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Title: Validation and Verification of MCNP6 as a New Simulation Tool Useful for Medical Applications

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Validation and Verification of MCNP6 as a New Simulation Tool Useful for Medical Applications

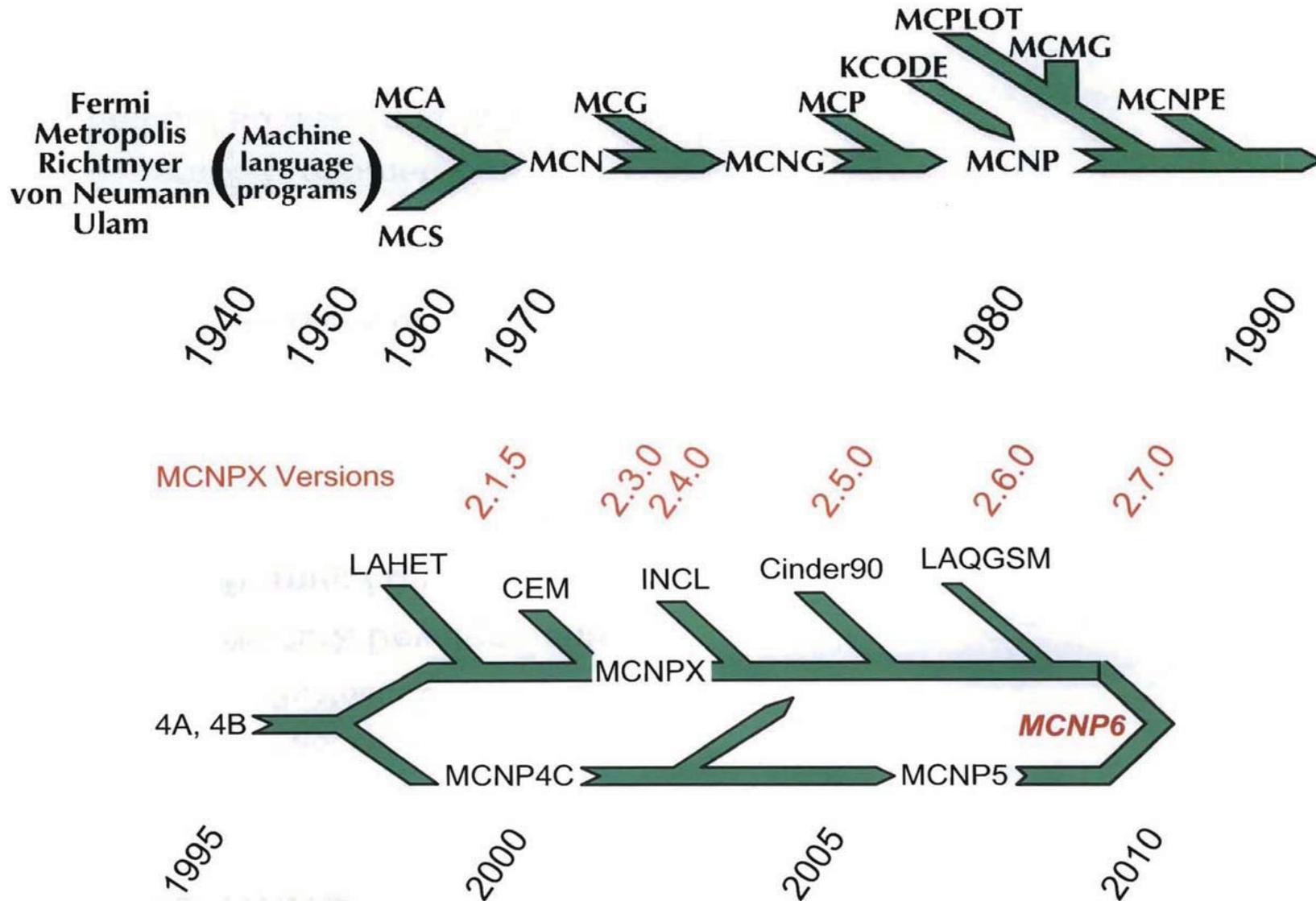
Stepan G. Mashnik

Monte Carlo Codes (XCP-3)
Los Alamos National Laboratory

1. Introduction
2. A Brief Survey of the CEM and LAQGSM Physics
3. Validation and Verification of MCNP6 using CEM and LAQGSM
4. Summary



A heritage of Monte Carlo Excellence:





Many people participated in development of the Cascade-Exciton Model (CEM) and the Los Alamos version of the Quark-Gluon String Model (LAQGSM) over their almost 40-year history.

The current contributors are:

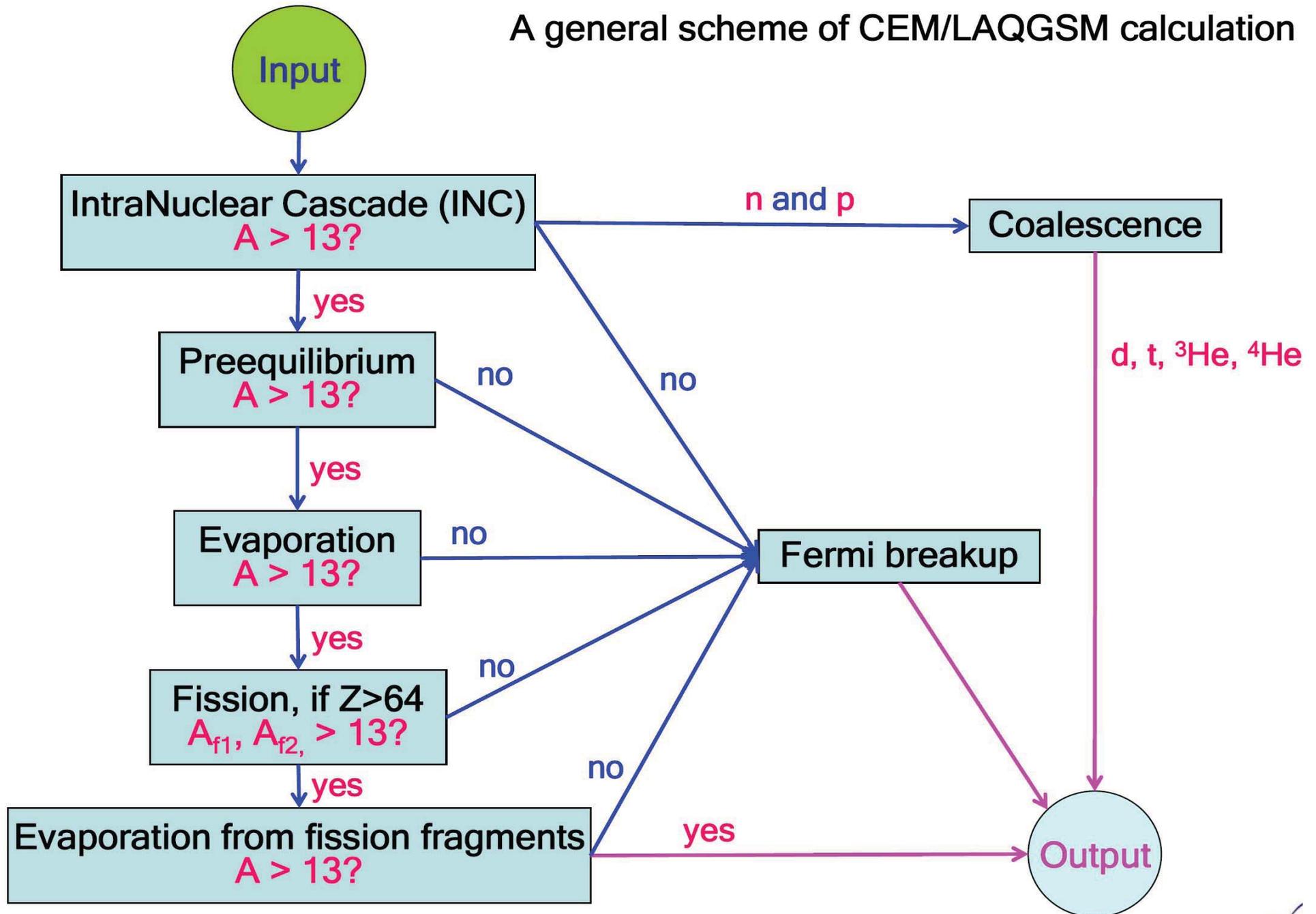
S. G. Mashnik, K. K. Gudima, A. J. Sierk,
M. I. Baznat, R. E. Prael, N. V. Mokhov.

A recent lecture with many references on our work may be found in:

S. G. Mashnik, K. K. Gudima, R. E. Prael, A. J. Sierk, M. I. Baznat,
and N. V. Mokhov, *CEM03.03 and LAQGSM03.03 Event
Generators for the MCNP6, MCNPX, and MARS15 Transport
Codes*, Joint ICTP-IAEA Advanced Workshop on Model Codes for
Spallation Reactions, February 4-8, 2008, ICTP, Trieste, Italy,
LA-UR-08-2931, Los Alamos (2008), E-print: arXiv:0805.0751.



A general scheme of CEM/LAQGSM calculation





Proc. ND2010 April 26-30, 2010, Jeju Island, Korea, in press:

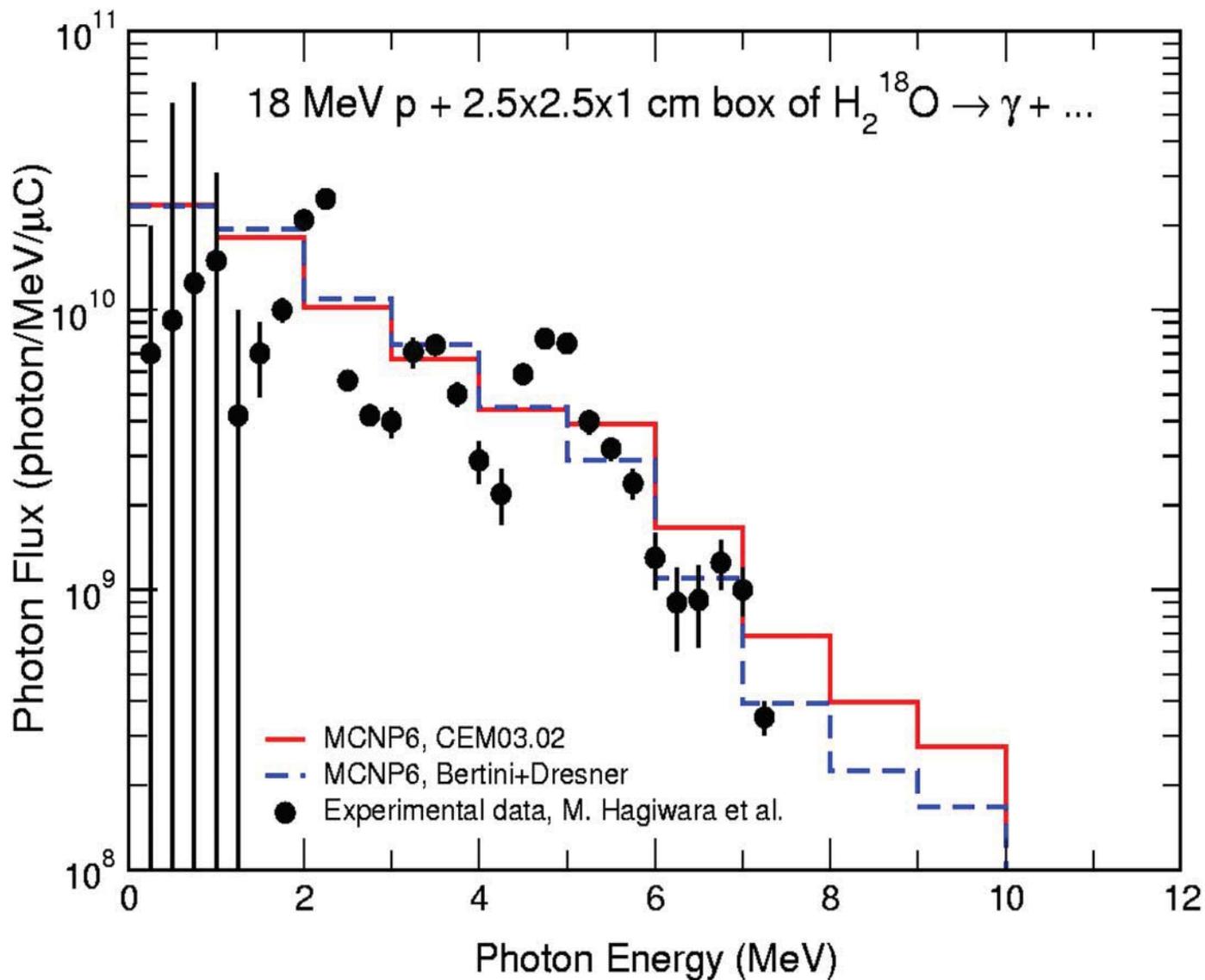
Spectrum Measurement of Neutrons and Gamma-rays from Thick H_2^{18}O Target Bombarded with 18 MeV Protons

M. Hagiwara^{a)}, T. Sanami^{a)}, Y. Iwamoto^{b)}, N. Matsuda^{b)}, Y. Sakamoto^{b)}, Y. Nakane^{c)},
H. Nakashima^{c)}, K. Masumoto^{a)}, Y. Uwamino^{d)} and H. Kaneko^{e)}

In recent years, positron emission tomography (PET) has become a common technique of the functional imaging for brains and organs. A number of cyclotrons are installed in medical facilities to produce radionuclides for PET. In PET, one of the most commonly used radiopharmaceuticals is fluorodeoxyglucose (FDG), which is tagged with the radioactive ^{18}F isotope. The isotope is obtained from the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ reaction when ^{18}O -enriched water (H_2^{18}O) is bombarded with a proton beam. The nuclear reaction produces neutrons and γ -rays simultaneously. The energy spectrum and angular distribution should be estimated for radiation safety and clearance of the facility.



Experimental data are from: M. Hagiwara et al., Proc. ND2010, in press





Radiochim. Acta **98**, 447–457 (2010)

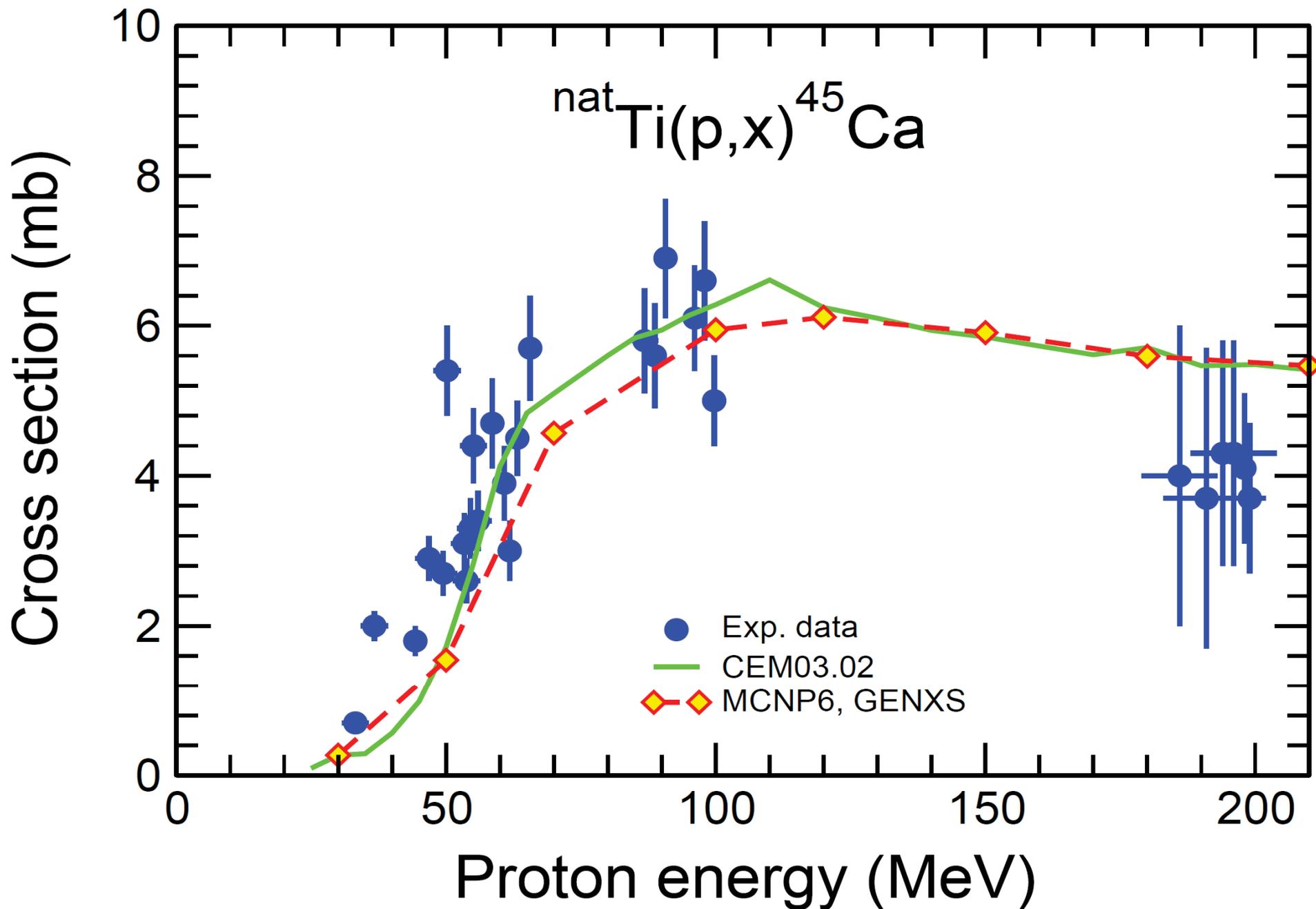
Excitation functions of nuclear reactions leading to the soft-radiation emitting radionuclides ^{45}Ca , ^{49}V and ^{204}Tl in beam collimator materials used in proton therapy

By S. M. Qaim*, K. Ketterer, Yu. N. Shubin⁺, S. Sudár[#] and H. H. Coenen

In proton therapy of deep-lying tumours, the projectile energy is generally varied between 60 and 230 MeV, and the beam collimation to the desired shape and form is achieved using special collimators. Due to the generally low beam current incident on the tumour, often not much attention is paid to the activation of the collimator, although the beam extracted from the cyclotron/accelerator loses a considerable part of its intensity in the collimator during its fine tuning and shaping. Thus it appeared instructive to us to study the formation of activation products, especially the long-lived ones, in two commonly used collimator materials. The information obtained should be useful with regard to radiation protection of therapy personnel.

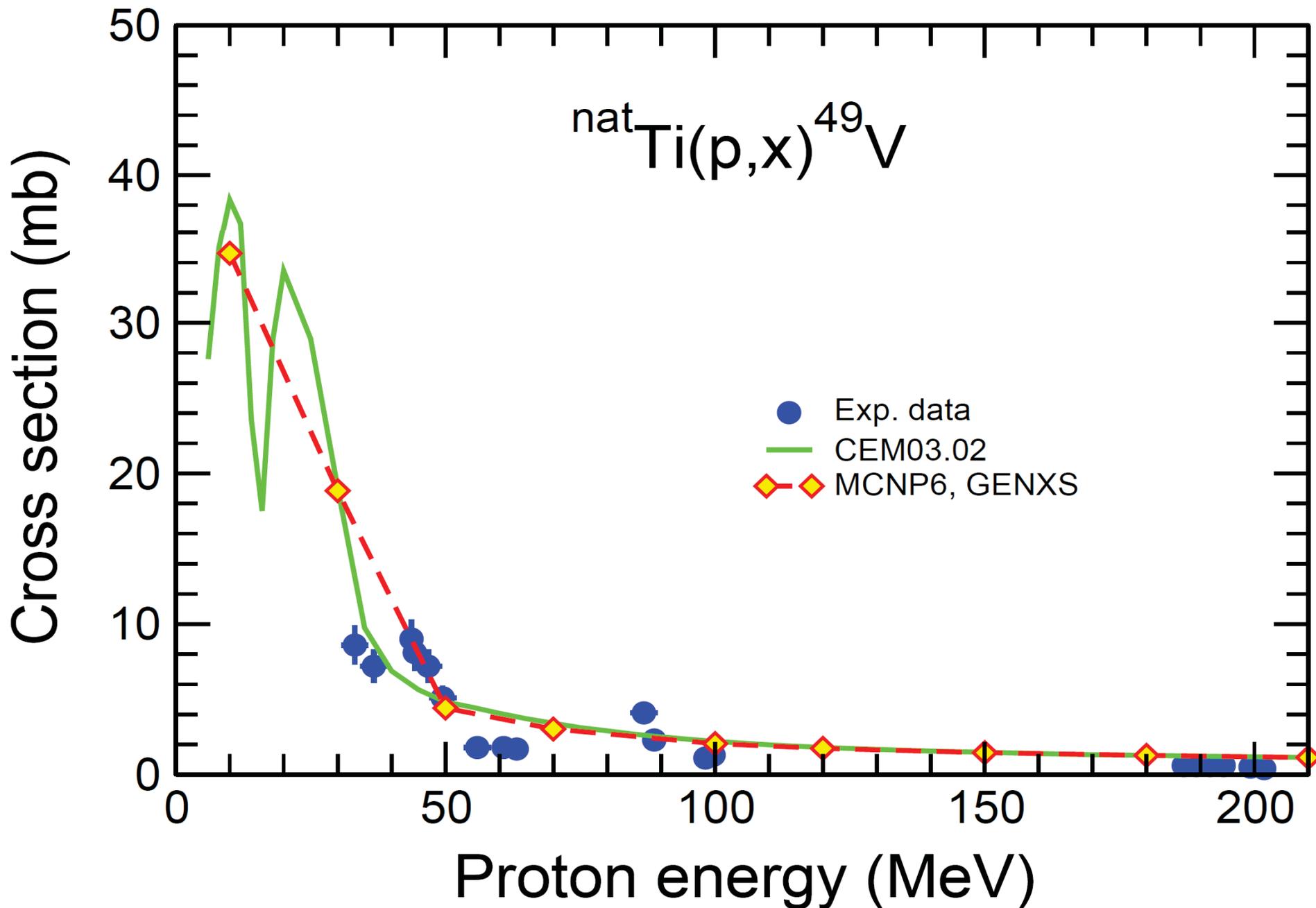


Experimental data are from: S. M. Qaim et al., Radiochim. Acta 98 (2010) 447





Experimental data are from: S. M. Qaim et al., Radiochim. Acta 98 (2010) 447





Alpha Particle therapy using actinium (Ac-225) and its daughter product bismuth (Bi-213) is a new and promising treatment for many forms of cancer. Clinical trials for acute myeloid leukemia have been promising, with about 25% of terminal patients going into remission.

Researchers throughout the world are examining approaches for prostate cancer, bladder cancer, ovarian cancer, pancreatic cancer, melanoma and non-Hodgkin's lymphoma. Unfortunately, there is not enough supply of the medical Ac-225 to support current world research needs much less therapeutic use.

The National Institutes of Health (NIH) conservatively projects world demand for Ac-225 at 7,500 mCi per year by 2009 yet current world production is less than 600 mCi per year. Without additional supplies, further progress on clinical and preclinical research is at serious risk.



Accelerator-Based Production Of The Therapy Isotope Ac-225

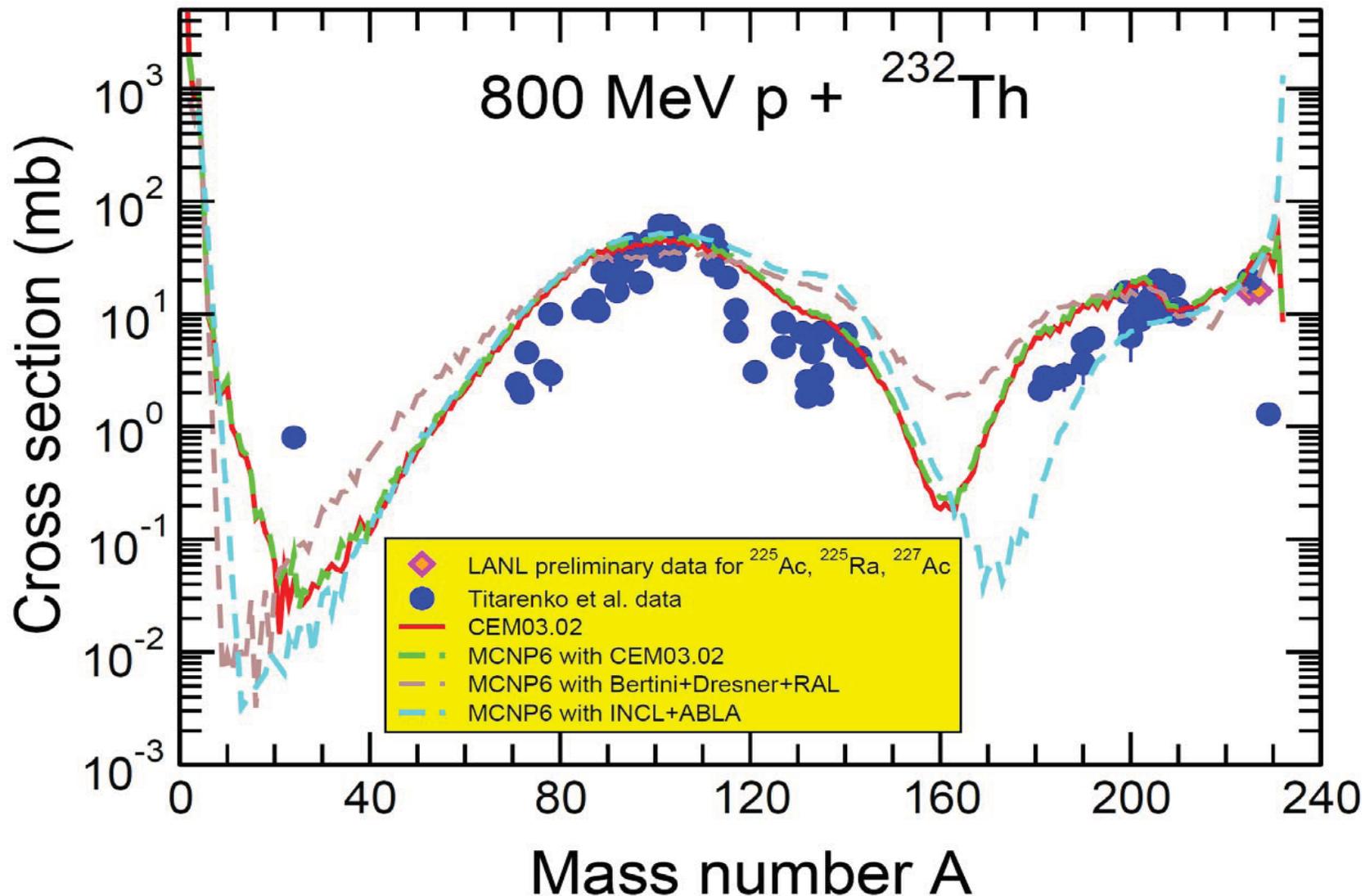
Presented by John Weidner

Team Members: Meiring Nortier (lead), Hong Bach, Mike Fassbender, George Goff, Wayne Taylor, Frank Valdez, Laura Wolfsberg, Mike Cisneros, Don Dry, Mike Gallegos, Russ Gritzko, Leo Bitteker, Aaron Couture, John Ullmann, Steve Wender



Purpose And Goal Of This Research

- **Experiment tied to DOE Office of Science (Nuclear Physics) FY10 funding for “Accelerator-Based Production of Ac-225”**
- **Purpose is to determine the commercial viability of Ac-225 production using appropriate accelerators**
- **Our procedure involves irradiating Th-232 foils with proton beams to determine the Ac-225 production cross section at proton energies from 40-200 MeV and 800 MeV**



LANL preliminary data are by John Weidner, Meiring Nortier et al., to be published; Titarenko et al data are from: Proc. 3rd Int. Conf. on Accelerator Driven Transmutation Technologies and Applications (ADTT99), Praha, 7-11 June 1999, Czech Republic; EXFOR data base: #ENTRY O0997



Radiotherapy With Protons And Ion Beams

Oliver Jäkel^{a, b}

CP1231, *La Rábida 2009, International Scientific Meeting on Nuclear Physics, Basic Concepts in Nuclear Physics: Theory, Experiments, and Applications*, edited by J. A. Caballero, C. E. Alonso, M. V. Andrés, J. E. García-Ramos, and F. Pérez-Bernal © 2010 American Institute of Physics 978-0-7354-0776-3/10/\$30.00

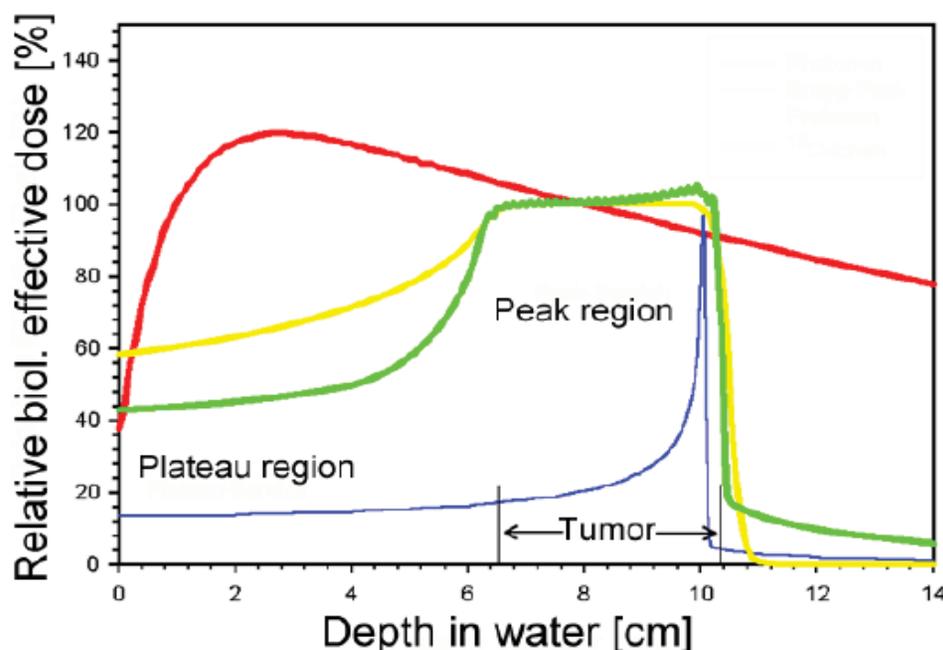


FIGURE 4. Biologically effective dose, as a function of the penetration depth in water, for MeV photon beams (15 MeV, red line), mono-energetic carbon ions (220 MeV/u, blue line) and spread-out Bragg peaks of protons (120 MeV; yellow line) and carbon ions (220 MeV/u; green line). The given numbers are relative units, normalized to dose at 8cm depth. For protons a constant RBE of 1.1 is assumed. The RBE for carbon was calculated using the track structure model (reproduced from [7]).



1. Radiotherapy with charged hadron beams

Clinical results

1. Skull base chordoma

Radiation quality	^{12}C (GSI)	Photons (FSRT)
5-years local tumour control	70 %	50 %

D. Schulz-Ertner et al.: Int. J. Radiat. Oncol. Biol. Phys. (in press)
 J. Debus et al.: Int. J. Radiat. Oncol. Biol. Phys. 47 (2000) 591

2. Bronchial carcinoma

Radiation quality	^{12}C (HIMAC)	Photons
5-years survival	40 - 60 %	10 - 30 %

T. Miyamoto et al.: Radiother. Oncol. 66 (2003) 127

3. Prostate carcinoma

Radiation quality	^{12}C (HIMAC)	Photons (IMRT)
Side effects in the urogenital tract	6 %	28 %

H. Tsujii et al.: Int. J. Radiat. Oncol. Biol. Phys. 63 (2005) 1153
 M.J. Zelefsky et al.: Int. J. Radiat. Oncol. Biol. Phys. 53 (2002) 1111

1954 – 2006: p : 45000, lons : 6000, π^- : 1000 vs. 200.000 RT/ α in D
 ~ 20 serious projects worldwide

Base: J. Sisterson, Particles 35 (2005), extrapolated

Adapted from: Wolfgang Enghardt, "In-beam PET - the Visualization of Nuclear Fragmentation," International Conference on Nuclear Fragmentation (NUFRA07), September 24 - October 1, 2007, Kemer, Turkey, <http://fias.uni-frankfurt.de/nufra2007/>

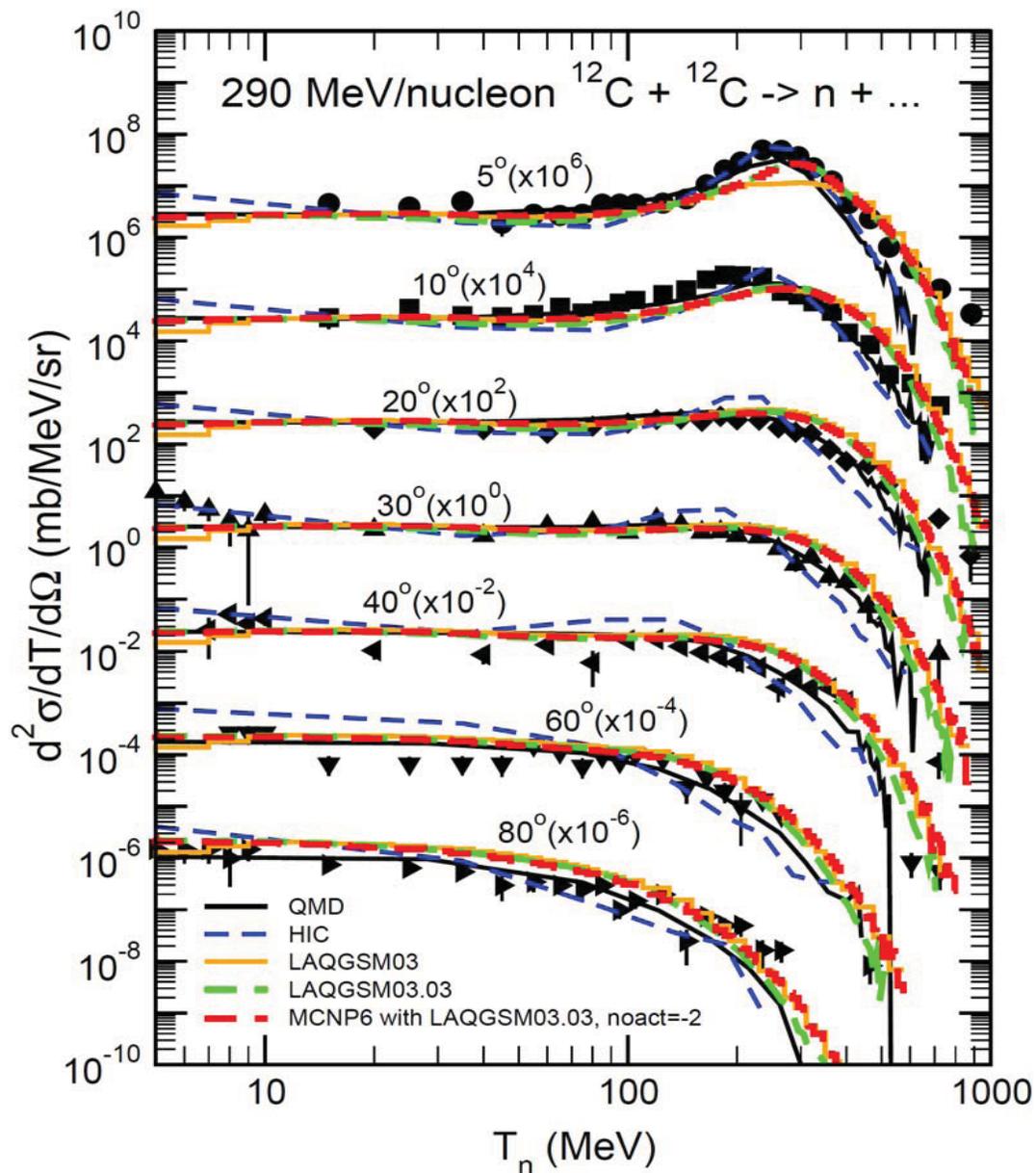


Carbon beam radiotherapy centers:

Name	City	Country	Status	First treatment
NIRS-HIMAC	Chiba	Japan	In operation	1994
GSI	Darmstadt	Germany	Clinical tries completed	1997-2008
HIBMC	Hyogo	Japan	In operation	2001
HIT	Heidelberg	Germany	Opened (11/2009)	2009
GHMC	Gunma	Japan	Opened	2010
CNAO	Pavia	Italy	Inauguration (02/2010)	End of 2010
PTC	Marburg	Germany	Under construction	2011
NRoCK	Kiel	Germany	Under construction	2012
ETOILE	Lyon	France	Project	2015
ARCHADE	Caen	France	Project	2015
MedAustron	Weiner Neustadt	Austria	Project	



Experimental data are from: Y. Iwata et al., Phys. Rev. C64 (2001) 054609;
 QMD, HIC, and LAQGSM03 results are from: H. Iwase et al., AIP 769 (2005) 1066





The distributions of positron emitting fragments can be used to monitor particle therapy



in situ



- Dose delivered to patient
- Measured distribution of positron-emitting nuclei

GSI, Darmstadt



in silico



- Calculated dose for this patient
- Calculated distribution of positron-emitting nuclei

Comparison

Conclusion on delivered dose

Adapted from: I. Pshenichnov, A. Larionov, I. Mishustin, and W. Greiner, "Nuclear Reactions in Heavy-Ion Therapy Studied with the GEANT4 Toolkit," International Conference on Nuclear Fragmentation (NUFRA07), September 24 - October 1, 2007, Kemer, Turkey, <http://fias.uni-frankfurt.de/nufra2007/>



Our Los Alamos high-energy transport code MCNPX has been validated and used in proton therapy for a variety of clinical and research applications, see, e.g.:

M. R. James et al., NIM A562 (2006) 819;

J. D. Fontenot et al., Med. Phys. 34 (2007) 489;

M. C. Harvey et al., Med. Phys. 35 (2008) 2243;

J. Herault et al., Med. Phys. 35 (2008) 2243;

W.D. Newhauser et al., Phys. Med. Biol. 52 (2007) 4569;

J. C. Polf et al., Med. Phys. 34 (2007) 4219;

P. J. Taddei et al., Phys. Med. Biol. 53 (2008) 2131;

Y. Zheng et al., J. Nucl. Mater. 361 (2007) 298;

T. Urban and J. Kluson, PNST10136 (2010);

. . .



Our low-energy transport code MCNP5 has been validated and even more widely used in a variety of medical applications, see, e.g.:

J. T. Goorley et al., LANL Report LA-UR-02-7205;

T. Goorley and D. Olsher, LA-UR-05-2755;

A. Lazarine and T. Goorley LANL Reports LA-UR-05-4598,
LA-UR-05-6402, and LA-UR-06-4904;

A. L. Reed, LA-UR-10-4133;

I. Gerardy et al., J. Phys.: Conf. Ser. 102 (2008) 012012;

J. Zhang et al., Health Phys. 91 (2006) S59;

I. Gerardy, Appl. Rad. Isot. 68 (2010) 735;

Y.J. Huang and M. Blough, J. Appl. Clinic. Med. Phys., 11 (2010) 46;

H. G. Hughes and J. T. Goorley, LA-UR-10-05424 (2010);

...



We even distribute officially via RSICC at Oak Ridge with MCNP5/X the *Medical Physics Calculations With MCNP: A Primer*, LANL Report LA-UR-07-4133, Los Alamos (2007) by A. L. Reed.

We also provide a MCNP Medical Physics Geometry Database on our MCNP web page opened only to official MCNP5 users; see e.g., T. Goorley, "MCNP Medical Physics Geometry Database" Los Alamos National Laboratory (2008):

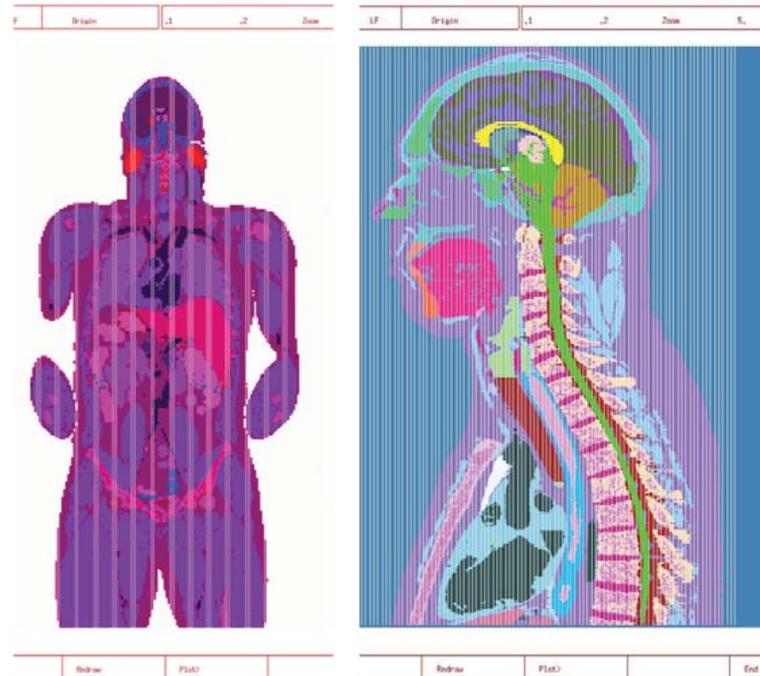
([LA-UR-08-2113](#)) - Presentation Overheads,
([LA-UR-08-2113B.zip](#)) - Full Database

This is why we can expect that MCNP6, the latest and most advanced Los Alamos transport code representing a merger of MCNP5 and MCNPX, should be even more successful and useful for various medical applications.



VIP Man

- Whole Body Phantom
- Based on NIH VIP-Man Project
- 6, 100, 300 Million Voxel Models
- 1 or 4 mm³
- Available from Prof. Xu of RPI – not in MP database



http://www.rpi.edu/dept/radsafe/public_html/home.htm

Image from
MCNP5 plotter

Adopted from: Tim Goorley and Dick Olsher, Using MCNP5 for Medical Physics Applications, LA-UR-05-2755, presented at the American Nuclear Society Topical Meeting - Monte Carlo 2005, Chattanooga, TN, USA, April 17-21, 2005



Summary

- MCNP6, the latest and most advanced LANL transport code, representing a merger of MCNP5 and MCNPX has been Validated and Verified (V&V) against different experimental data and results by other codes relevant to medical applications
- In the present work, we V&V MCNP6 using mainly the latest modifications of the Cascade-Exciton Model (CEM) and of the Los Alamos version of the Quark-Gluon String Model (LAQGSM) event generators CEM03.02 and LAQGSM03.03. We found that MCNP6 describes well data of interest for medical applications measured on both thin and thick targets and agrees very well with similar results obtained with other codes; **MCNP6 may be a very useful tool for medical applications**
- We plan to make MCNP6 available to the public via RSICC at Oak Ridge in the middle of 2011 but we are allowed to provide it to friendly US Beta-users outside LANL already now. **Potential US Beta-users interested in using now MCNP6 should contact our XCP-3 Group Leader, Dr. Tim Goorley: jgoorley@lanl.gov**