

# Updating the MCNP Guide Extension with supermirror absorption and neutron polarization

Kyle Grammer, Franz Gallmeier

April 13, 2026

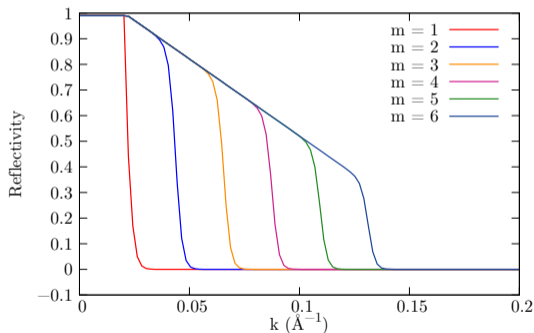


# Neutron guide extension history



## Implementations

- 2009: first implementation in MCNPX (Gallmeier et al. 10.13182/NT09-A9304)
- 2020: event biasing in MCNP6 (Magán and Bergmann 10.1016/j.nima.2019.163168)
- 2026: supermirror absorption and polarization (Grammer and Gallmeier 10.1016/j.nima.2025.171067)

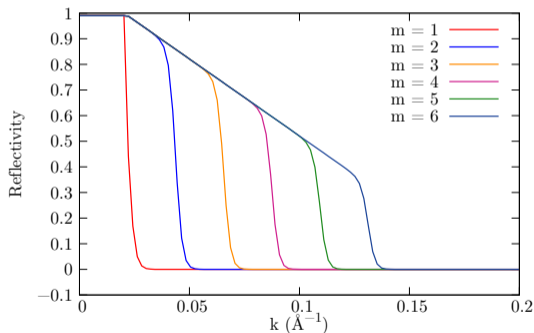


# Neutron guides



## Input cards

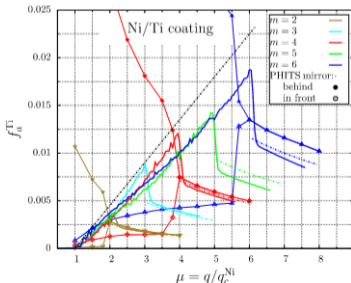
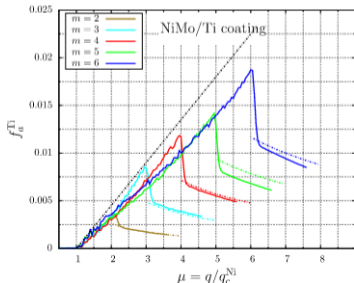
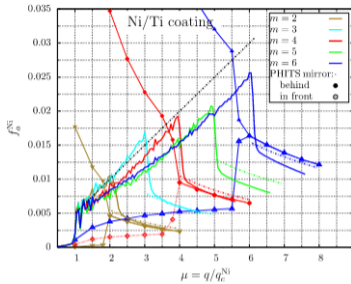
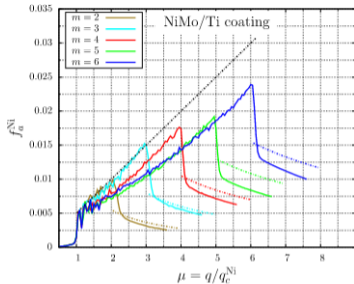
- `reffN  $R_0$   $q_c$   $m$   $\alpha$   $W$` 
  - $R_0$  reflectivity
  - $q_c$  critical momentum transfer  $\text{\AA}^{-1}$
  - $m$  m-value ( $m = 1$  nickel)
  - $\alpha$  slope above  $q_c$
  - $W$  supermirror cutoff
- `refleM  $S$   $N$   $-C$` 
  - $S$  surface number
  - $N$  reff card number
  - $C$  cell number



# Neutron guide absorption

- Can have significant impact on shielding due to dose rate coefficient for high energy gammas from capture on nickel compared to from 478 keV from B-10.
- Reflection for neutrons with  $q > q_c$  occurs at some depth in the supermirror layers according to Bragg's law, thus the full incident beam penetrates the supermirror layers and could be absorbed.
- Modeling a guide (2009 version) as a reflecting surface at the vacuum-supermirror boundary with a supermirror layer below would under-estimate the gamma production.
- Modeling a guide (2009 version) as a reflecting surface at the supermirror-substrate boundary with a supermirror layer above would over-estimate the gamma production.
- The 2020 version had a reflection depth estimation that was presented at ICANS XXIII, but this has been disabled in the 2026 version.
- The 2026 version uses a virtual supermirror layer material and produces gammas according to the model given in Kolevatov, Schanzer, Böni (doi: [10.1016/j.nima.2018.12.069](https://doi.org/10.1016/j.nima.2018.12.069)).

# Kolevator Model for Absorption



- Neutron absorption fraction per incident neutron ( $f_a^x$ ) for species  $x$
- $q < q_c$ :  

$$f_a^x = (1 - R_0)(1 - \exp\left[\frac{-2\pi\Sigma_a^x\Delta}{\lambda q_c}\right])$$
- NiMo  $q_c < q < mq_c$ :  $f_a^x = gq/q_c$
- Ti  $q_c < q < mq_c$ :  

$$f_a^x = g(q/q_c - 1)$$
- NiMo  $q > mq_c$ :  

$$f_a^x = \frac{g}{\mu}(m + 0.1)^2$$
- Ti  $q > mq_c$ :  

$$f_a^x = \frac{g}{\mu}(m + 0.1)(m - 0.9)$$
- $g$  is taken to be dependent on capture cross section
- Plots from doi:  
[10.1016/j.nima.2018.12.069](https://doi.org/10.1016/j.nima.2018.12.069)

# Input updates - Supermirror absorption



## Input cards

- Spin up `reffN R0 qc m alpha W R1 Sigmaa1 Sigmaa2 Sigmaa3 M1 M2 M3`
  - $R_0$  reflectivity at  $q = q_c$
  - $q_c$  critical momentum transfer  $\text{\AA}^{-1}$
  - $m$  m-value ( $m = 1$  nickel)
  - $\alpha$  slope above  $q_c$
  - $W$  supermirror cutoff
  - $\Sigma_a^x$  absorption cross section for species  $x$  ( $\text{cm}^{-1}$ )
  - $R_1$  reflectivity at  $q = 0$
  - $M_x$  material number for species  $x$ )
- Unchanged: `refleM S N -C`
- New `rflag` modes 3 and 4, which perform supermirror absorption per incident neutron (all reflections) and per non-reflected neutron (biasing with increased weight), respectively.
- $R_0$  has a new meaning and  $R_1$  added because  $R(q < q_c)$  may not be constant (such as a FeSi polarizing supermirror), if  $R_1$  is not set by the user, then  $R_1 = R_0$  (preserves back-compatibility).
- Macroscopic cross sections are given by the user for each species ( $M_x$ ) of the supermirror layers, which should be specified as materials in the MCNP input file.

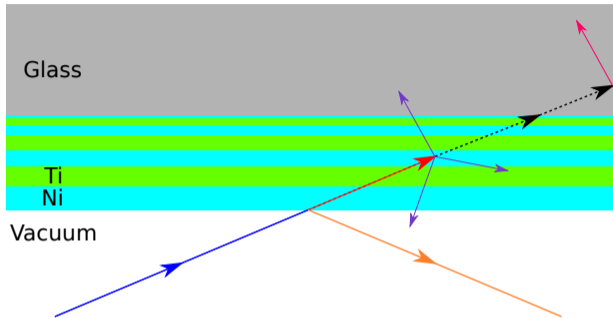
# Input updates - Polarization



## Input cards

- reffN  $R_0$   $q_c$   $m$   $\alpha$   $W$   $R_1$   $\Sigma_a^1$   $\Sigma_a^2$   $\Sigma_a^3$   $M_1$   $M_2$   $M_3$
- reffM  $R_0$   $q_c$   $m$   $\alpha$   $W$   $R_1$   $\Sigma_a^1$   $\Sigma_a^2$   $\Sigma_a^3$   $M_1$   $M_2$   $M_3$
- reffP  $R_N$   $R_M$   $P$ 
  - Spin up  $R_N$  and spin down  $R_M$  reflectivity parameters specified on reff cards.
  - Third reff card points to the first two and specifies an initial polarization,  $P$ .
  - On the first interaction with a mirror, the neutron track is split into spin up and spin down tracks with weights  $w_{\text{up}} = \frac{1+P}{2}w_0$  and  $w_{\text{down}} = 1 - w_{\text{up}}$
- $R_0$  has a new meaning and  $R_1$  added because  $R(q < q_c)$  may not be constant (such as a FeSi polarizing supermirror), if  $R_1$  is not set by the user, then  $R_1 = R_0$  (preserves back-compatibility).
- Macroscopic cross sections are given by the user for each species of the supermirror layers, given on the  $M_x$  parameters.
- Works with rflag 0, 2, 3, and 4.

# Process of reflecting a neutron with absorption

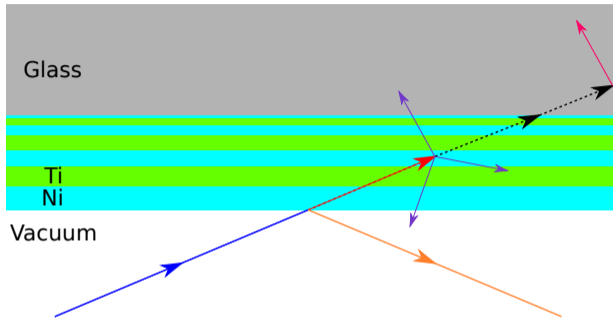


## Assumptions

- Interior vacuum region.
- Alternating layers with varying thicknesses of NiMo and Ti,  $\approx 3000$  layers with full thickness  $\approx 10 \mu\text{m}$
- Borofloat glass substrate, 5 mm.

- Neutron of weight  $W = W_0$  enters (blue)
- Neutron of weight  $W = R(q)W_0$  reflects (orange)
- Neutron of weight  $W = [1 - R(q)]W_0$  enters virtual supermirror layers (red)
- Gammas of weight  $W = f_{1,2,3}(1 - r)W_0$  are produced from species  $x = \text{Ni, Ti, Mo}$  (purple)
- Neutron of weight  $W = [1 - R(q) - f_1 - f_2 - f_3]W_0$  enters glass substrate (black)

# Reflecting a neutron with polarization and absorption

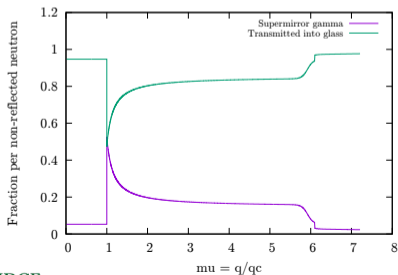
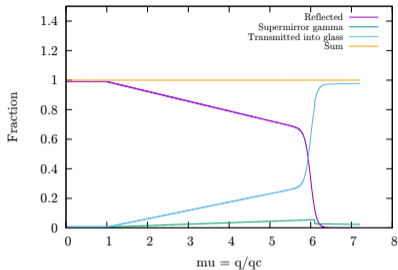


## Polarization

- Polarization case first splits incoming neutron into spin up and spin down parts according to  $P$  parameter and then proceeds to split accordingly into reflected/transmitted/absorbed components.
- Later reflections use the previously set spin for this neutron track.

- Neutron of weight  $W = W_0$  enters (blue)
- Neutron of weight  $W = R(q)W_0$  reflects (orange)
- Neutron of weight  $W = [1 - R(q)]W_0$  enters virtual supermirror layers (red)
- Gammas of weight  $W = f_{1,2,3}(1 - r)W_0$  are produced from species  $x = \text{Ni, Ti, Mo}$  (purple)
- Neutron of weight  $W = [1 - R(q) - f_1 - f_2 - f_3]W_0$  enters glass substrate (black)

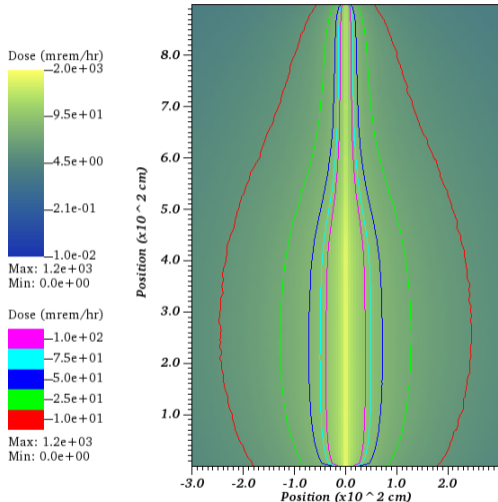
# Neutron guide weight balance



## Description

- Reflected, transmitted, and supermirror absorption component weights per incident neutron on a supermirror guide.
- Weights sum to unity, as expected.
- Over much of the region  $q_c < q < mq_c$ , 20% of non-reflected neutrons are absorbed in the supermirror layers.
- $\approx 5\%$  of incident neutrons at high angle of incidence will become high energy gammas with higher flux to dose coefficient than 478 keV, which implies supermirror absorption is a significant contribution to photon dose rate and should increase dose rates near a guide by a factor of  $\approx 2 - 3$ .

# Behavior with different rflag conditions

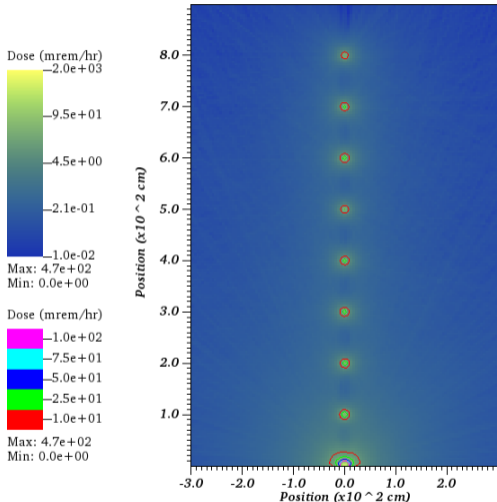


## rflag = 0, analog reflection

- Behavior of 2009 Guide extension.
- Random number throw ( $r$ ) at reflecting surface, and the neutron track either reflects (if  $r < R(q)$ ) or transmits (if  $r > R(q)$ ) and continues.
- Statistical sampling of effect of gamma production from neutrons transmitted into substrate may be poor in regions where  $R$  is close to unity. Basically, “explicit” reflection.
- No contribution of absorption in the supermirror layers without adding thin layer of material.

- Photon dose rate

# Behavior with different rflag conditions

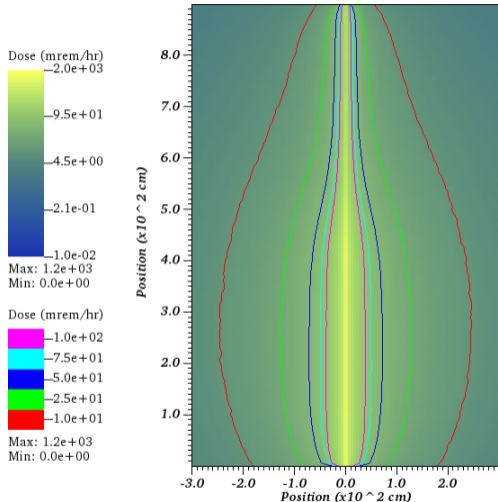


- Photon dose rate

## rflag = 1, always reflect

- Behavior introduced in 2020 Guide extension.
- Neutron always reflects with weight  $w = R(q)w_0$ .
- No gamma production and no transmission of neutrons into the substrate.
- No contribution of absorption in the supermirror layers without adding thin layer of material.
- Allows faster accumulation of statistics for neutrons that propagate through the guide system.

# Behavior with different rflag conditions

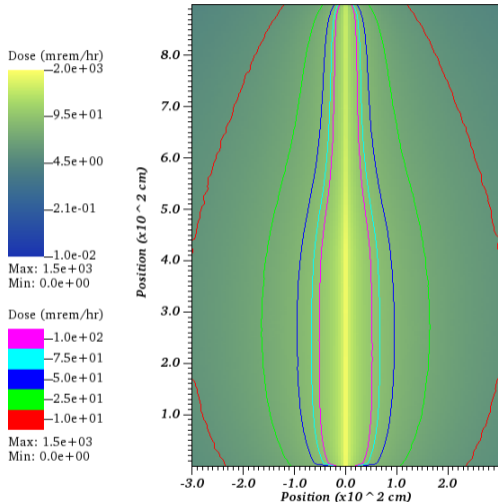


## rflag = 2, splitting at the surface

- Behavior similar to 2020 Guide extension.
- Neutron splits at reflecting surface into reflected and transmitted parts with weight  $W = R(q)W_0$  and  $W = [1 - R(q)]W_0$ , respectively.
- Statistical sampling of transmission into the substrate and reflection down the guide is improved, basically, “implicit” reflection.
- No contribution of absorption in the supermirror layers without adding thin layer of material.

- Photon dose rate.

# Behavior with different rflag conditions

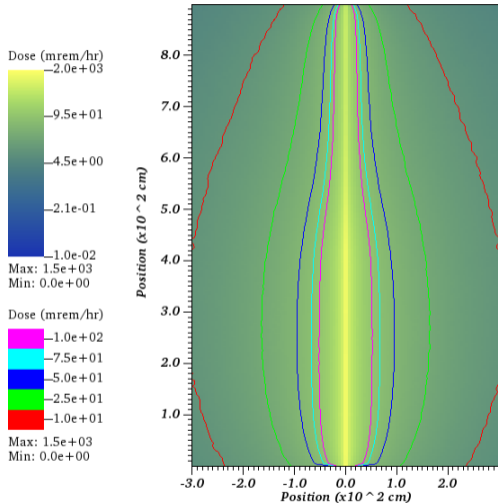


rflag = 3, abs. per incident neutron

- Behavior of 2026 Guide extension.
- Neutron splits at reflecting surface into reflected and transmitted parts with weight  $W = R(q)W_0$  and  $W = [1 - R(q)]W_0$ , respectively.
- Statistical sampling of transmission into the substrate and reflection down the guide is improved, basically, “implicit” reflection.
- Has contribution of absorption in the supermirror layers without adding thin layer of material because it is treated virtually.

- Photon dose rate.

# Behavior with different rflag conditions

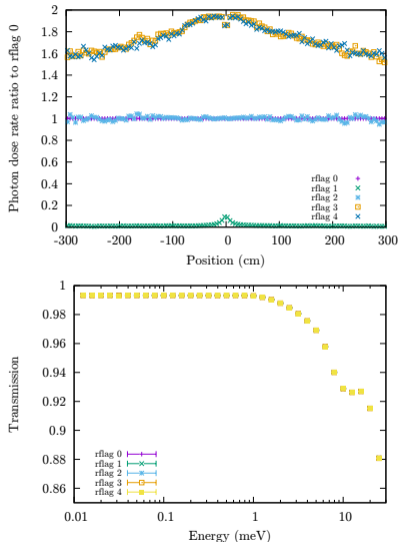


rflag = 4, abs. per non-reflected neutron

- Behavior of 2026 Guide extension.
- Neutron splits at reflecting surface into reflected and transmitted parts with weight  $W = R(q)W_0$  and  $W = [1 - R(q)]W_0$ , respectively.
- Statistical sampling of transmission into the substrate and reflection down the guide is improved, basically, “implicit” reflection.
- Virtual supermirror layer. Slightly lower statistics than rflag = 3 with slightly faster run-time.

- Photon dose rate.

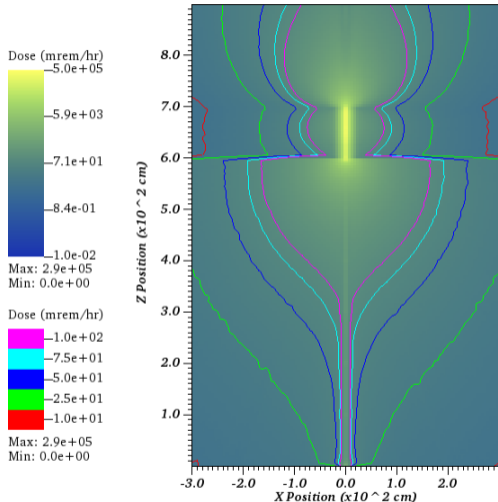
# Behavior with different rflag conditions



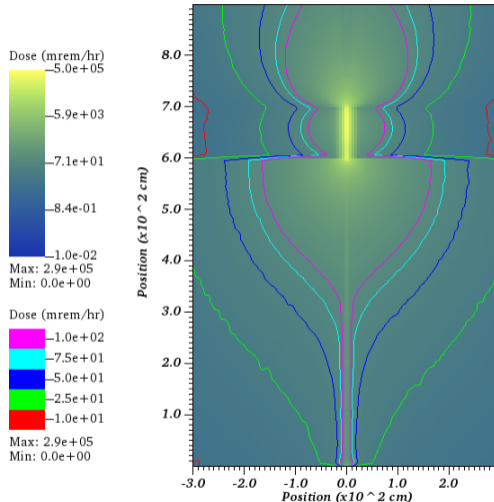
## Comparison

- Photon dose rate slice taken across the guide at  $z = 7$  m for each rflag case shows:
  - rflag 0 and 2 agree
  - rflag 3 and 4 agree
  - rflag 1 dramatically undercounts gammas
  - rflag 3 and 4 are approximately a factor of 2 higher dose rate
- Neutron transmission down the guide system (bottom) is consistent for all rflag cases (as expected).

# Photon dose rate around shielded $\nu$ -cavity

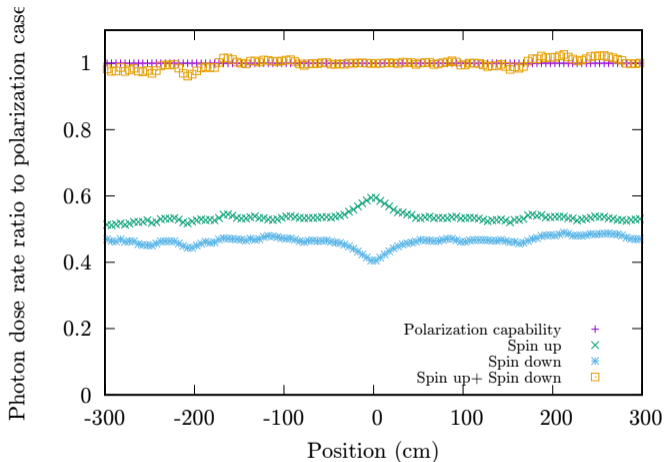


- Sum of Spin up, spin down calculations.



- Single calculation with polarization.

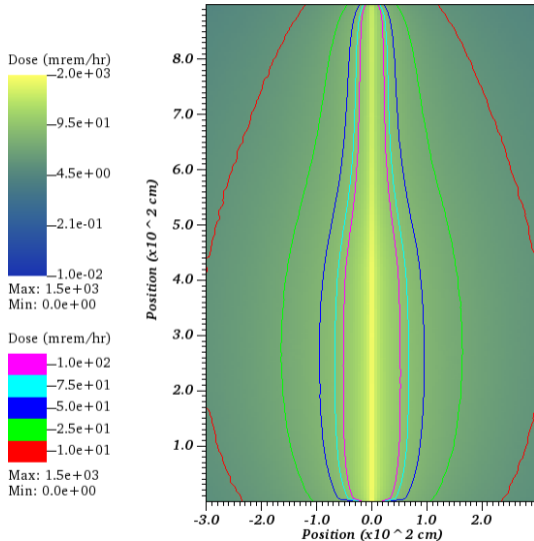
# Behavior with polarization enabled



## Comparison

- Photon dose rate slice taken across the guide at  $z = 7$  m for each polarization case using rflag=3 shows:
  - spin up and spin down are comparable
  - Polarization capability agrees with spin up + spin down sum.

# Conclusions



## Conclusions

- The Guide extension has a long history of development and improvement.
- The newest implementation adds supermirror absorption using a virtual layer of supermirror material that can produce gammas.
- Dose rates calculated from this implementation are consistent with expectations and more accurate for shielding purposes than cases assuming a thin layer of supermirror material in the model geometry.