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Analysis of the AGS Experiment on a Mercury Target with a Moderator and a Lead Reflector Bombarded by GeV Energy Protons

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Abstract

The AGS experiment on a mercury target with a moderator and a lead reflector bombarded by GeV energy protons was analyzed to investigate prediction capability of Monte Carlo simulation codes used in neutronic designs of spallation neutron sources. The NMTC/JAM code was used for nucleon meson transport calculations above 20 MeV while the MCNP-4A code with the JENDL cross section library was used for neutron transport below 20 MeV. The MCNPX code with the LA-150 library was also used for a reference. The calculations were compared with the experimental data obtained with 1.94, 12 and 24 GeV proton beams: (1) neutron flux distributions along the mercury target and (2) spectral fluxes of thermal neutrons extracted from a light water moderator. As a result, it was found that all the calculations predicted these experimental results with accuracies better than ± 50 % in absolute values. Accordingly, it was concluded that these calculation codes were adequate for neutronics designs of spallation neutron sources.

1. Introduction

Several spallation neutron sources driven by MW order proton accelerators are under planning. To provide experimental data for validation of neutronic calculations for such neutron sources, a series of neutronic experiments on a mercury target has been conducted by using AGS at BNL, under the AGS Spallation Target Experiment (ASTE) collaboration. The first stage of the experiments [1-3] investigated neutron production characteristics of a bare mercury target bombarded by 1.6, 12 and 24 GeV proton beams. In the second stage of the experiments [4-6], a light water moderator and a lead reflector were attached to the bare mercury target to simulate basic physical processes of spallation neutron sources, i.e., neutron production in the mercury target, reflection in the lead reflector, and thermalization in the moderator. Activation reaction-rate distributions and spectra of thermal neutrons leaking from the moderator were measured with bombarding the mercury target by 1.94, 12 and 24 GeV protons. In this study, the latter experiment was analyzed by using several calculation codes to investigate accuracy of the calculation methods in prediction of neutronic performance of spallation neutron sources.

2. Brief Description of the Experiment

Figures 1-3 shows experimental configurations. These figures are produced by using a geometry plotter of the MCNP code [7] with an input data for analyses that will be described later. Although the geometry is somewhat simplified for easy modeling, these figures would help readers to understand the experimental configurations. Dimensions of important components in millimeters are as follows: the mercury target (200 ϕ x 1300), the lead reflector (~ 1000 x 1000 x 1000) and the light water moderator (100 x 100 x 50).

For measurements of neutron flux distributions along the mercury target, the foil activation technique was adopted [4]. As shown in Fig. 2, four detector arrays of activation foils denoted as *Main*, *Sub-1*, *Sub-2* and *Sub-3* were attached on the target to monitor beam position dependency of activation reaction-rates. Detector materials used were Al, Co, Ni, Nb, In and Bi, and total 16 kinds of activation reactions were measured.

For measurements of spectral fluxes of thermal neutrons leaking from the moderator, a newly developed technique, "current-mode time-of-flight (TOF) technique" [5, 6], was used. As Fig. 3 illustrates, ^{6}Li- and ^{7}Li-glass scintillation detectors were placed at 18 m from the moderator. To investigate moderator position dependencies on thermal neutron intensity, measurements were repeated by changing the position of the mercury target on the axis of the proton beam.

Proton beams of three distinct energies, 1.96, 12 and 24 GeV, bombarded the mercury target. An absolute number of protons in each pulse was monitored by an integrating current transformer (ICT). The $Cu(p,x)^{24}Na$ reaction-rate was also used to determine the proton beam intensity. Numbers of protons per pulse were ~ 10^{12} regardless of the proton energy. To monitor beam profiles, a separated ionization chamber (named as *CHIDORI*) and imaging plates (IP) with activation of aluminum foils were employed. Proton beams of 12 and 24 GeV were well focused to ~ 20 mm in full width at half maximum (FWHM) while those of 1.94 GeV were rather broadened to ~ 60 mm in FWHM.

3. Code Analysis

3.1 Code and Data

Three combinations of Monte Carlo simulation codes and cross section data libraries were employed for the analysis.

(a) NMTC/JAM version 1.00 [8] (E_{tran} = 20 MeV)
MCNP-4A [7] with JENDL-3.2 [9] and JENDL Fusion File [10]
(JAERI standard)

(b) NMTC/JAM version 1.00 (E_{tran} = 150 MeV)
MCNPX 2.1.5 [11] with LA-150 [12]

(c) MCNPX 2.1.5 with LA-150 (E_{tran} = 150 MeV)

Differences in cross section data in JENDL and LA-150 below 20 MeV are considered to be small according to benchmark calculations for D-T fusion applications, and both case (a) and

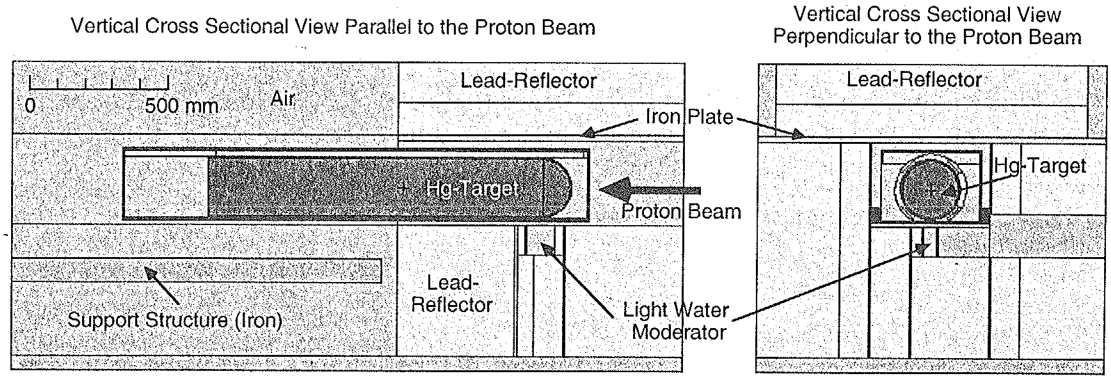

Fig. 1 Vertical cross sectional view of the experimental geometry.

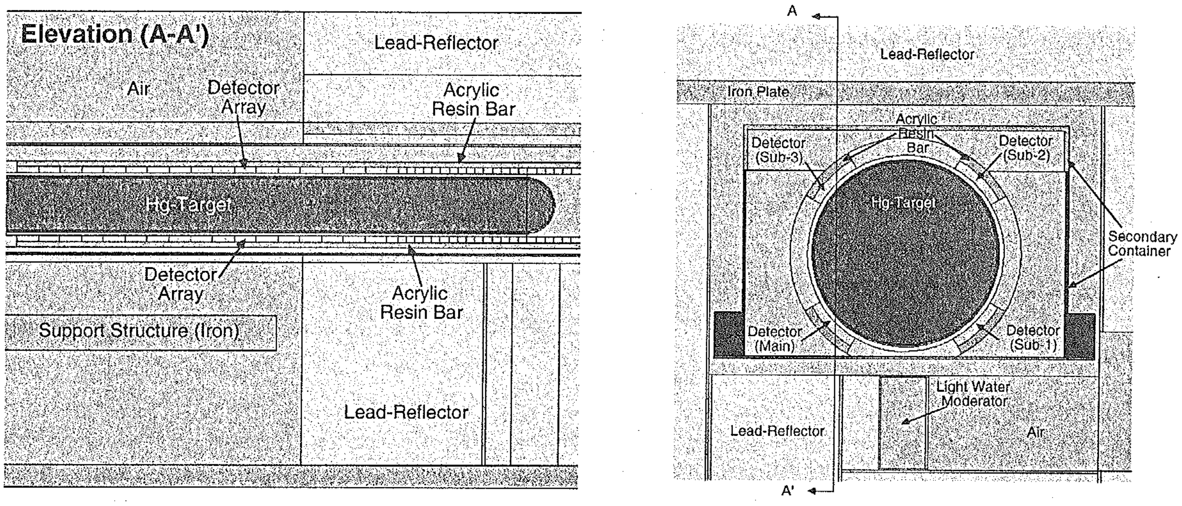

Fig. 2 Details of the target and the detector arrays.

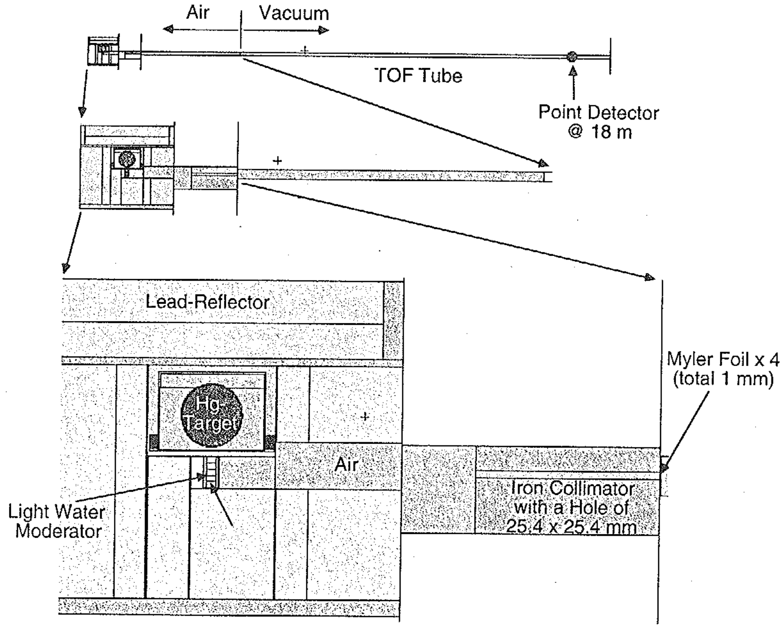

Fig. 3 Experimental arrangement for the TOF measurement.

case (b) use NMTC/JAM for high energy parts of calculation. When results by the case (a) and (b) are compared, we can investigate differences in a transition energy (E_{tran}) at which a low energy code takes over neutron transport calculations from a high energy code. In the energy range from 20 to 150 MeV, NMTC/JAM is still running for case (a) while MCNPX with LA-150 has already taken over the calculation. By comparing results obtained by case (b) and (c), we can compare the two high energy codes, NMTC/JAM and the LAHET and FLUKA modules in MCNPX.

3.2 Consideration on Beam Position

The activation reaction-rates measured on the four detector arrays are very sensitive to the incident proton beam position. When a beam center shifts just 10 mm in elevation, a ratio of a reaction-rate on the *Sub-3* bar to that on the *Main* bar increases by 40 % according to a survey calculation. Center positions and widths in vertical and horizontal directions for each proton pulse is provided basing on the beam profiles measured by *CHIDORI*. When the center positions and widths provided were used in the calculations, the calculations however did not reproduce reaction-rate ratios between two adjacent bars in some cases. The contradiction might be due to miss-alignment of experimental instruments. On the other hand, the reaction-rate ratios would reflect the real situation, i.e., the ratio works as another beam position monitor. Hence, in the calculations, the beam center was adjusted to reproduce the measured reaction-rate ratios: shifted by 20 mm upward for the 12 and 24 GeV proton beams.

3.3 Activation Cross Section

Activation cross sections are important to reduce reaction-rates. Although cross sections for low threshold reactions have been established, those for high threshold reactions still have some ambiguities in their values. In this analysis, a dosimetry cross section set [13] that was produced by considering differential cross section data as well as results of several integral activation experiments was used. Figure 4 shows two examples of cross section.

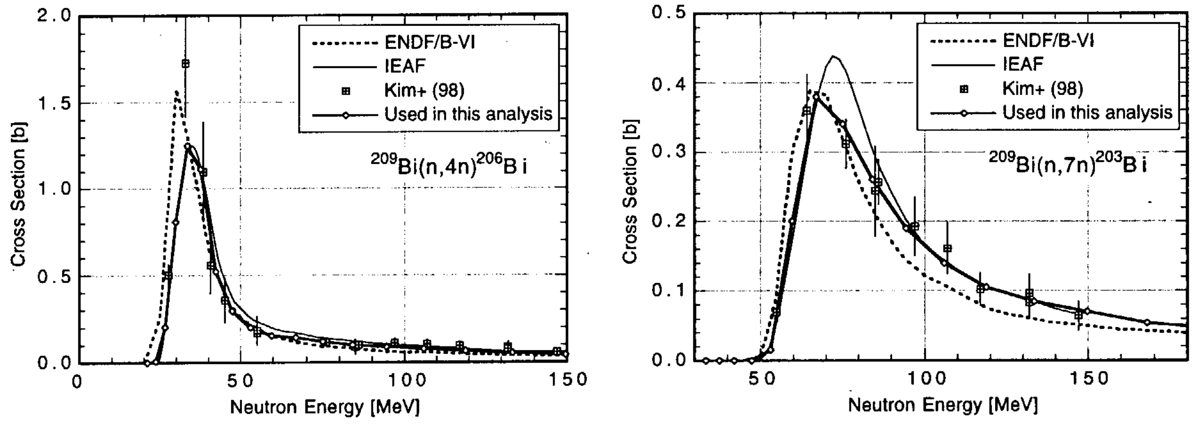

Fig. 4 Activation cross sections for the $^{209}Bi(n,4n)^{206}Bi$ and $^{209}Bi(n,7n)^{203}Bi$ reactions in ENDF/B-VI [14], IEAF [15], measured data by Kim [16] and the data used in this analysis.

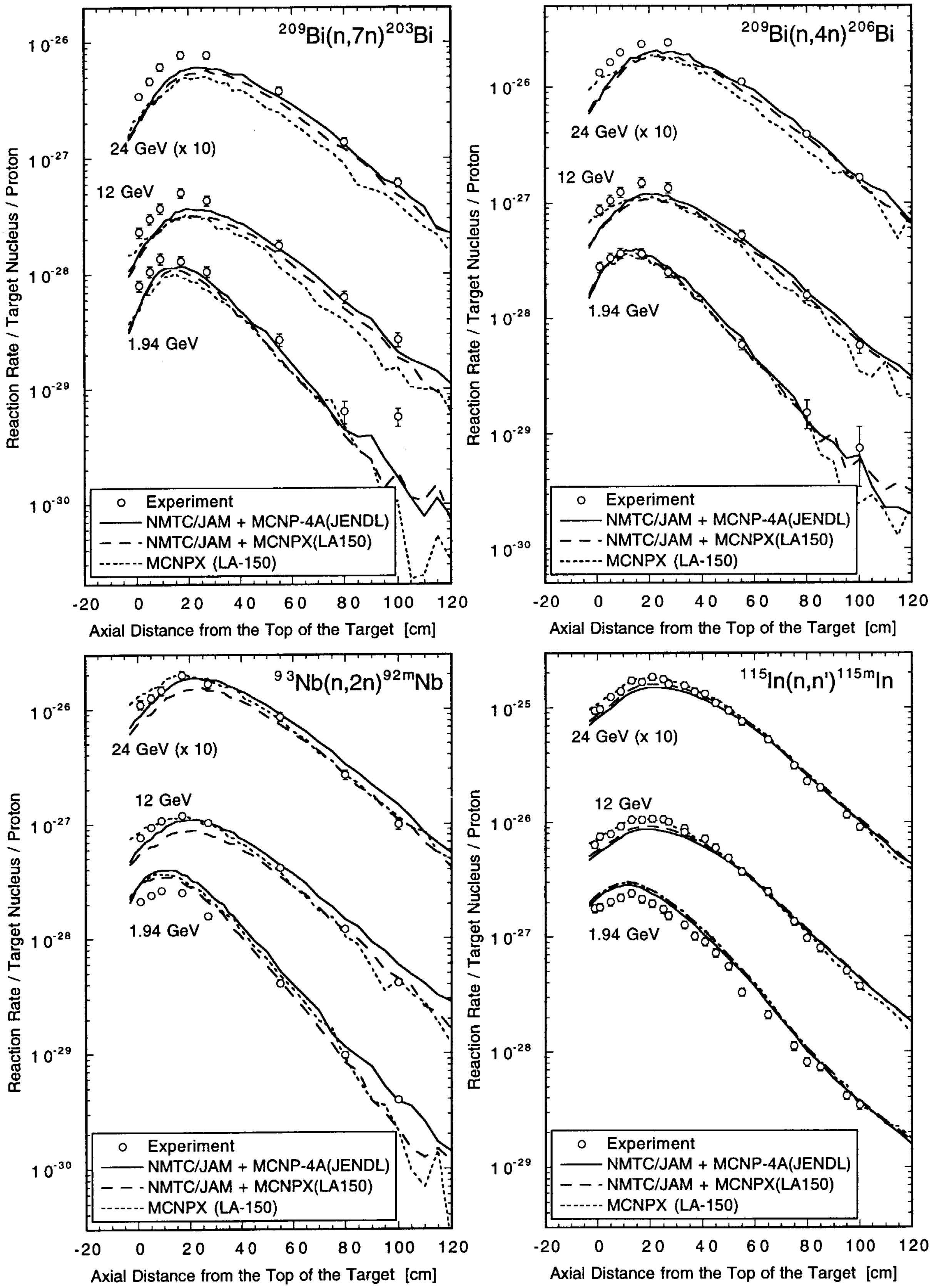

Fig. 5 Measured and calculated reaction-rate distributions on the *Main* bar for the $^{209}Bi(n,7n)^{203}Bi$, $^{209}Bi(n,4n)^{206}Bi$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{115}In(n,n')^{115m}In$ reactions for the 1.94, 12 and 24 GeV proton energies. The four reactions are induced mainly by neutrons in the 60-100 MeV, 30-50 MeV, 10-20 MeV and 1-10 MeV energy ranges, respectively.

4. Results and Discussion

4.1 Activation Reaction-rate Distribution

Measured and calculated reaction-rate distributions on the *Main* bar for the $^{209}Bi(n,7n)^{203}Bi$, $^{209}Bi(n,4n)^{206}Bi$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{115}In(n,n')^{115m}In$ reactions are compared in Fig. 5. As a whole, all calculated results agree very well with the experimental data in both intensity and shape of the spatial distributions. A general trend is found that neutron fluxes in an approximate energy range between 30 to 100 MeV represented by the two bismuth reaction-rates are underpredicted by ~ 30 % by all calculations while the discrepancies decrease for lower neutron energies represented by the niobium and the indium reactions (approximately 1 ~ 20 MeV neutrons).

Discrepancies among the three cases of calculations are not so significant. For the $^{209}Bi(n,7n)^{203}Bi$ reaction, results by the NMTC/JAM with MCNP and JENDL are closest to the experimental data among the three. For the $^{115}In(n,n')^{115m}In$ reaction, the MCNPX calculation gives the best agreement to the experiment compared to the other calculations.

When we look at one set of code and data, trends in agreements between the experiment and the calculation for 12 and 24 GeV are similar while not so for 1.94 GeV. There are two possible reasons for the distinct trends. One reason would be in the differences in physics model. The NMTC/JAM and MCNPX codes use the Bertini model for intranuclear cascade calculation below ~ 3.5 GeV while they use the JAM model and high energy models in FLUKA, respectively, above ~ 3.5 GeV. Another reason would be in the experimental conditions. Proton beams for 1.94 GeV is much broader than those for 12 and 24 GeV.

In the experiment, fifteen threshold reactions with threshold energies ranging from 0.3 MeV to 45 MeV were measured. By utilizing these reaction-rates, neutron flux spectra at the sample positions were derived as shown in Fig. 6 by the spectrum adjustment method with the SAND-II code [17]. Since the adjusted spectrum is just a reflection of the original reaction-rates, relation between the adjusted and calculated spectra is the same as mentioned in the discussion of reaction-rates. All the calculations trace the adjusted spectra appropriately.

4.2 Thermal Neutron Spectrum

Figure 7 compares measured and calculated thermal neutron spectra leaking from the light water moderator. As a whole, again, all the calculated results agree very well with the experimental data. In the epi-thermal energy region above 0.3 eV, neutron fluxes by the three calculations for 12 GeV and 24 GeV are slightly smaller than the experimental values, while those for 1.94 GeV are slightly larger. The results are just the same as those for neutron fluxes around 1 MeV (see Fig. 6). This implies that we can rely on the cross section data for materials used in the experiment in the energy range from 1 MeV to 0.3 eV where much efforts have been devoted in developing cross section data libraries for fission and fusion applications.

Neutron fluxes in the thermal energy region are calculated larger than those in the epi-thermal region compared to the experiment, although differences are small as ~ 20 %. It is difficult to think that the reason lies in the calculation. Probably, neutron absorption by some thermal sensors and their supporting structure in the moderator, and by glue to seal the aluminum container would be the reason because the parasitic absorption is not considered in the calculation.

In Fig. 8, moderator position dependencies of thermal neutron flux integrated in the en-

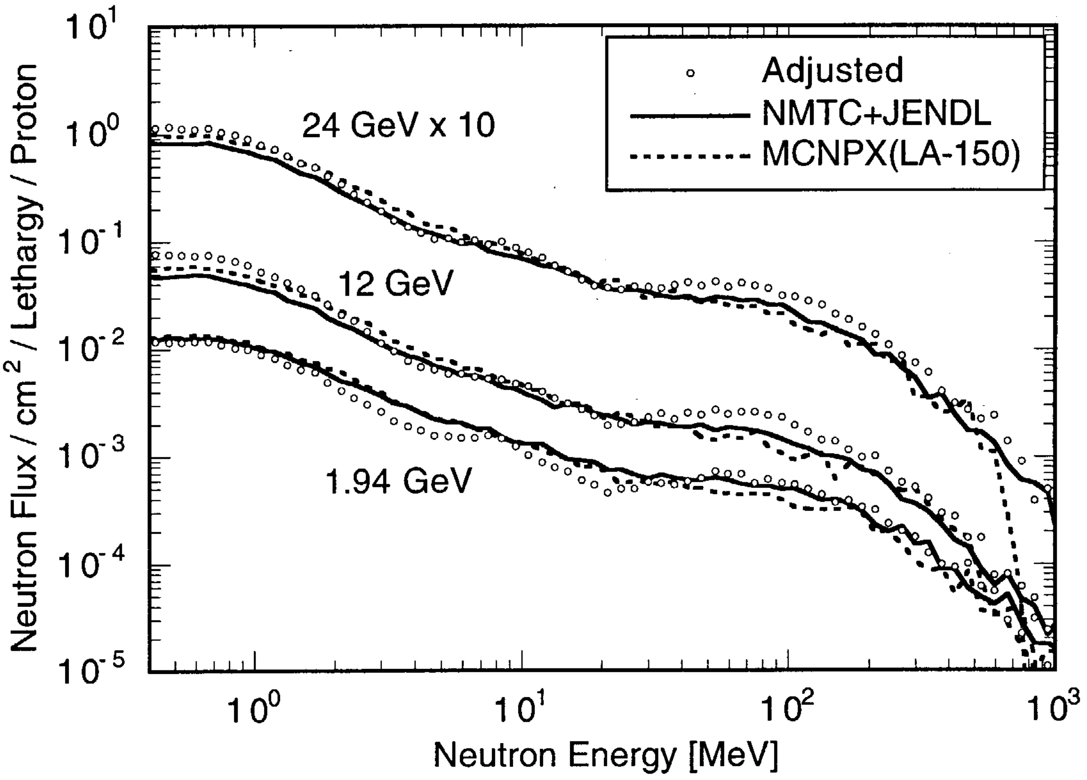

Fig. 6 Neutron spectra at the 16 cm position on the *Main* bar adjusted according to the measured reaction-rates in comparisons with the calculated spectra.

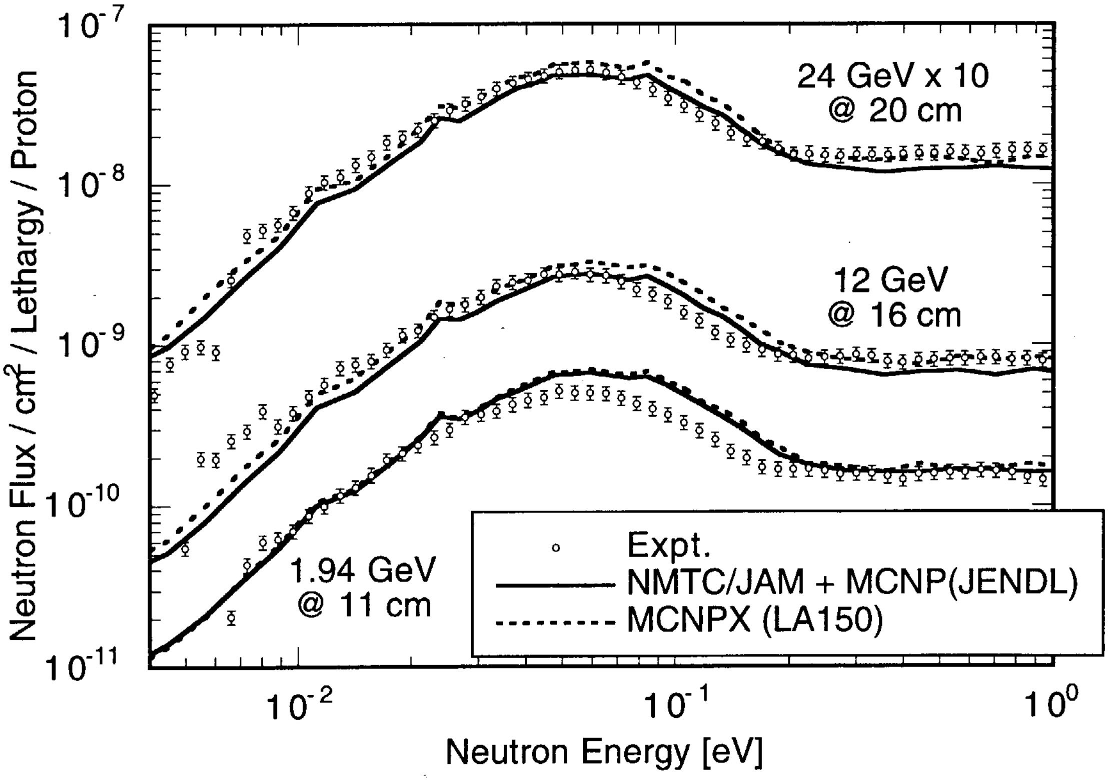

Fig. 7 Measured and calculated thermal neutron spectra for the three proton energies.

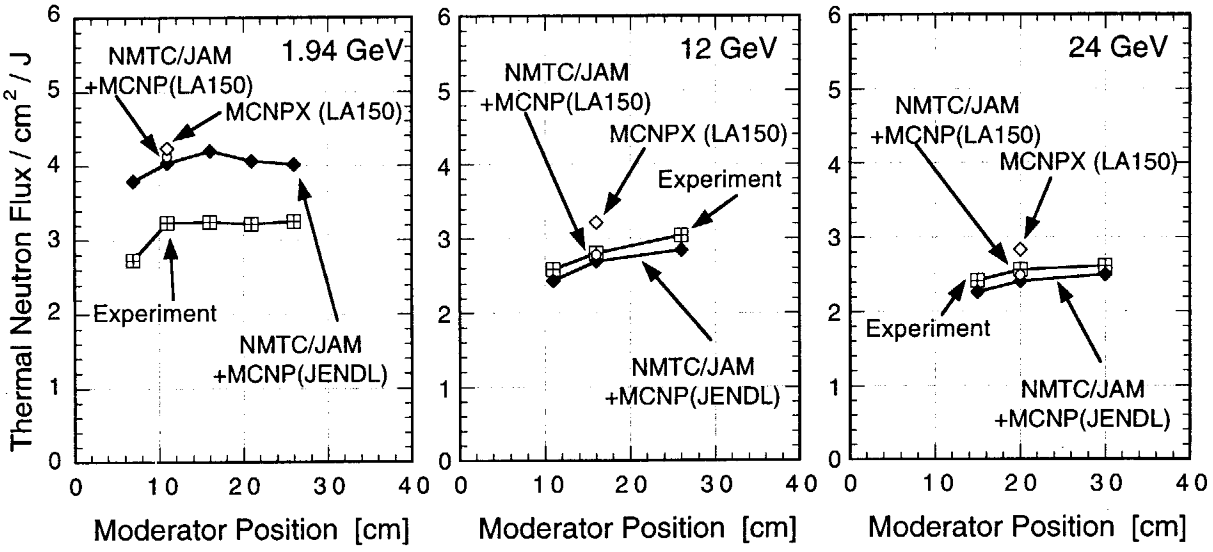

Fig. 8 Moderator position dependencies of thermal neutron flux integrated in the energy range from 0.007 eV to 0.3 eV. The NMTC/JAM and MCNP(LA150) calculations (open circles) and the MCNPX(LA150) calculations (open diamonds) are plotted only for one moderator position for each proton energy.

ergy range from 0.007 eV to 0.3 eV are presented. Although some discrepancies are found in the flux intensity, especially for the 1.94 GeV case as observed in Fig. 7, the moderator position dependencies are reproduced adequately by the calculations for all the three proton energies. The good agreements indicate that the neutron production process in the mercury target by proton induced spallation reactions as well as the neutron transport process in the lead reflector are treated adequately in the calculations.

Conclusion

According to the analysis of the AGS experiment on the mercury target with the moderator and the reflector, all the adopted calculations showed very excellent prediction capabilities for the fast neutron distributions along the target as well as spectral fluxes of neutrons extracted from the moderator. All the calculations predicted these experimental results with accuracies better than ± 50 % in absolute values. It should be noted that the energy range treated in this analysis ranged from 24 GeV to the thermal energy, more than 12 orders of magnitude starting a GeV energy proton incident. It was demonstrated that we could rely on the calculation codes and nuclear data bases used in this study (the NMTC/JAM, MCNP-4A, and MCNPX codes and the JENDL and LA-150 libraries) for designing spallation neutron sources.

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