Preliminary P_{1n} and P_{2n} Calculations Including Background Coincidences for BRIKEN RUN148

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for the
BRIKEN Collaboration

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Some Preliminary Results

Nucleus	Q_β (MeV)	$Q_{\beta n}$ (MeV)	$Q_{\beta nn}$ (MeV)	P_n (%)	P_{2n} (%)	P_n(Lit) (%)	P_{2n}(Lit) (%)
^{77}Cu	10.3	5.7	-2.2	29(1)	0.0(5)	30.3(2)	0.0
^{78}Cu	13.0	6.2	1.6	39.5(5)	0.0(5)	65(20)/ 44(5)	
^{79}Cu	11.5	7.5	0.9	62.6(5)	0.0(5)	55(17)/ 72(12)	
^{80}Cu	15.2	8.9	5.1	57.5(1)	0.0(+5,-10)	?	
^{81}Cu	14.4	11.8	5.9	73.0(5)	0.0(+5,-10)	?	
^{84}Ga	13.9	8.8	5.2	37.5(10)	1.5(5)	74/20/ 51	
^{85}Ga	13.1	10.2	5.0	74.5(10)	1.5(1)	35/>40/ 70(5)	
^{86}Ga	15.3	11.0	7.9	59.0(5)	16(1)	60(10)	20(10)
^{87}Ga	14.5	12.1	7.7	65.5(5)	17.0(5)	?	?

Uncertainties are from fit only.
Many other uncertainties to be included.

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Uncertainties are from fit only.
Many other uncertainties to be included.

Approach

List possible implants, beta triggers, neutrons, and random neutrons.

Flat background terms *i.e.* no $T_{\beta n}$ dependence

{Implant}	{ β }	{Neutron}	{Associated P_{jn}}	{Number Neutrons}
r_I	r_β	r_{0n}	–	0
r_I	r_β	r_{1n}	–	1
r_I	r_β	r_{2n}	–	2
r_I	$\tilde{\varepsilon}_{\beta 0n}$	r_{0n}	$\tilde{P}_{0n}$ (no T dep)	0
r_I	$\tilde{\varepsilon}_{\beta 0n}$	r_{1n}	$\tilde{P}_{0n}$ (no T dep)	1
r_I	$\tilde{\varepsilon}_{\beta 0n}$	r_{2n}	$\tilde{P}_{0n}$ (no T dep)	2
r_I	$\tilde{\varepsilon}_{\beta 1n}$	$\tilde{\epsilon}_{11n}r_{0n}$	$\tilde{P}_{1n}$ (no T dep)	1
r_I	$\tilde{\varepsilon}_{\beta 1n}$	$\tilde{\epsilon}_{11n}r_{1n}$	$\tilde{P}_{1n}$ (no T dep)	2
r_I	$\tilde{\varepsilon}_{\beta 1n}$	$\tilde{\epsilon}_{11n}r_{2n}$	$\tilde{P}_{1n}$ (no T dep)	3
r_I	$\tilde{\varepsilon}_{\beta 1n}$	$\tilde{\epsilon}_{10n}r_{0n}$	$\tilde{P}_{1n}$ (no T dep)	0
r_I	$\tilde{\varepsilon}_{\beta 1n}$	$\tilde{\epsilon}_{10n}r_{1n}$	$\tilde{P}_{1n}$ (no T dep)	1
r_I	$\tilde{\varepsilon}_{\beta 1n}$	$\tilde{\epsilon}_{10n}r_{2n}$	$\tilde{P}_{1n}$ (no T dep)	2
ϵ_I	r_β	r_{0n}	–	0
ϵ_I	r_β	r_{1n}	–	1
ϵ_I	r_β	r_{2n}	–	2

r_x = random x

ε_x = efficiency of detecting x

ε_{jkn} the probability to detect k neutrons if j are emitted

P_{jn} = j neutron emission fraction

x tilde = all implants including nuclei considered which has $T_{\beta n}$ dependence with arbitrary start time so no $T_{\beta n}$ dependence overall!

Real decay terms, *i.e.* $T_{\beta n}$ dependent terms.

{Implant}	{ β }	{Neutron}	{Associated P_{jn}}	{Number Neutrons}
ϵ_I	$\varepsilon_{\beta 0n}$	r_{0n}	P_{0n} (T dep)	0
ϵ_I	$\varepsilon_{\beta 0n}$	r_{1n}	P_{0n} (T dep)	1
ϵ_I	$\varepsilon_{\beta 0n}$	r_{2n}	P_{0n} (T dep)	2
ϵ_I	$\varepsilon_{\beta 1n}$	$\epsilon_{11n}r_{0n}$	P_{1n} (T dep)	1
ϵ_I	$\varepsilon_{\beta 1n}$	$\epsilon_{11n}r_{1n}$	P_{1n} (T dep)	2
ϵ_I	$\varepsilon_{\beta 1n}$	$\epsilon_{11n}r_{2n}$	P_{1n} (T dep)	3
ϵ_I	$\varepsilon_{\beta 1n}$	$\epsilon_{10n}r_{0n}$	P_{1n} (T dep)	0
ϵ_I	$\varepsilon_{\beta 1n}$	$\epsilon_{10n}r_{1n}$	P_{1n} (T dep)	1
ϵ_I	$\varepsilon_{\beta 1n}$	$\epsilon_{10n}r_{2n}$	P_{1n} (T dep)	2

Two neutron decay terms, *i.e.* also $T_{\beta n}$ dependent terms.

{Implant}	{ β }	{Neutron}	Associated P_{xn}	{ Number of Neutrons }
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,2n}r_{0n}$	P_{2n}	2
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,2n}r_{1n}$	P_{2n}	3
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,1n}r_{0n}$	P_{2n}	1
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,1n}r_{1n}$	P_{2n}	2
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,1n}r_{2n}$	P_{2n}	3
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,0n}r_{0n}$	P_{2n}	0
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,0n}r_{1n}$	P_{2n}	1
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,0n}r_{2n}$	P_{2n}	2
ϵ_I	$\varepsilon_{\beta 2n}$	$\epsilon_{2,0n}r_{3n}$	P_{2n}	3
3	Neutron	and	Greater	Decays
⋮	⋮	⋮	⋮	⋮

Approach

List ways to add up implants, beta triggers, neutrons, and random neutrons
versus
number of neutrons detected.

$$\frac{N_0'}{N} = F_0 + \epsilon_I P_{0n} \varepsilon_{\beta 0n} r_{0n} + \epsilon_I P_{1n} \varepsilon_{\beta 1n} \epsilon_{10n} r_{0n}$$

$$\frac{N_1'}{N} = F_1 + \epsilon_I P_{0n} \varepsilon_{\beta 0n} r_{1n} + \epsilon_I P_{1n} \varepsilon_{\beta 1n} \epsilon_{11n} r_{0n} + \epsilon_I P_{1n} \varepsilon_{\beta 1n} \epsilon_{10n} r_{1n}$$

$$\frac{N_2'}{N} = F_2 + \epsilon_I P_{0n} \varepsilon_{\beta 0n} r_{2n} + \epsilon_I P_{1n} \varepsilon_{\beta 1n} \epsilon_{11n} r_{1n} + \epsilon_I P_{1n} \varepsilon_{\beta 1n} \epsilon_{10n} r_{2n}$$

Total N'_j number of counts (includes flat background)

F_j = sum of flat background terms for j detected neutrons

Approach

Solve for P_{jn}.
Notice minimal impact of implant efficiency, β efficiency, and rate of zero neutron background coincidence on P_j.

$$\begin{pmatrix} N_0/N \\ N_1/N \\ N_2/N \end{pmatrix} = \begin{pmatrix} N_0'/N \\ N_1'/N \\ N_2'/N \end{pmatrix} - \begin{pmatrix} F_0 \\ F_1 \\ F_2 \end{pmatrix} = \epsilon_I \varepsilon_\beta r_{0n} \left(E\right) \begin{pmatrix} P_{0n} \\ P_{1n} \\ P_{2n} \end{pmatrix}$$

with

$$\left(E\right) = \begin{pmatrix} 1 & a_1 \epsilon_{10n} & a_2 \epsilon_{20n} \\ r_{1n}/r_{0n} & a_1 \left(\epsilon_{11n} + \epsilon_{10n} r_{1n}/r_{0n}\right) & a_2 \left(\epsilon_{21n} + \epsilon_{20n} r_{1n}/r_{0n}\right) \\ r_{2n}/r_{0n} & a_1 \left(\epsilon_{11n} r_{1n}/r_{0n} + \epsilon_{10n} r_{2n}/r_{0n}\right) & a_2 \left(\epsilon_{22n} + \epsilon_{21n} r_{1n}/r_{0n} + \epsilon_{20n} r_{2n}/r_{0n}\right) \end{pmatrix}$$

and $a_j = \varepsilon_{bjn} / \varepsilon_{b0n}$ = relative electron efficiency for βs emitted with j neutrons
and N_j = Real count for j neutrons.

$$\begin{pmatrix} P_0 \\ P_1 \\ P_2 \end{pmatrix} = \frac{1}{\epsilon_I \varepsilon_\beta r_{0n} N} \left(E\right)^{-1} \begin{pmatrix} N_0 \\ N_1 \\ N_2 \end{pmatrix} .$$

Approach

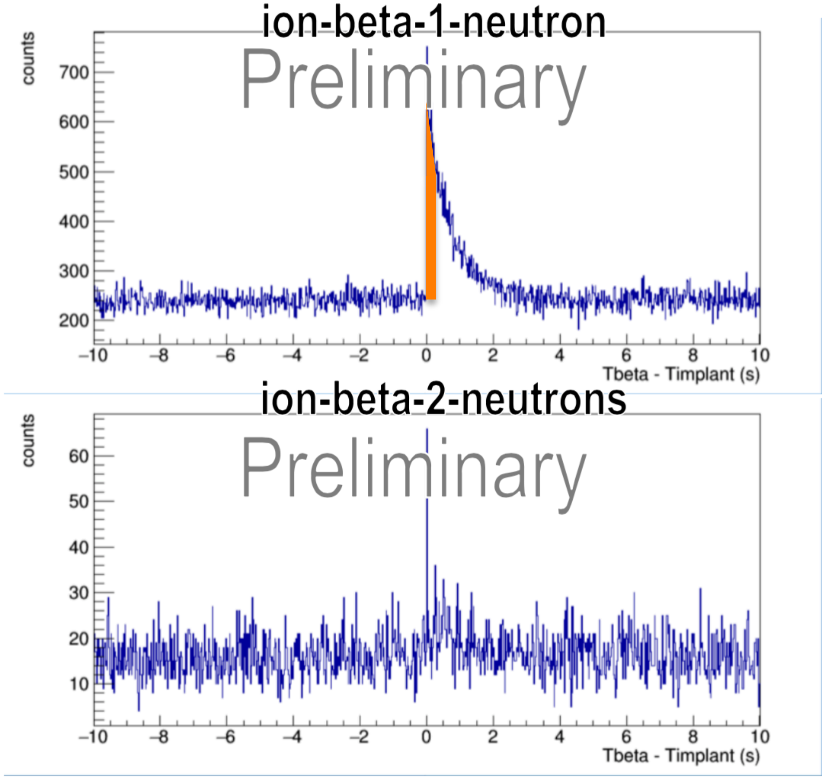
How do we measure N_0, N_1, and N_2?
Integrate over 1 half-life and then add in Bateman correction for no neutron daughters in N_0. For certain nuclei more needs to be included. For example ones with high P_n. This is on the to do list which will affect decays further from stability.

Half-lives are taken from literature or from the P_{2n} versus time histogram if unknown.
The P_{2n} decay curves should have the cleanest $T_{\beta n}$ dependence of all of the time curves.

For all of the calculations we assume a 0.60 (60%) single neutron efficiency.

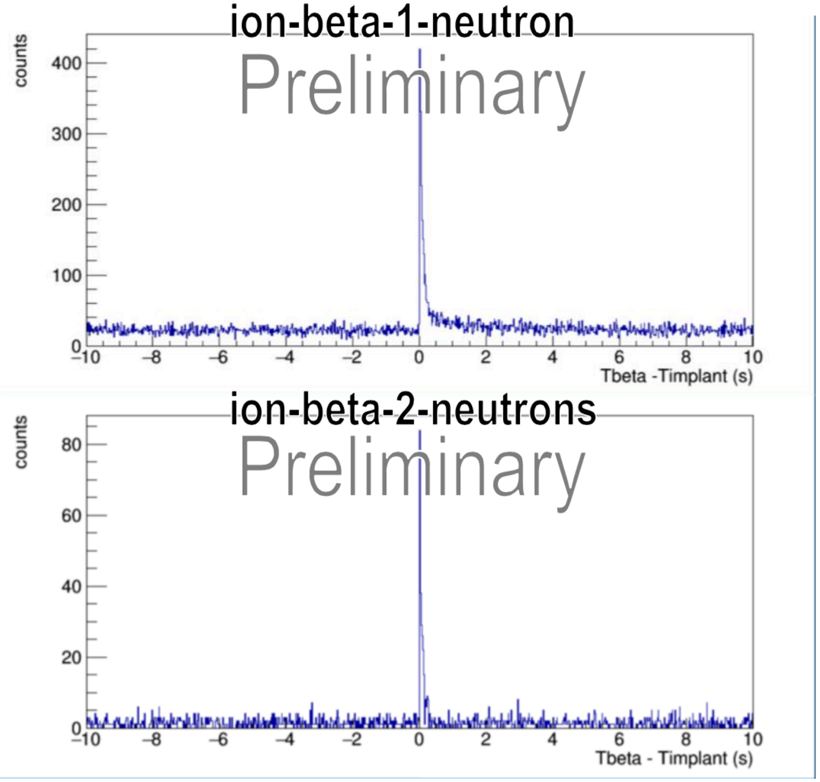
Approach to Calculating N_j

^{77}Cu: Pn = 0.303 (22), Qβ2n < 0
(S. V. Ilyushkin et al. PRC 80, 054304)



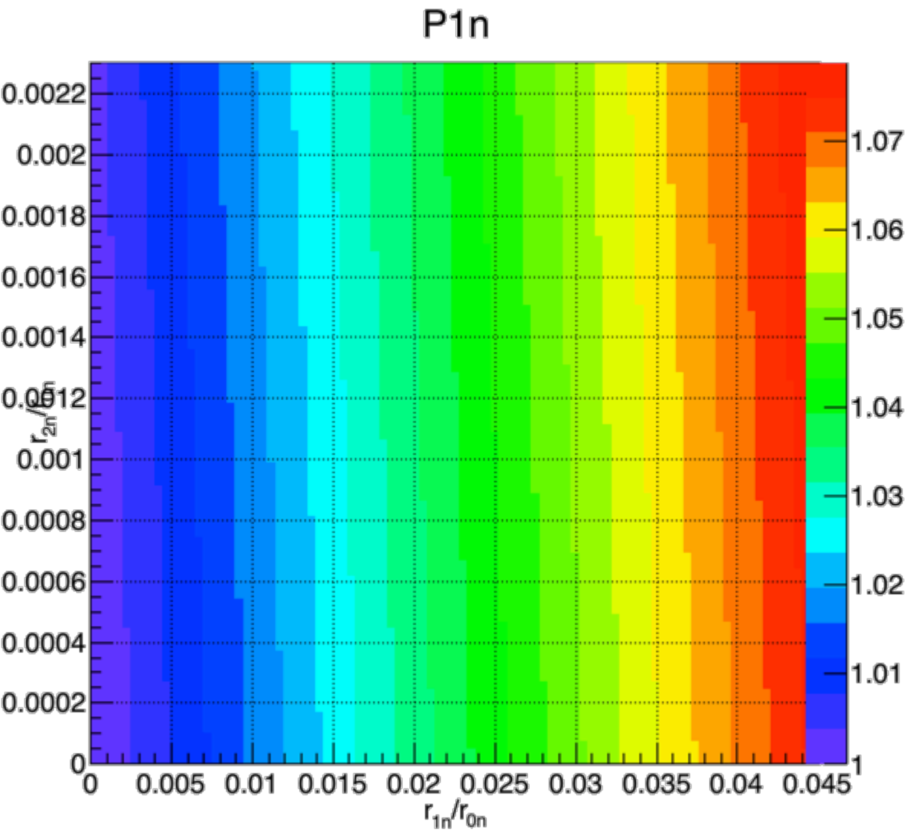
P_{1n} = 29(1)% P_{2n} = 0.0(5)%

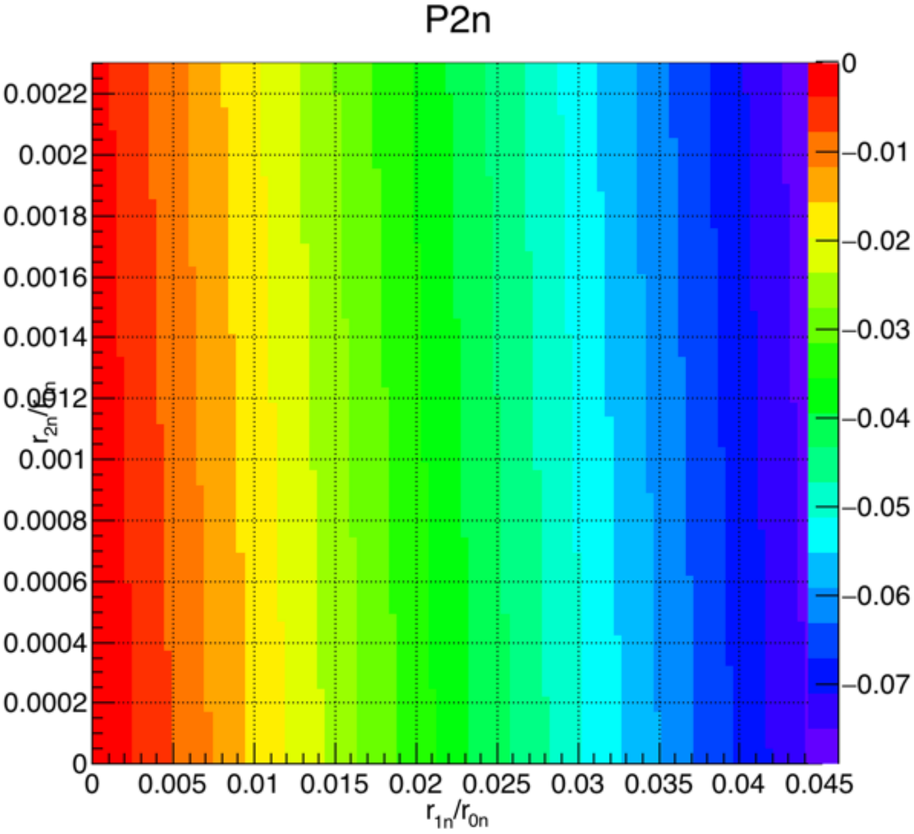
^{86}Ga: Pn = 0.6 (1), P2n = 0.2 (1)
(K. Miernik et al. PRL 111, 132502)



P_{1n} = 59.0(5)% P_{2n} = 16(1)%

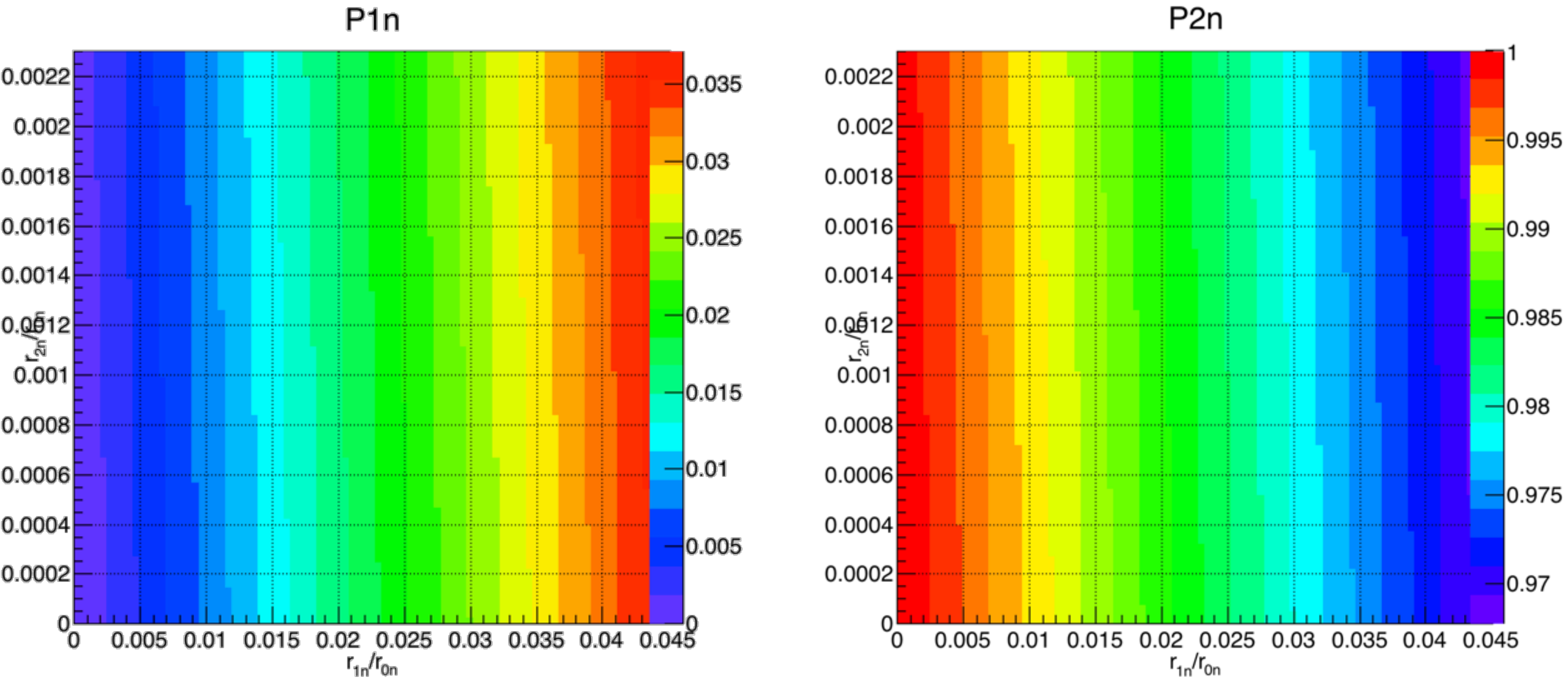
Example: 100% P_{1n} Feeding





For $N_0 = 400$, $N_1 = 600$, $N_2 = 0$, and no noise, $P_{1n} = 1.0$, $P_{2n} = 0.0$.
It Works!

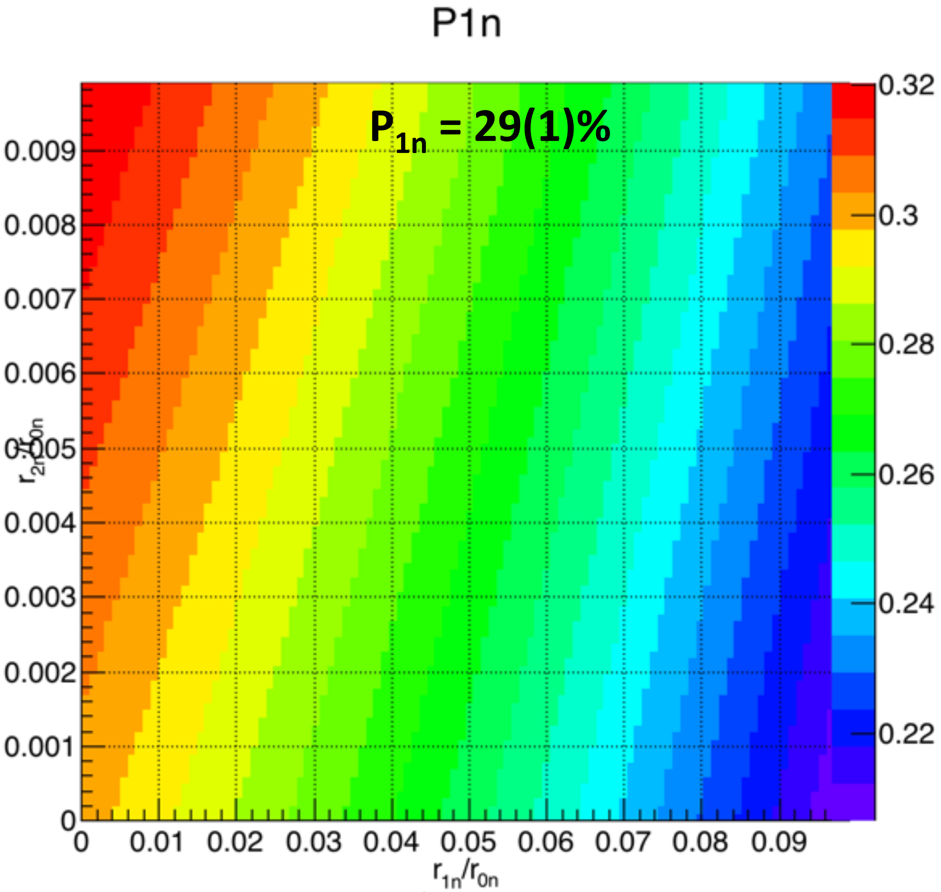
Example: 100% P_{2n} Feeding



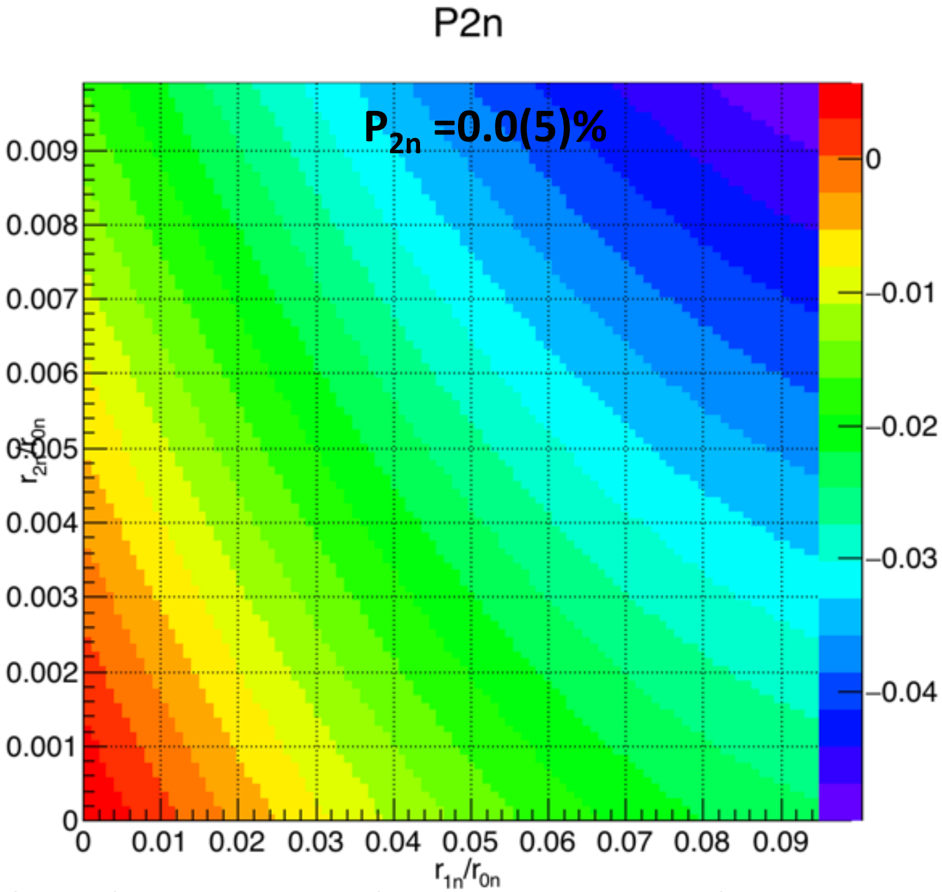
For $N_0 = 160$, $N_1 = 480$, $N_2 = 360$, and no noise, $P_{1n} = 0.0$, $P_{2n} = 1.0$.
It Works!
All other values will work since they are literally a linear combo of this and the previous slide.
For some parameters the matrix is near singular, but not in general for our high neutron efficiency and other β-efficiency parameters.

Example: ^{77}Cu

$T_{1/2}$ =469±8ms (from β-n decay), P_{1n}(lit) =0.30±0.02


P1n

P_{1n} = 29(1)%


P2n

P_{2n} =0.0(5)%

Input: Number counts in N_0, N_1, and N_2 less than $T_{1/2}$ and then N_0 corrected by approximate Bateman Equation.

X axis is 1 neutron noise rate divided by zero neutron noise rate.

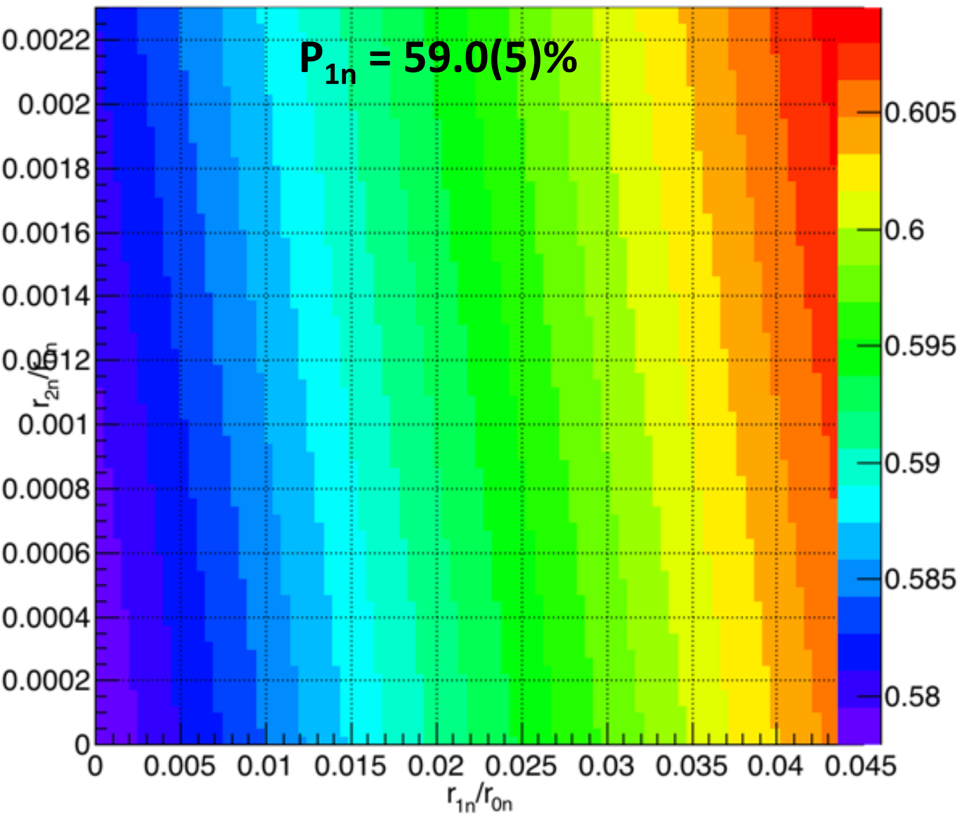
Y axis is 2 neutron noise rate divided by zero neutron noise rate.

Can use P_{2n} = 0 to estimate noise on P_{1n} graph.

Example: ^{86}Ga

$T_{1/2}$ (lit)=43(+21-15)ms, P_{1n}(lit) =0.6±0.1, P_{2n}(lit) =0.2±0.1

P1n



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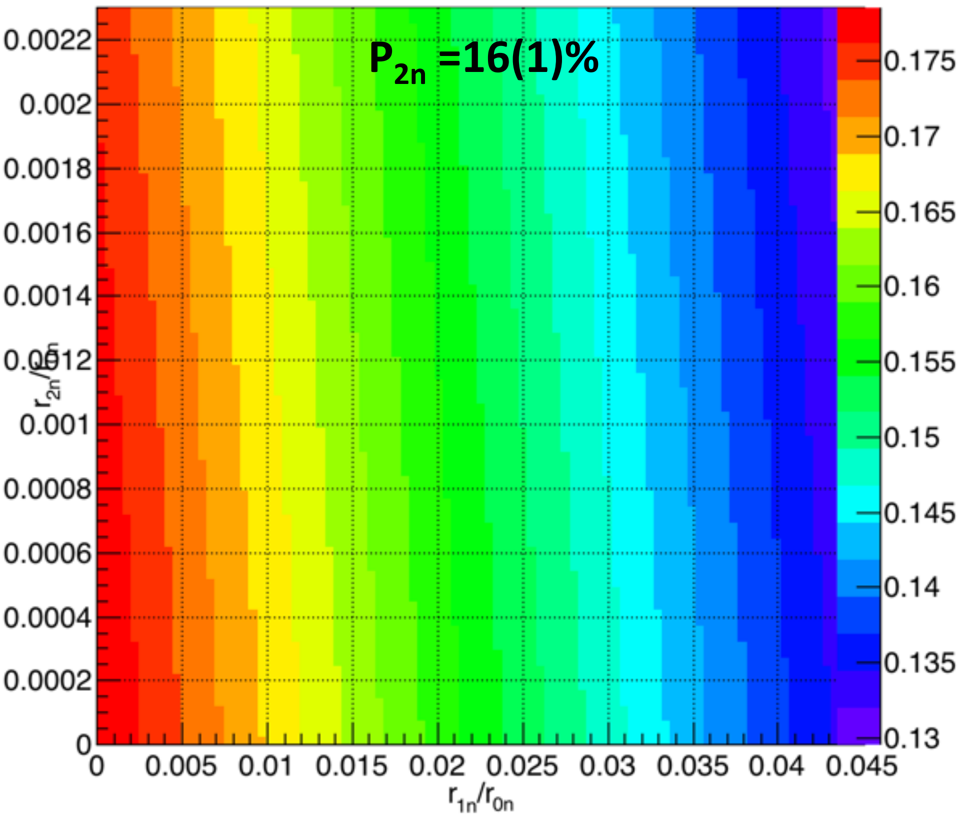


P_{2n} =16(1)%

Input: Number counts in N_0, N_1, and N_2 less than $T_{1/2}$ and then N_0 corrected by approximate Bateman Equation.

Can use estimated noise from ^{77}Cu and other P_{2n} = 0.

$T_{1/2}$ = 52(5)ms from P_{2n} counts versus time.

Observations

Many of our values are smaller than previous values. This seems OK since nobody else seems to consider in a quantitative way background counts, aka false positive neutron events.

Half-lives we get from the two neutron curves seem acceptable, though further thought should be given to this to make sure.

P_{2n} is zero for all energetically forbidden P_{2n} decays.
We can (and do) use this information to estimate the noise levels.

Errors do NOT include anything other than the variance of the noise fits shown in the P_{1n} and P_{2n} graphs.

Improvements/Plans

Need to include daughter neutron decays in Bateman correction.
i.e. daughter decays in the N_1 and N_2 channels and their cross talk.

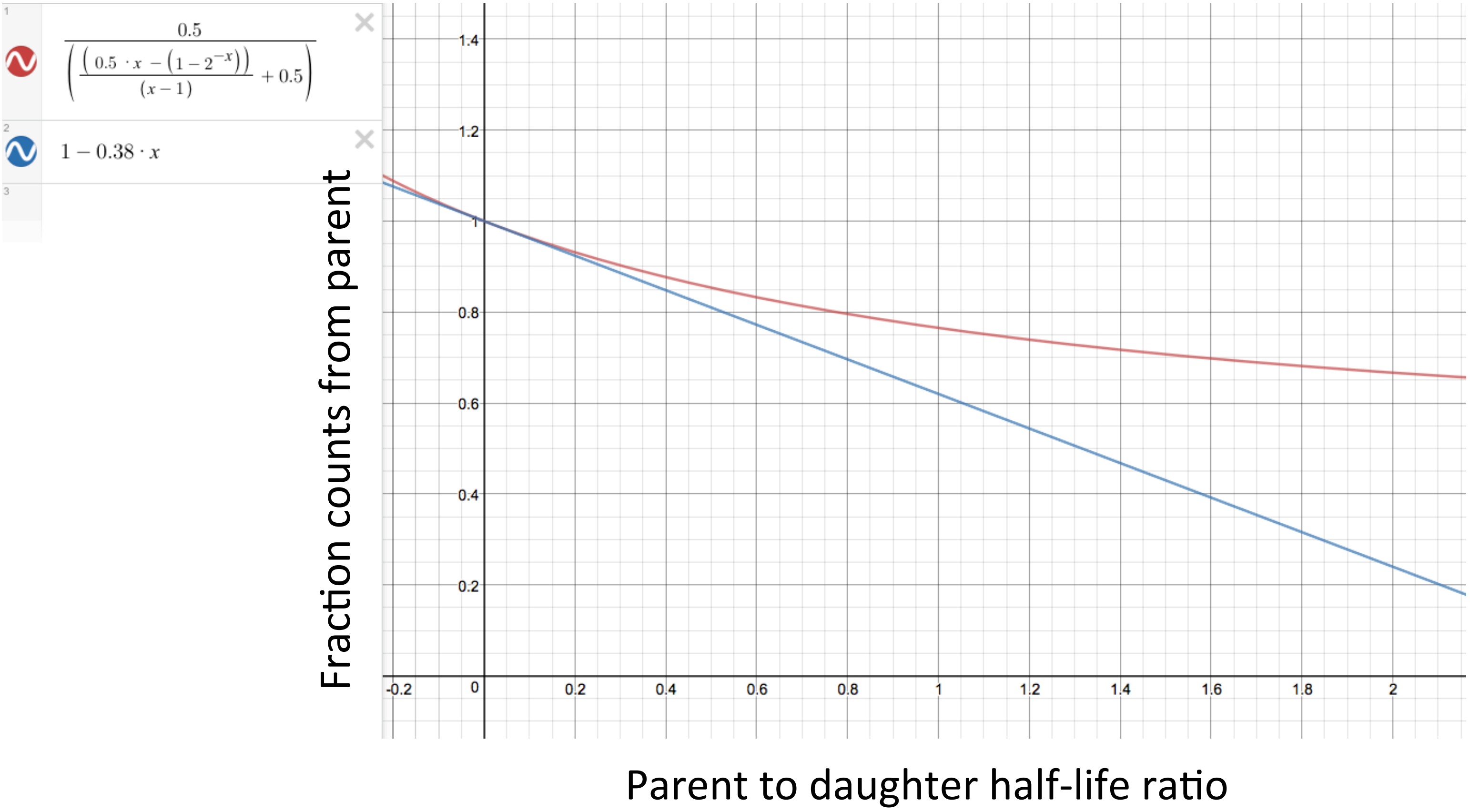
Vary the number of counts per neutron channel in order to get statistical uncertainties for the P_{jn}.

Check influence of neutron efficiency on P_{jn}.

Check influence of β_{xn} efficiency on P_{jn}.

Extra Slides

N_0 Bateman Correction



$$\frac{0.5}{\left(\frac{\left(0.5\cdot x-\left(1-2^{-x}\right)\right)}{(x-1)}+0.5\right)}$$

$$1-0.38\cdot x$$

Blue is approximate, rust color is exact equation.