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Title: Correlated Gammas from MCNPX using CGM

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ABSTRACT

Prior to the integration of the Cascading Gamma-ray and Multiplicity (CGM) code, the Monte Carlo Transport code MCNPX lacked the ability to produce correlated secondary particle/gamma emissions. CGM 2.0 was previously linked to MCNPX 2.7.C as a patch file to provide the capability to generate correlated secondary gammas. The previous linking strategy sent excitation energies, from MCNPX to CGM 2.0, to compute correlated secondary emissions for non-fission reactions based only on the lump sum of secondary neutron energies; furthermore, the previous linking strategy did not account for fission reactions. CGM has since been fully integrated into MCNPX 2.7.0 and now has a more comprehensive approach for computing excitation energy as well as a treatment for fission reactions. Excitation energy is now computed using both a lump sum of secondary neutron and charge particle energy, and fission reactions are treated by the LLNL library. This paper details a brief overview of the new integration methodology followed by several test cases highlighting the gamma spectrum and multiplicity distributions, beyond doubles and triples, computed from the CGM/MCNPX code.

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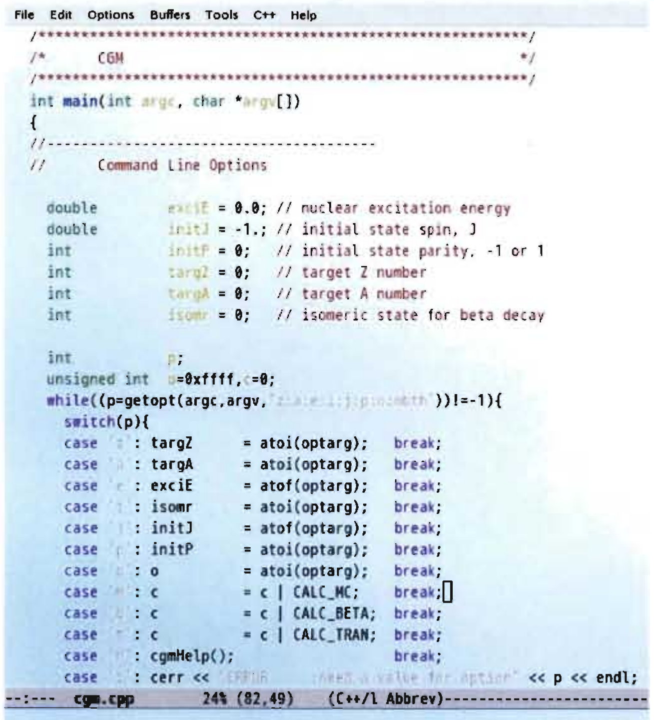
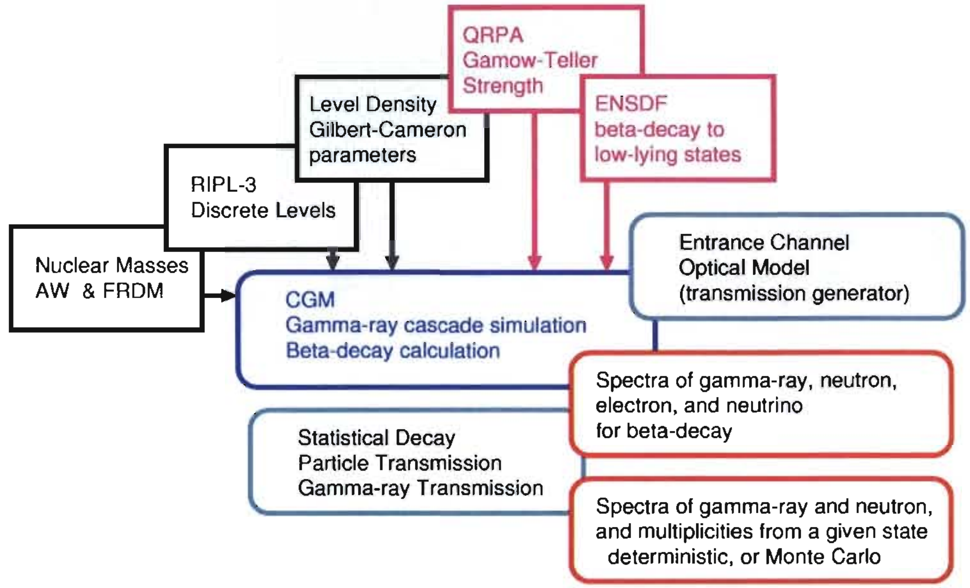
Outline

- CGM Code Overview
- CGM Integration into MCNPX
- Results
- Conclusions
- Future Work

Overview - CGM Code

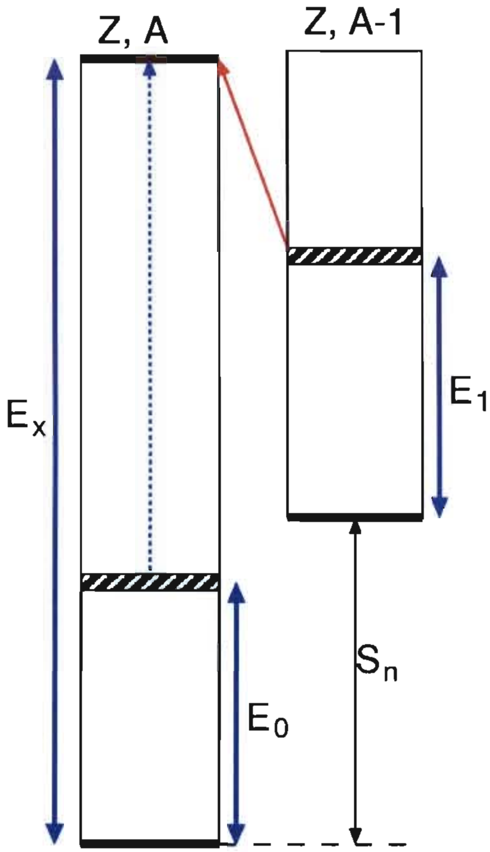


```
File  Edit  Options  Buffers  Tools  C++  Help
/****************************************************************/
/*      CGM                                                     */
/****************************************************************/
int main(int argc, char *argv[])
{
//----------------------------------------
//      Command Line Options

  double        exciE = 0.0; // nuclear excitation energy
  double        initJ = -1.; // initial state spin, J
  int           initP = 0;   // initial state parity, -1 or 1
  int           targZ = 0;   // target Z number
  int           targA = 0;   // target A number
  int           isomr = 0;   // isomeric state for beta decay

  int           p;
  unsigned int  o=0xffff,c=0;
  while((p=getopt(argc,argv,"z:a:e:i:j:p:o:mbth"))!=-1){
   switch(p){
   case 'z' : targZ     = atoi(optarg);   break;
   case 'a' : targA     = atoi(optarg);   break;
   case 'e' : exciE     = atof(optarg);   break;
   case 'i' : isomr     = atoi(optarg);   break;
   case 'j' : initJ     = atof(optarg);   break;
   case 'p' : initP     = atoi(optarg);   break;
   case 'o' : o         = atoi(optarg);   break;
   case 'm' : c         = c | CALC_MC;    break;
   case 'b' : c         = c | CALC_BETA;  break;
   case 't' : c         = c | CALC_TRAN;  break;
   case 'h' : cgmHelp();                  break;
   case ':' : cerr << "ERROR     :need a value for option" << p << endl;
--:---  cgm.cpp       24% (82,49)    (C++/l Abbrev)----------------------
```



- **CGM was derived from CoH3 code for**
  - Studying beta-delayed neutron and gamma emission
  - An event generator for the transport code MCNP
  - A Monte Carlo approach to the prompt fission neutron spectrum

Overview – Emission Probability



- **Gamma-ray emission**

$$P(\varepsilon_\gamma)dE_0 = \frac{T_\gamma(E_x - E_0)\rho(Z,A,E_0)}{N} dE_0$$

- **Neutron emission**

$$P(\varepsilon_n)dE_1 = \frac{T_n(E_x - S_n - E_1)\rho(Z,A-1,E_1)}{N} dE_1$$

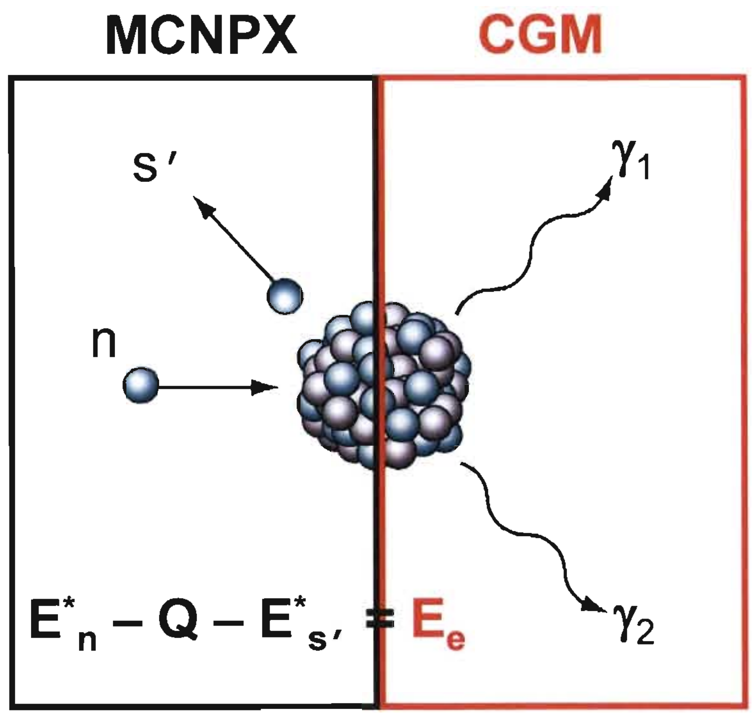
where $T_{n,\gamma}$ are the transmission coefficients, $\rho(Z,A,E)$ is the level density, and the normalization *N* is given by

$$N = \int_0^{E_x} T_\gamma(E_x - E_0)\rho(Z,A,E_0)dE_0 + \int_0^{E_x - S_n} T_n(E_x - S_n - E_1)\rho(Z,A-1,E_1)dE_1$$

- Integration performed only for spin and parity conserved states
- At low excitation energies, discrete level data is used (RIPL-3)

Overview - Monte Carlo CGM Version 3.4

```
// $Id: cgm.cpp,v 1.8 2010/11/15 23:19:05 kawano Exp $
/******************************************************************************/
/**                                                                          **/
/**    C G M  :  Cascading Gamma-ray and Multiplicity                       **/
/**                                      Version 3.4    Sinope (2011)       **/
/**                                                        T. Kawano        **/
/**    History                                                               **/
/**    1.0  2008 May  (Io)         Hauser-Feshbach for gamma spectra         **/
/**    2.0  2008 Jul. (Europa)     Gamma cascade by Monte Carlo              **/
/**    -    2008 Dec. (Ganymede)   CoH3beta branch full Hauser-Feshbach code **/
/**    3.0  2009 Sep. (Amalthea)   Backport version from CoH3-Callisto       **/
/**    3.1  2010 Feb. (Himalia)    Beta decay enhanced                       **/
/**    3.2  2010 Apr. (Elara)      Monte Carlo recovery version              **/
/**    3.3  2011 Jan. (Pasiphae)   Multiple neutron emission version         **/
/**    3.4  2011 Jun. (Sinope)     Monte Carlo with neutron emission version **/
/**                                                                          **/
/**                                    Los Alamos National Laboratory        **/
/**                                                                          **/
/******************************************************************************/
                                ...
#ifndef CGM
int main(int argc, char *argv[])
#else
extern "C"
{
void cgm(int, int, float, float *);
}
void cgm(int nz, int na, float ee, float rr[9])
#endif
{
//----------------------------------------
//      Command Line Options

  double        exciE = 0.0; // nuclear excitation energy
  double        initJ = -1.; // initial state spin, J
  int           initP = 0;   // initial state parity, -1 or 1
  int           targZ = 0;   // target Z number
  int           targA = 0;   // target A number
  int           isomr = 0;   // isomeric state for beta decay
  unsigned long nsim  = 0;   // number of Monte Carlo sampling
```



CGM Integration into MCNPX

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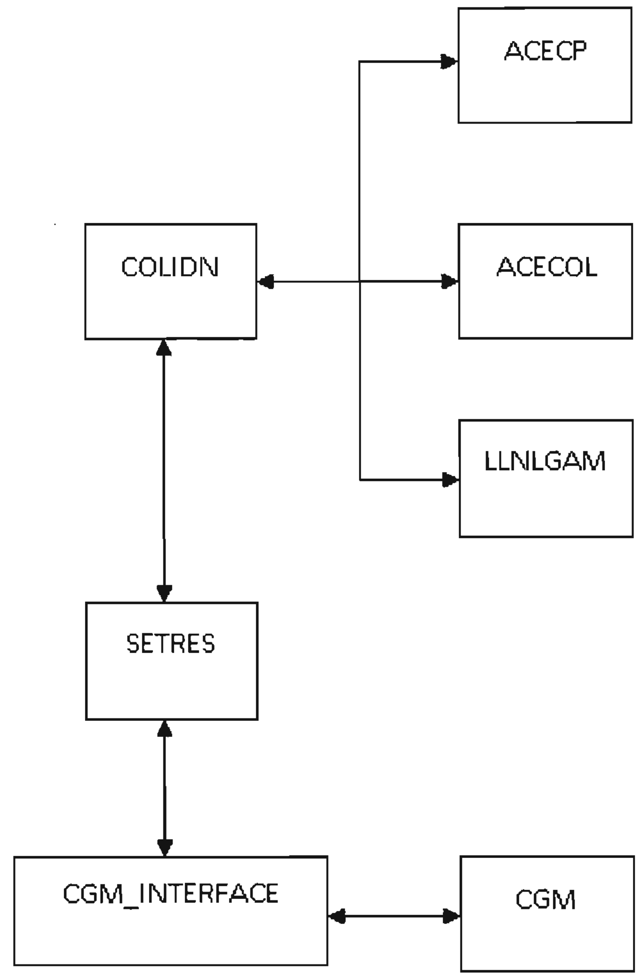
- **COLIDN determines**
  - Charged secondary particles
  - Number of secondary neutrons
  - Fission vs. non-fission
- **ACECP**
  - Produces secondary charged particles
  - Energy of charged particles
- **ACECOL**
  - Calculates total energy of non-fission neutrons
- **LLNLGAM**
  - Uses LLNL library for fission reactions
- **SETRES**
  - Determines residual nucleus
- **CGM_INTERFACE**
  - Calculates residual excitation energy (Ee)
  - Passes Ee and residual ZA to CGM
  - Receives gamma energies from CGM



Results

- **Gamma Spectrum and Multiplicities**
  - 14 MeV neutrons on Mg-24
  - Thermal neutrons on Ni-61
  - 14 MeV neutrons on Ni-61
  - Thermal neutrons on Ge-73
  - 14 MeV neutrons on W-183
  - Thermal neutrons on W-183

Results - Example MCNPX Input Deck

```
test CGM for 14 mev n plus 24Mg
1  1  -1.738  -1   imp:n,p,h,a,d=1
2  0               1   imp:n,p,h,a,d=0

1  so  1

mode  n p h a d
phys:n 7j 2  $ Use CGM
cut:n 2j 0 0 $ Force analog capture
m1    12024.70c 1
lca   7j -2
sdef  par=n erg=14
f1:p  1
e1   1e-3 999i 20.0
f21:p  1
e21   1e-3 99i 20.0
c
nps   1e7
```

New 8th entry on the PHYS:N card

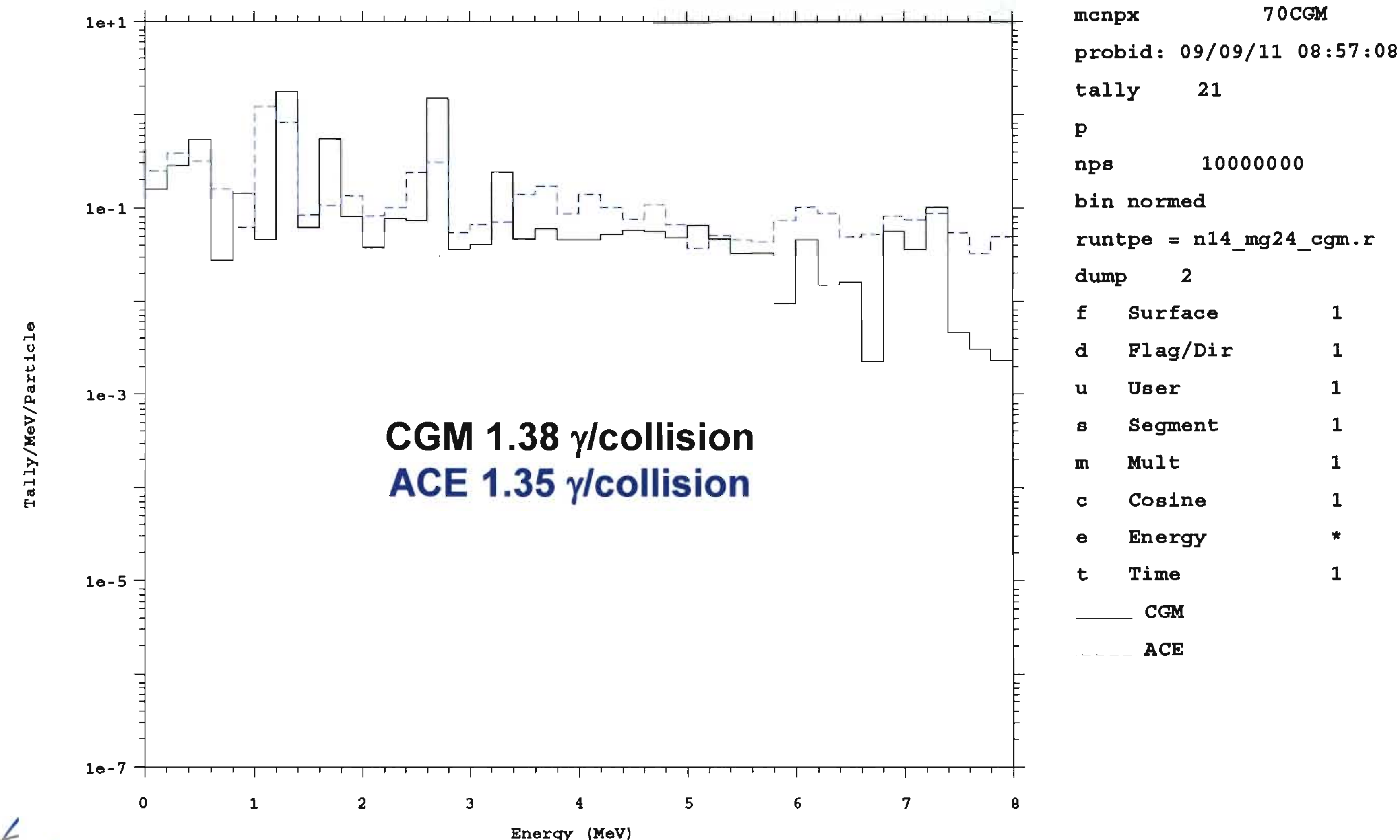
Neutron induced photon production method (table data energy range)

= 0 : no gamma production from neutrons;

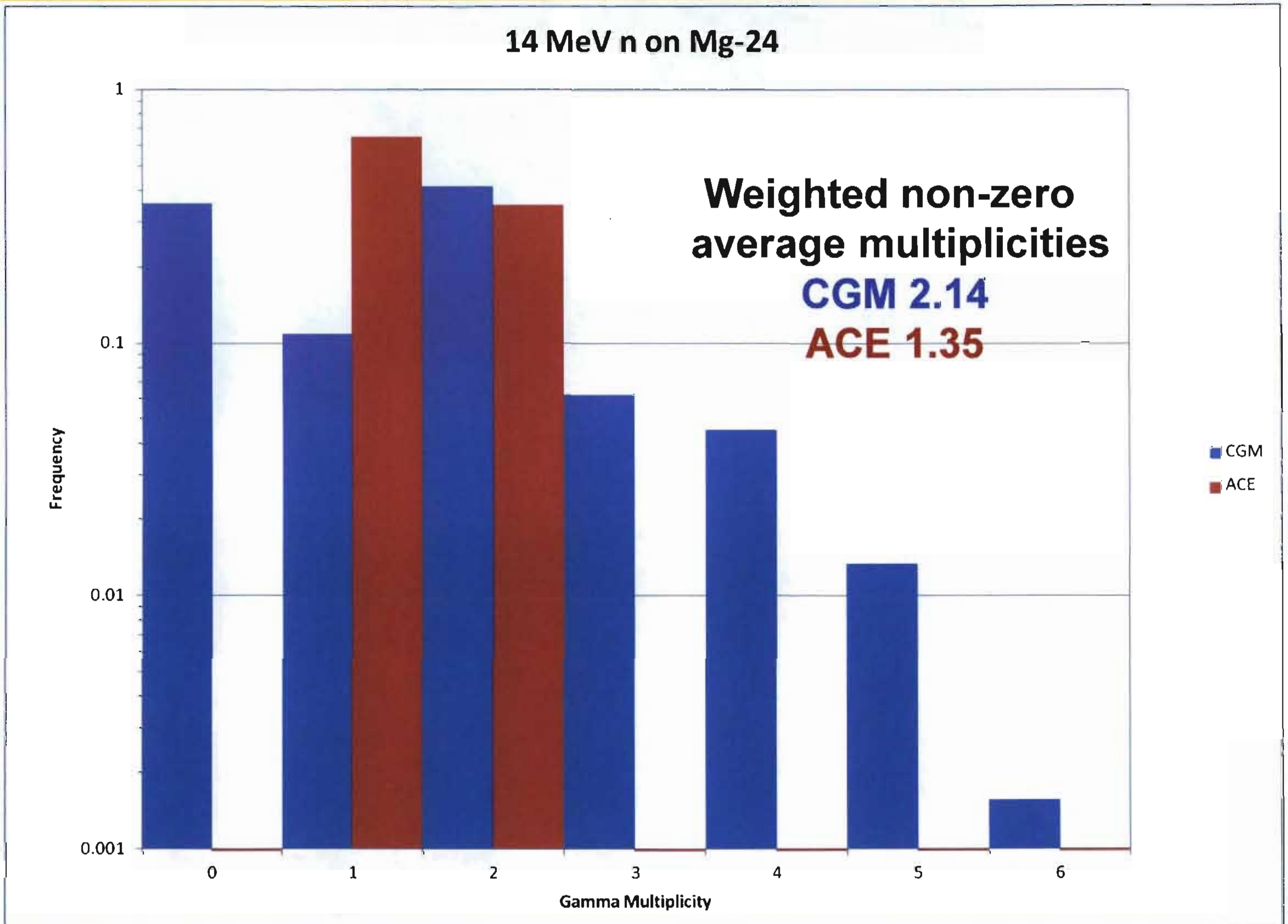
= 1: ACE library gamma production (DEFAULT);

= 2 : CGM correlated gamma production. This turns on LLNL fission (5th entry on the PHYS:N card set to 5)

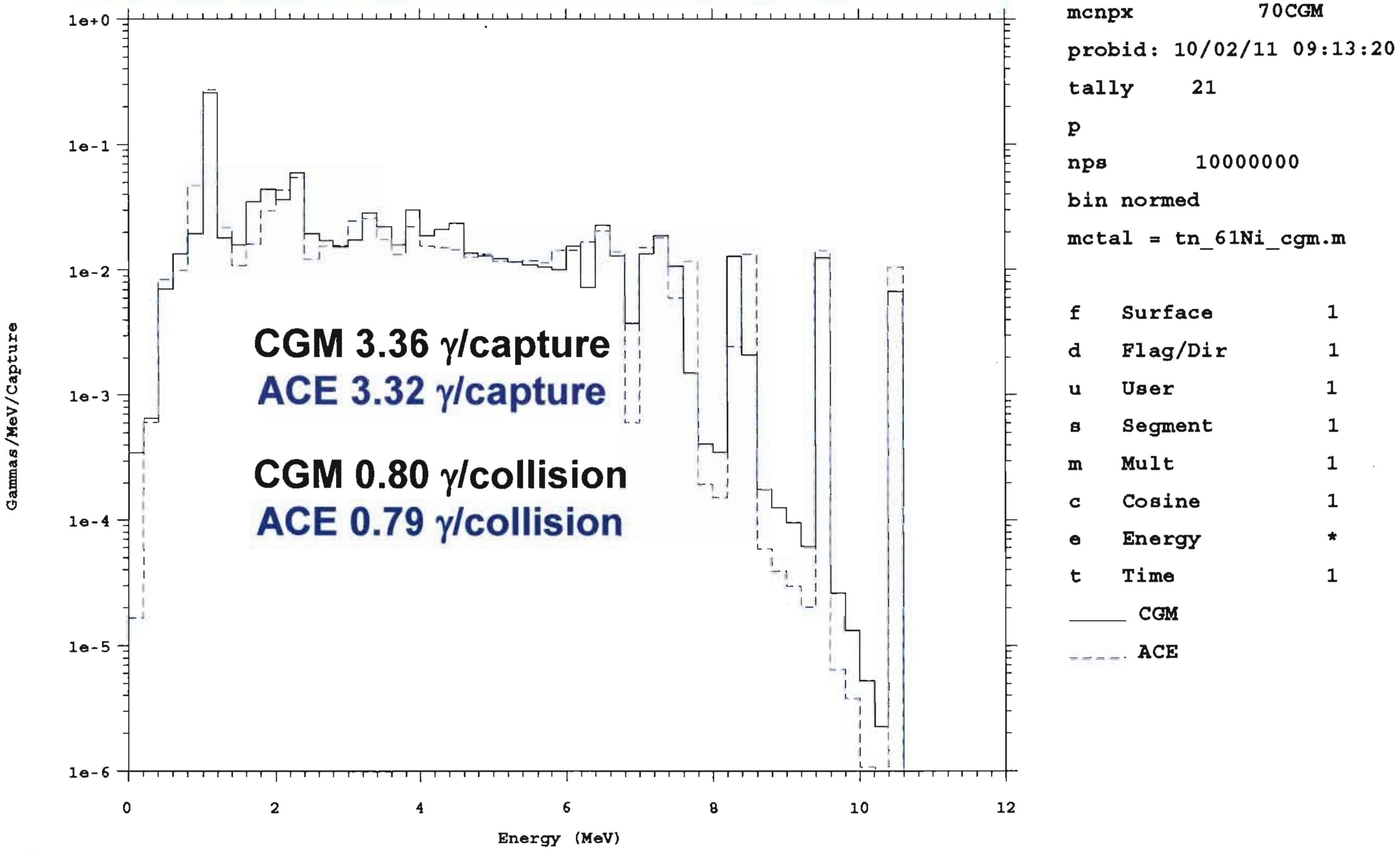
Results – 14 MeV Neutrons on Mg-24



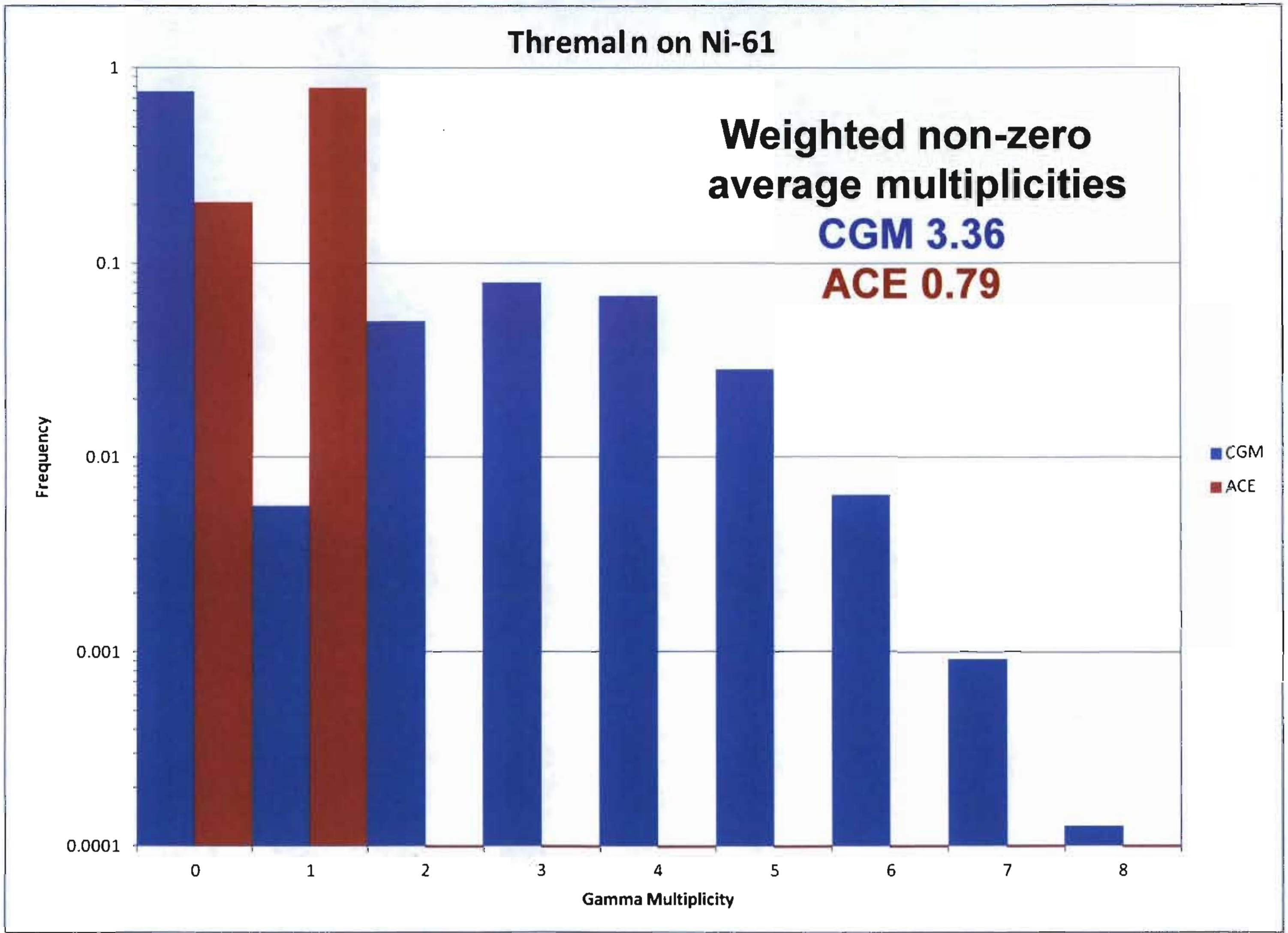
Results - 14 MeV Neutrons on Mg-24



Results – Thermal Neutrons on Ni-61



Results – Thermal Neutrons on Ni-61



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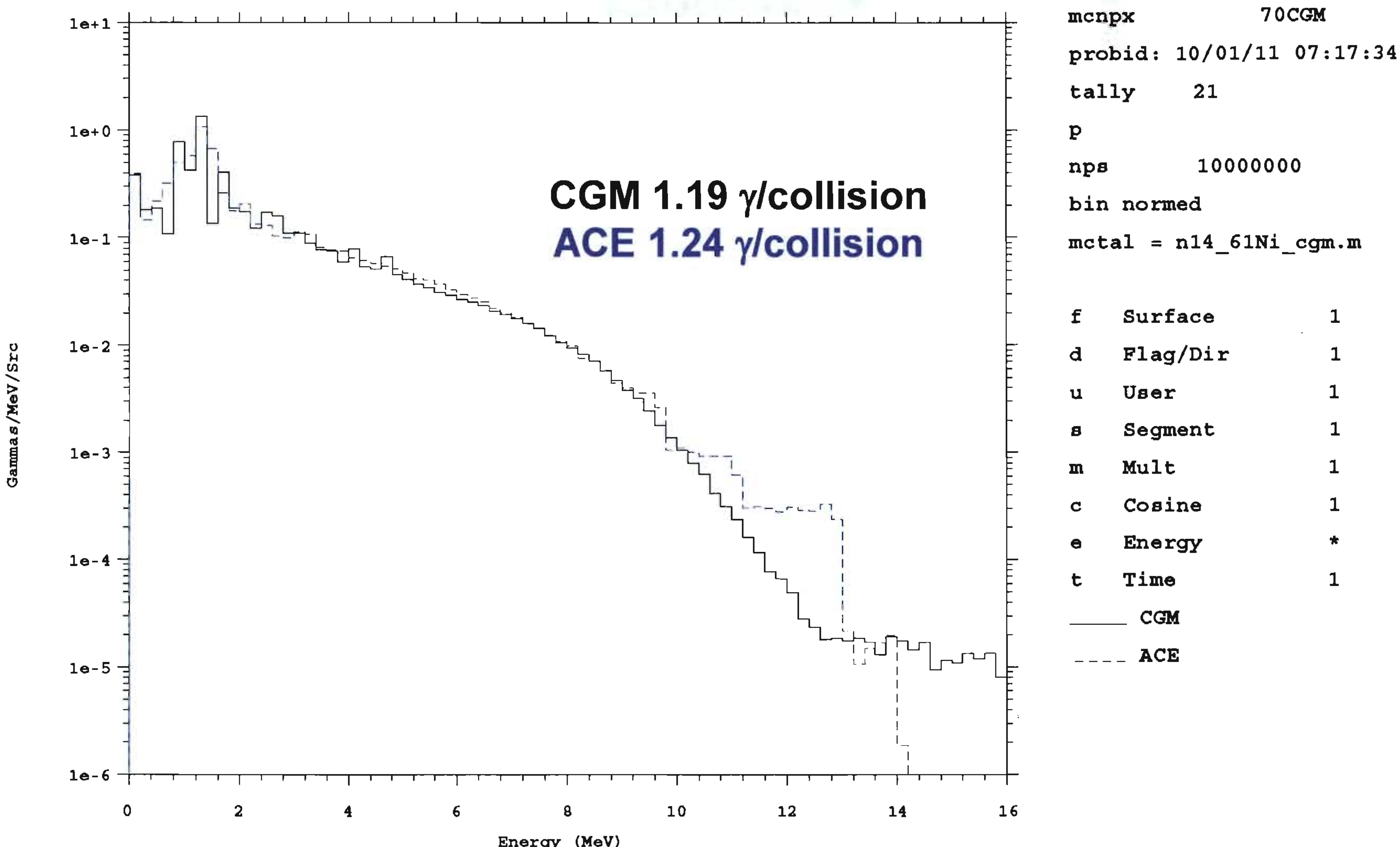
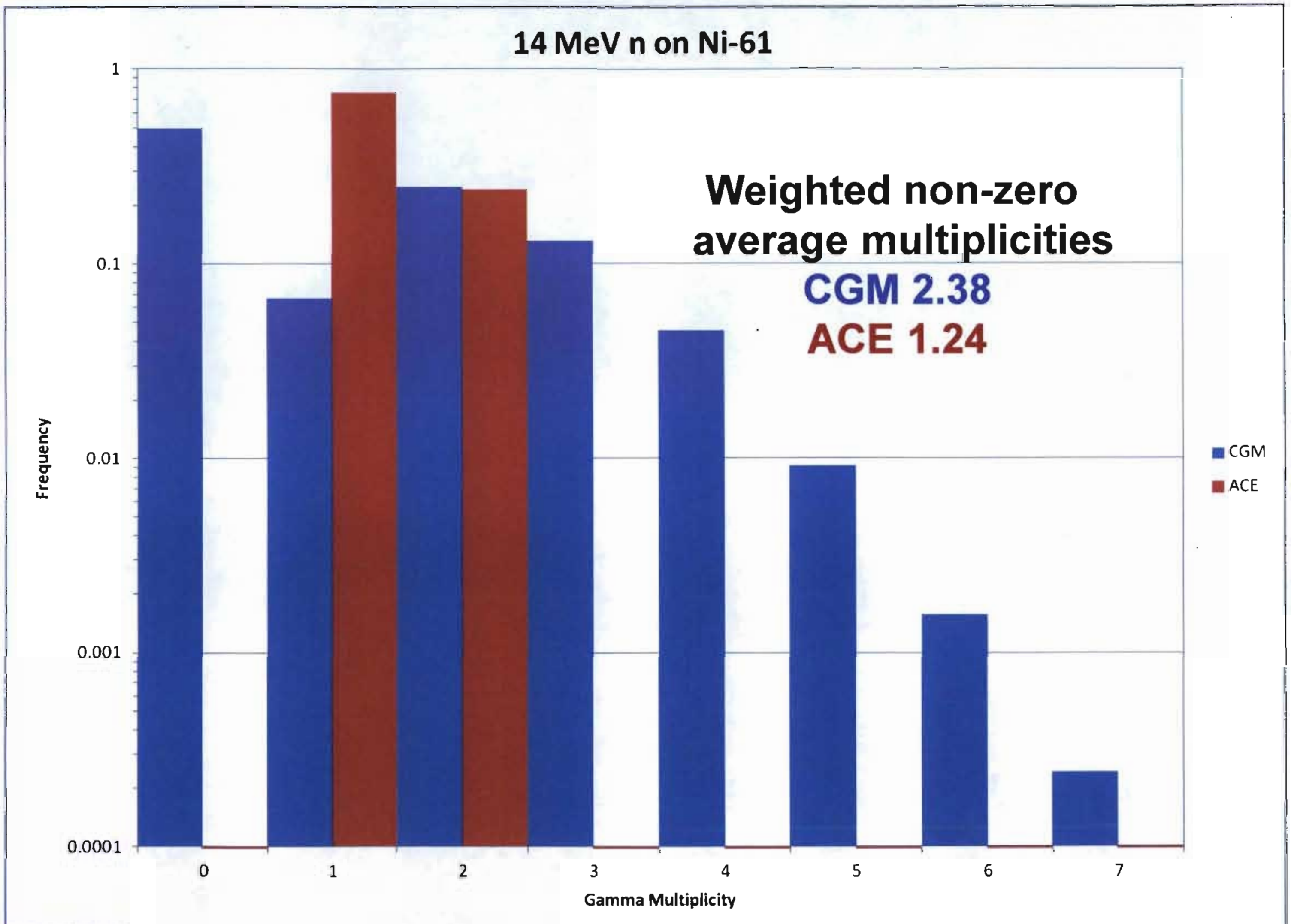
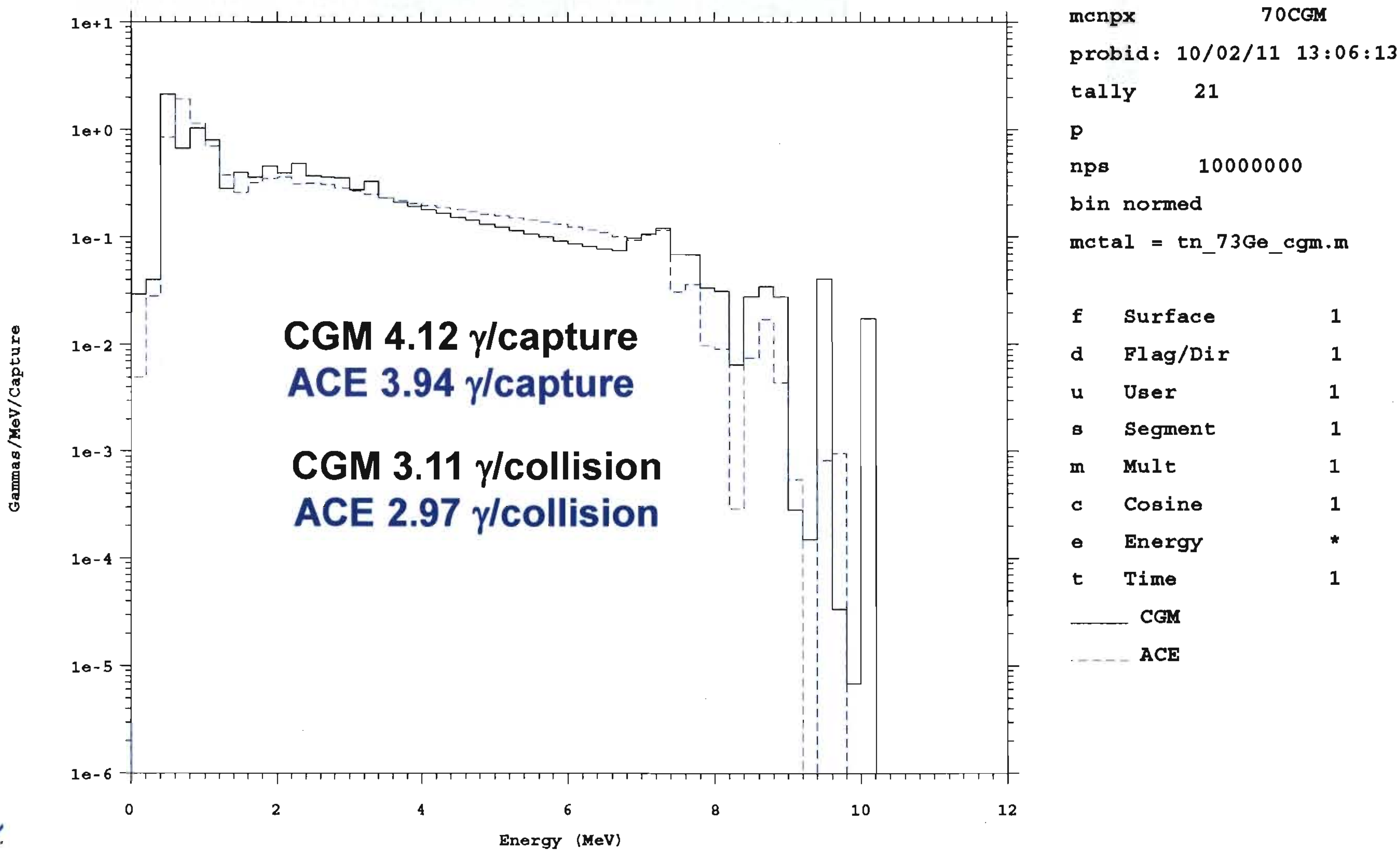
Results – 14 MeV Neutrons on Ni-61



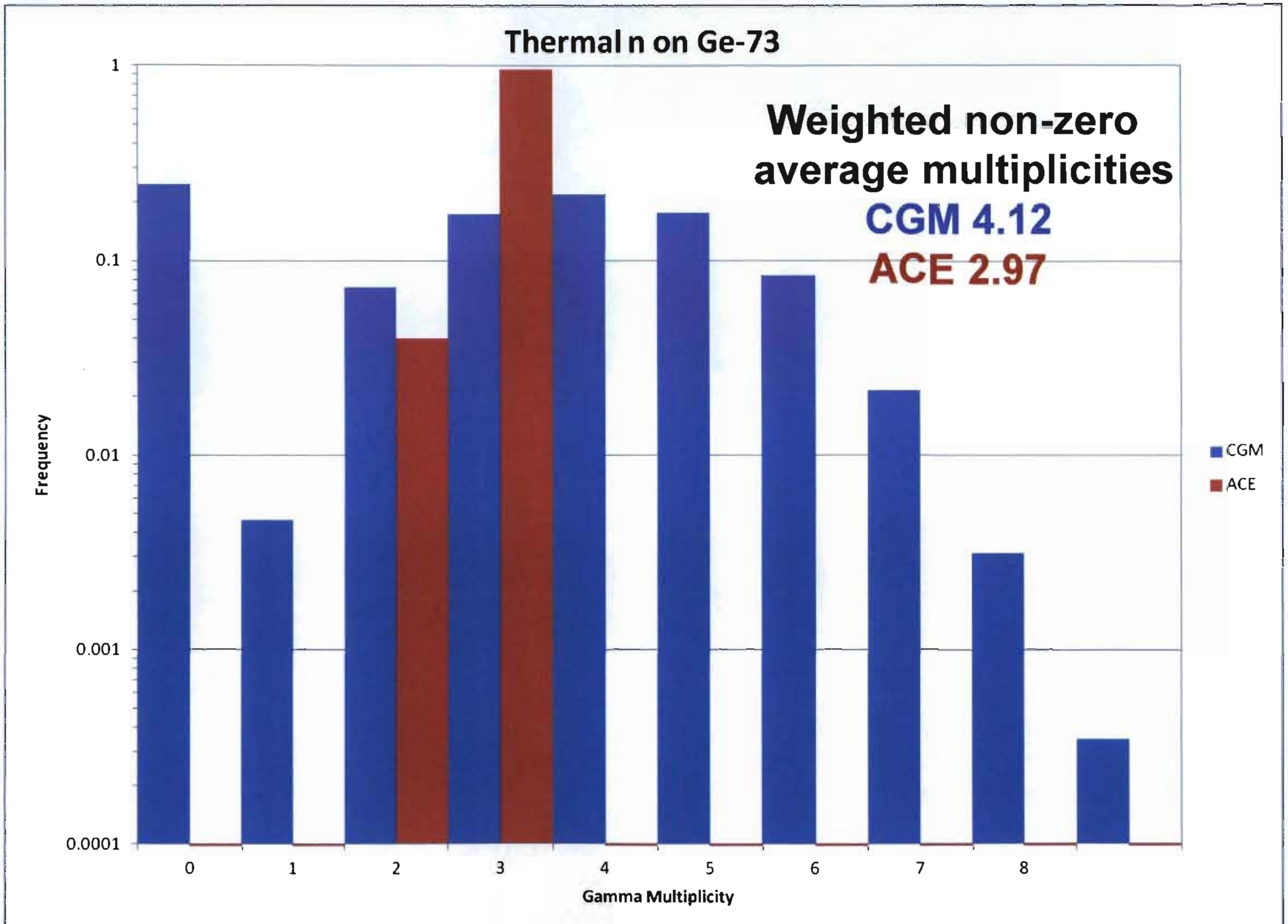
Results – 14 MeV Neutrons on Ni-61



Results – Thermal Neutrons on Ge-73



Results – Thermal Neutrons on Ge-73



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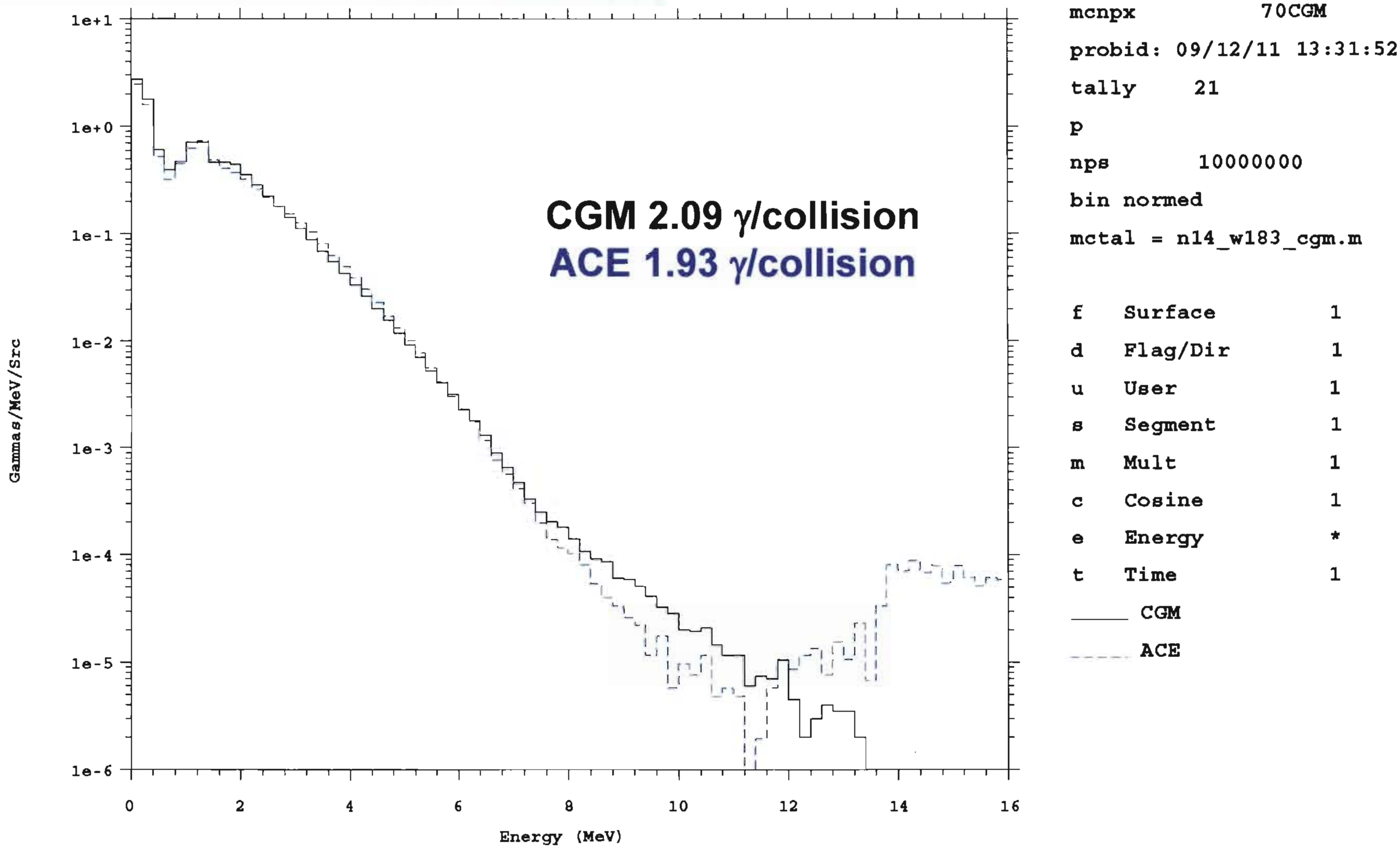
Results – 14 MeV Neutrons on W-183



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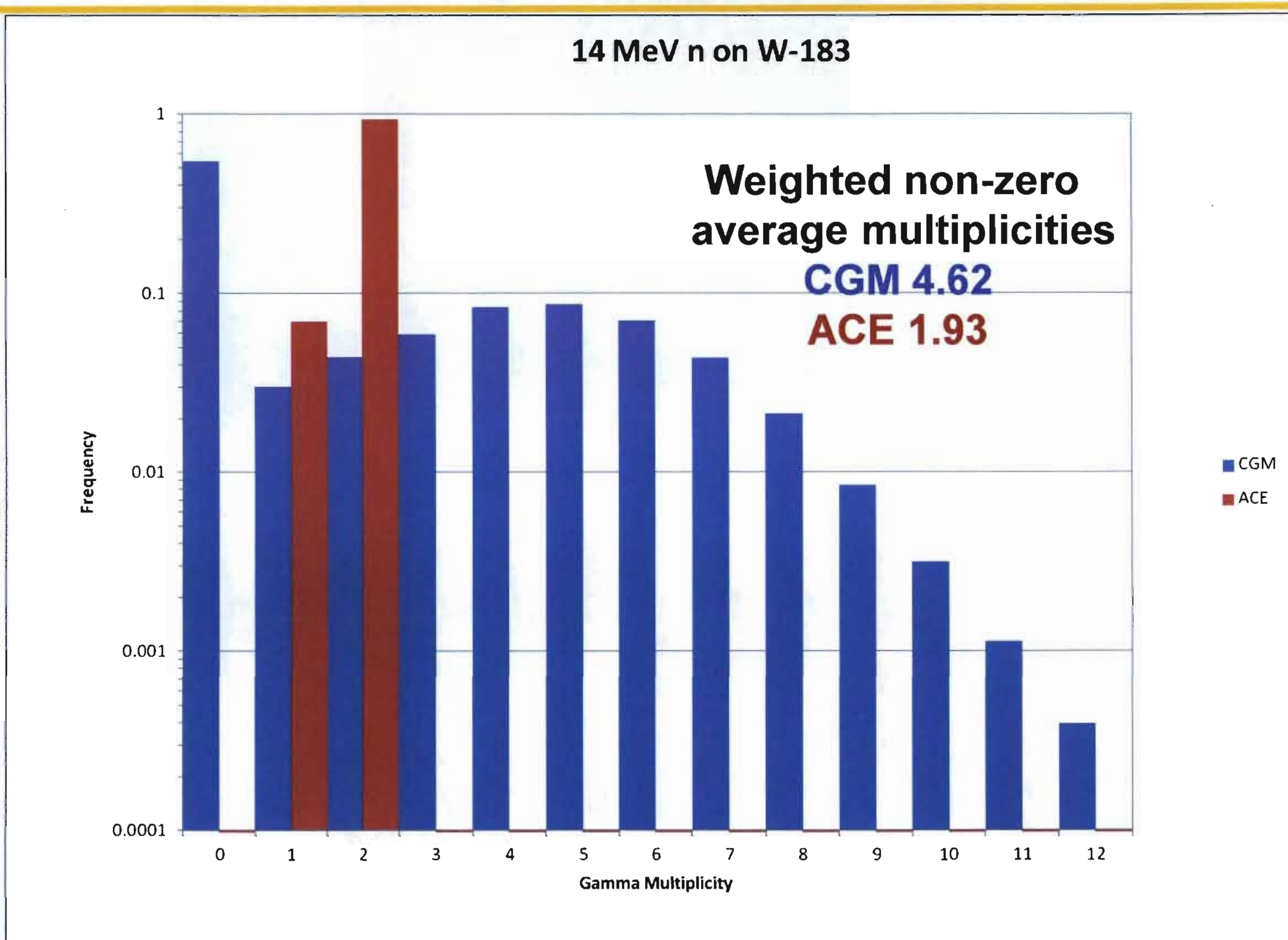
Results – 14 MeV Neutrons on W-183



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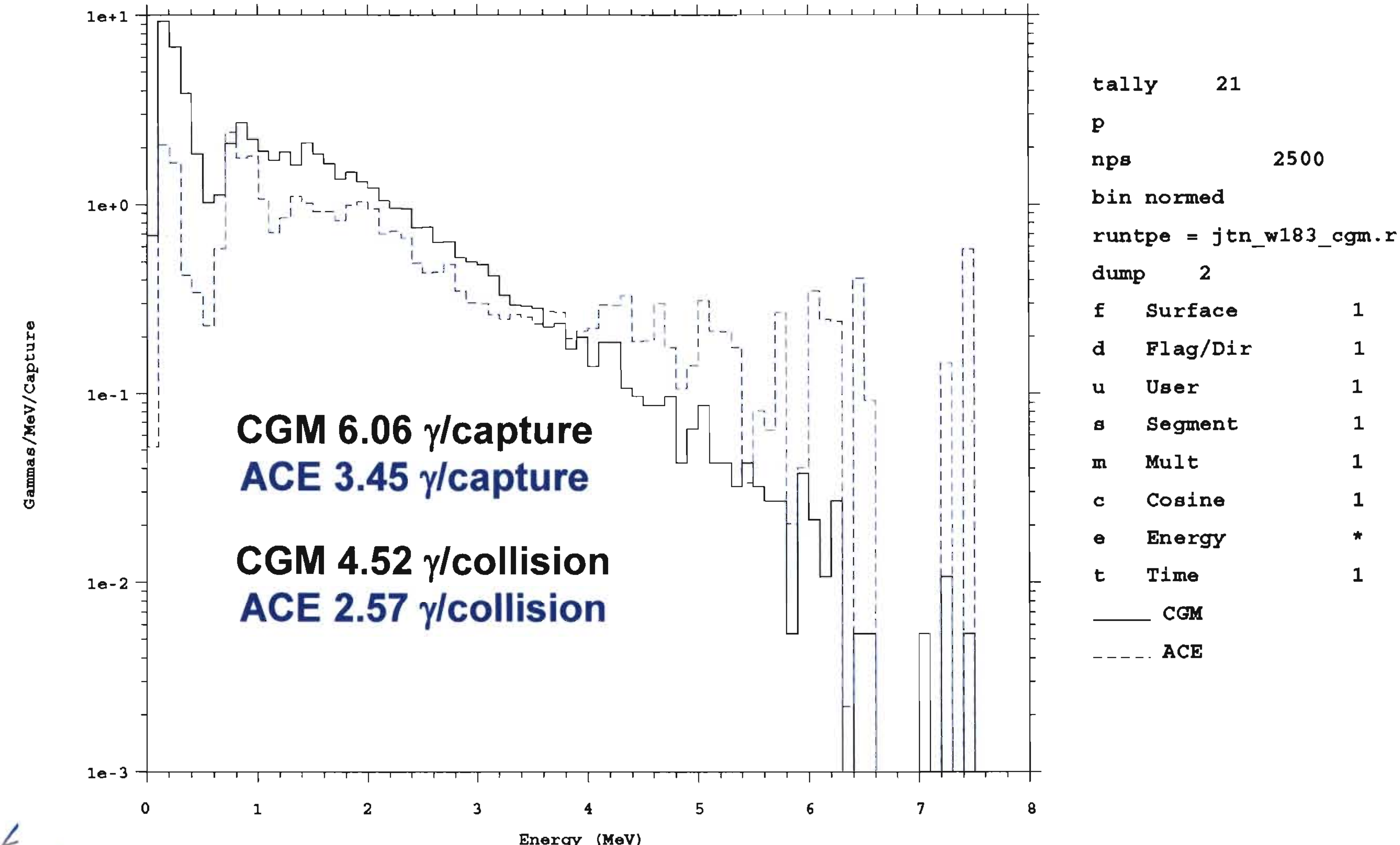
Results – Thermal Neutrons on W-183



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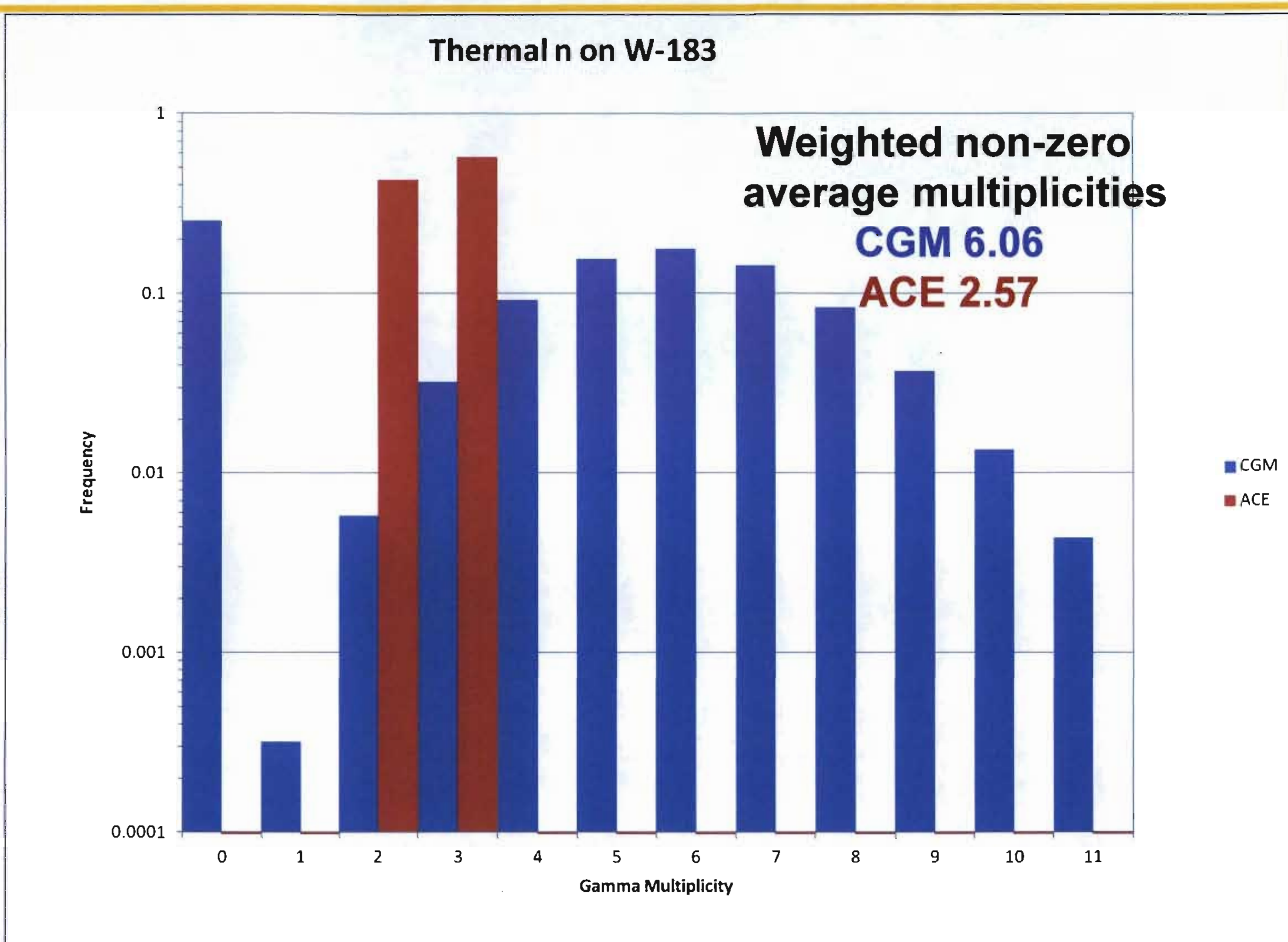
Results – Thermal Neutrons on W-183



Summary

- Isotopes above carbon
- Now have a spectra of multiplicities vs. integer sampling
- Correlated gammas
- Differences if integral multiplicities for some isotopes
- New entry on the PHYS:N card

Future Work/New Features

- Compare results with published multiplicities and spectra
- Improve residual excitation energy equation
- Include correlated neutron generation from CGM
- Update to COH to provide full interaction correlation for neutron interactions
- Integrate improvements for MCNP6 spring release

Questions

We would like to acknowledge the sponsorship of the Domestic Nuclear Detection Office.