken for spectra corresponding to those sources that we calibrate to quantify the size of these effects in the NIST bath. Since emission rate measurements rely on the count rate ratio between the client source and NBS-1, it is the ratio of these corrections that ultimately gets factored in. Line 21 indicates that an uncertainty of 50 % is being assigned to each of these corrections. This table should be updated when reliable new cross section data become available for MCNP.

Knitting this file in RStudio results in a final report that presents the emission rate, $k = 1$ relative uncertainty, reference date, and NBS-1 emission rate on the reference date (near the bottom of the report). The emission rate S is calculated according to the simple formula:

$$S = S_{NBS-1} F \frac{R}{R_{NBS-1}} \frac{c}{c_{NBS-1}},$$

Where R is the ensemble average background subtracted client source count rate in the bath, R_{NBS-1} is the ensemble average background subtracted NBS-1 count rate in the bath, S_{NBS-1} is the known source strength of NBS-1 on the calibration date, $F = 1$ if the *active* channel is "main", $F = 80.7$ if the *active* channel is “remote”, and both c's are obtained by summing the source-appropriate column in Table 2. The report also presents numerous graphs and tables that can be used to evaluate the quality of the measurement. These values must be put into a formal calibration report.

Table 2 The magnitude of correction or effect in % for the indicated types of neutron source. Calculations carried out using MCNP for a MnSO4 bath with dimensions and manganese concentration the same as that at NIST. We multiply the Cavity flux/Q correction by a factor that ranges from 1to 3 depending on the size of the source encapsulation. Larger Sources correspond to larger factors.

Source of correction	**^{252}Cf**	**^{239}Pu-Be**	**Am-Be**	**Ra-Be (α,n)**	**AmB**	**AmF**	**Am-Li**	**Ra-Be NBS-1**	**SbBe**
Fast leakage	0.073	0.333	0.41	0.193	0.013	0	0	0	0
Thermal leakage	0.012	0.050	0.08	0.026	0.007	0.003	0	0	0
Oxygen capture	0.557	2.092	2.704	1.528	0.254	0	0	0	0
Sulfur capture	0.283	0.913	0.79	0.627	0.274	0.06	0	0	0
Teflon capture	0.118	0.700	0.12	0.530	0.160	0.095	0.095	0.06	0
Cavity flux/Q	0.186	0.141	0.11	0.190	0.156	0.197	0.350	0.27	0.52

Acceptance Criteria

Agreement between new values of R_{NBS-1} and previous values at the 1 % or better level provides a complete validation of the entire measurement system including electronics, efficiency of the detectors, and the behavior of the bath. There is a long history of R_{NBS-1} values available. New values should be within 2 % of the trend suggested by previous values unless the reason for the difference is understood (for example additional $MnSO_4$ has been added to the bath). When this is not the case, it usually means that some part of the apparatus is not functioning properly (for example, neutron absorbing material may have been inadvertently introduced into the bath). In this case, calibrations must stop and the cause of the deviation must be determined and corrected. A thorough investigation shall accompany any deviation that cannot be corrected to within the expected value range. These actions shall be documented and submitted for technical review.

In addition, it is important to look at all the individual counts to see whether there are any trends or outliers. Finally, when a previously calibrated source is recalibrated, the new number should agree with the previous number. When the calibration is finished, the source is returned to the client.

Determination of uncertainties

The basis for the determination of uncertainties associated with these measurements is the *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results* [4]. The expanded uncertainty consists of components evaluated by statistical means (the "Type A" uncertainties) and components determined on the basis of alternative techniques ("Type B" uncertainties). Type A uncertainties are the uncertainties on the *R*'s, typically less than 0.5 %. Type B uncertainties include the following:

- NBS-1 emission-rate (± 0.85 %)
- Detector calibration (± 0.85 %); this is present only when the "remote" detector is used (client source strength in the range 10^8 /s to 10^{10} /s)
- Uncertainty associated with the applied corrections for both NBS-1 and the calibrated source (± 0.3 %, and typically 1 to 2 %, respectively)

The final report includes the expanded uncertainty. The expanded uncertainty corresponds to the quadrature sum of the stated uncertainty components multiplied by a coverage factor equal to two (2). The expanded uncertainty, therefore, represents an approximate level of confidence of 95 %.

Documentation

Raw data is stored on the local bath computer hard drive. A copy of the data plus analysis files are stored on a shared Google Drive that is automatically backed up. The analysis computer contains the R project directory, a collection of client-specific directories, and the C++ code. These are regularly backed up onto OneDrive using SyncToy. In addition, a global logbook of bath-related activities including beyond-normal maintenance activities is maintained in room 245/B141.

For client calibration, prepare an electronic calibration report and obtain required signatures. This will be stored in the directory with the summary R-markdown files; it is also uploaded to the Salesforce interface as a necessary step in closing the calibration.

References

[1] E. Dale McGarry and Edward W. Boswell. Neutron source strength calibrations. Technical report, National Institute of Standards and Technology, 1988. NBS Special Publication 250-18.

[2] J. M. Adams. Present and future trends for neutron source calibrations at the National Institute of Standards and Technology. *Nucl. Instrum. Meth. B*, 213:218—222, 2004.

[3] Craig R. Heimbach. The neutron spectrum of NBS-1. J. ASTM International, Volume 3, Issue 4 (available online at www.astm.org).

[4] Barry N. Taylor and Chris Kuyatt. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297, September 1994.

Appendix A Calibration Report

REPORT OF CALIBRATION

Neutron Source Strength Calibration Report

NIST Report Folder Number: 682.03/O-0000000534-19
Service ID: 44020C
Report Date: August 13, 2003

Calibration Performed for: Si Grande Corp
Quelque part, USA

Neutron Source Description: Source Type: ^{252}Cf
Serial Number XXX-XX-XXXX

Calibration Results for Source Identified Above:

Calibrated neutron emission-rate:	$1.68 \times 10^8\ s^{-1}$
Relative expanded uncertainty:	± 4.30 % (95 % level of confidence)
Calibration date:	August 11, 2003
NBS-1 emission-rate on date of calibration:	$1.234 \times 10^6\ s^{-1}$

This calibration was performed by:

Maynard S. Dewey, Physicist
Neutron Physics Group

This calibration was reviewed by:

H. Pieter Mumm, Physicist
Neutron Physics Group

H. Pieter Mumm, Leader
Neutron Physics Group

For the Director of the National Institute of Standards and Technology:

Alan Thompson, Division Chief
Radiation Physics Division

Information on technical aspects of this report may be obtained from Maynard Dewey, National Institute of Standards and Technology, 100 Bureau Drive Stop 8463, Gaithersburg, MD 20899, m.dewey@nist.gov, or (301) 975-4843.

National Institute of Standards and Technology

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Appendix for ^{252}Cf Neutron Source Strength Calibration Reports

Calibration Method

Neutron source strength measurements performed in building 245, room B143 at NIST are accomplished by making a traceable comparison between the emission rate of the source being calibrated and the national primary standard source, NBS-1, whose emission rate has been determined absolutely. The measurements of source emission rate are made by activating a circulating, aqueous solution of manganese sulfate, and continuously counting the induced ^{56}Mn activity with a scintillation counter. During calibration, the neutron source is placed within a small Teflon cavity that is positioned at the center of the 1.27 m diameter spherical bath; activity measurements are taken once the bath has reached saturation. The purpose of the cavity is to reduce the absorption of thermal neutrons by the source. Corrections to the measured source strength have been applied in order to account for the following effects: capture of fast neutrons by oxygen and sulfur in the bath, capture of fast and thermal neutrons by fluorine in the Teflon source holder, neutron escape from the bath, and thermal neutron absorption in the source. Typical values for these corrections are:

Fast neutron capture by oxygen and sulfur:	0.840 %
Fast and thermal neutron capture by fluorine:	0.118 %
Neutron escape from the bath:	0.085 %
Thermal neutron absorption in the source:	0.186 %

Because the measurement is relative, it is not sensitive to environmental conditions in the lab (temperature, humidity, pressure). The reported emission rate tallies neutrons of all energies emerging in all directions from the source. The reported number contains no information about the neutron spectrum nor the angular distribution of the emitted neutrons. When the emission rate is combined with a Monte Carlo model of neutron interactions incorporating the source neutron spectrum, source geometry, and environment, then absolute neutron fields in the environment can be calculated.

Uncertainties

The expanded uncertainty consists of components evaluated by statistical means (“Type A” uncertainties) and components determined on the basis of alternative techniques (“Type B” uncertainties). The Type A and Type B uncertainty components relevant to this calibration are identified below.

Type A uncertainties:	Count-rate associated with NBS-1 (typically < 0.5 %)
	Count-rate associated with the calibrated source (typically < 0.5 %)
Type B uncertainties:	Uncertainty associated with the applied corrections for both NBS-1 and the calibrated source (± 0.3 %, and typically 0.25 % to 1 %, respectively)
	NBS-1 emission-rate (± 0.85 %)
	Detector calibration (± 0.85 %)

The expanded uncertainty reported corresponds to the quadrature-sum of the stated uncertainty components multiplied by a coverage factor, k, equal to two (2). The expanded uncertainty, therefore, represents an approximate level of confidence of 95 %. The results provided in this report relate only to the source listed in the “Neutron Source Description”.

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