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STUDY OF RESIDUAL NUCLIDE YIELDS FROM 0.1, 0.2, 0.6, AND 2.6 GeV PROTON-IRRADIATED THIN ^{NAT}Hg TARGETS

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Abstract

The direct γ-spectrometry method is used to measure more than 350 residual product nuclide yields from 0.1, 0.2, 0.8, and 2.6 GeV proton irradiated ^{nat}HgO targets. The γ-spectrometer resolution is 1.8 keV in 1332 keV γ-line. The resultant γ-spectra are processed by GENIE2000 code. The γ-lines are identified, and the cross-sections calculated, by the ITEP-designed SIGMA code using the PCNUDAT radioactive database. The ^{27}Al(p,x)^{22}Na reaction is used as monitor. The experimental results are compared with the yields simulated by the HETC, LAHET, INUCL, CEM95, CASCADE, and YIELDX codes that simulate hadron-nucleus interactions.

Introduction

Mercury is planned to use as target material in all the present-day designs of SNS facilities [1,2], thus necessitating that the HG-proton interaction characteristics should be studied in a broad energy range from a few MeV to 2-3 GeV. Among the characteristics, the yields of residual proton reaction product nuclei are of particular importance. They are the independent nuclear constants to be used in practical calculations and in verifying the codes for calculating the SNS facility design parameters, such as radioactivity both current and residual), deterioration of resistance to corrosion, yields of gaseous products, poisoning, etc.

Experiment

The experimental samples are 10.5-mm diameter samples manufactured by pressing fine-dispersed ^{nat}HgO powder. The weight contents of impurities in the samples do not exceed 0.16%, of which 0.01%Si, 0.03%Cl, 0.02%Ca, 0.04%Ti, 0.03%Fe, and 0.01%Ba. The total content of the rest 60 elements found by spark mass-spectrometry is below 0.02%.

The measurements were made by relative method using ^{27}Al(p,x)^{22}Na reaction to monitor the process. The monitors are the 10.5-mm Al foils with chemical impurities below 0.001%. Two independent proton beams from the ITEP U-2 synchrotron are used to irradiate the samples, namely, the low-energy (70-200 MeV) and high-energy (800-2600 MeV) beams.

Table 1 presents the characteristics of the experimental samples and monitors together with the main irradiation parameters.

The techniques for irradiating the samples and for processing the γ-spectra are presented in [3] together with the formulas to be used in determining the fragment nuclide yields.

Table 1. Parameters of experimental samples and monitors, the irradiation conditions, and the monitor reaction cross sections.

Proton energy, GeV	Sample thickness, mg/cm^2	Monitor thickness, mg/cm^2	Irradiation time, min	Mean proton flux density, p/cm^2/s	^{27}Al(p,x)^{22}Na cross section, mbarn
0.10	536.0	138.2	60	$2.5\cdot10^9$	19.1 ± 1.3
0.20	537.4	137.3	45	$7.1\cdot10^9$	15.1 ± 0.9
0.80	529.3	139.1	15	$1.5\cdot10^{10}$	15.5 ± 0.9
2.6	536.3	137.0	60	$4.9\cdot10^{10}$	11.7 ± 0.9

Experimental results

More than 350 yields of residual nuclei (from ^{22}Na[1] to ^{203}Hg) from 0.1, 0.2, 0.8, and 2.6 GeV proton-irradiated ^{nat}Hg have been measured. Fig. 9 shows the products that were measured at all the four energies.

The experimental data were compared with the LAHET, CEM95, INUCL, CASCADE, and YIELDX code-simulated yields. The comparison method and the references to descriptions of the codes can be found in [3]. It should be noted that the said codes, which simulate hadron-nucleus interactions, cannot simulate the independent and cumulative yields independently for the ground and metastable states of the produced radionuclides, whereas the yields of either ground or metastable states alone are often measured. Therefore, those particular measurement results were excluded from the comparison procedure. The only exclusion is the case of measuring both states, so the total yields could be compared with the simulation data. Table 2 and Figs. 1-4 present the results of the minute nuclide-by-nuclide comparison procedure.

Table 2. Statistics of the experimental-to-simulated yield comparisons

Code	E_p=0.1GeV, N_T = 45, N_G = 35			E_p=0.2GeV, N_T = 64, N_G = 50		
	$N_{C1.3}$ / $N_{C2.0}$ / N_S	⟨F⟩	S(⟨F⟩)	$N_{C1.3}$ / $N_{C2.0}$ / N_S	⟨F⟩	S(⟨F⟩)
LAHET	13/21/30	2.24	1.92	22/36/49	2.24	1.92
CEM95	6/15/28	2.29	1.61	20/31/39	2.13	1.91
INUCL	10/19/33	2.74	2.05	12/27/49	2.42	1.79
CASCADE	16/24/33	2.36	1.98	21/35/49	2.62	2.21
YIELDX	-	-	-	14/35/50	2.25	1.78
	E_p=0.8GeV, N_T = 106, N_G = 88			E_p=2.6GeV, N_T = 141, N_G = 121		
	$N_{C1.3}$ / $N_{C2.0}$ / N_S	⟨F⟩	S(⟨F⟩)	$N_{C1.3}$ / $N_{C2.0}$ / N_S	⟨F⟩	S(⟨F⟩)
LAHET	42/63/87	2.06	1.73	23/80/118	2.02	1.49
CEM95	30/46/59	2.35	2.13	46/77/91	2.27	2.11
INUCL	26/42/82	2.74	1.95	37/77/115	2.55	2.03
CASCADE	35/59/84	2.52	2.10	56/93/114	1.76	1.55
YIELDX	32/62/88	2.21	1.82	26/65/120	2.52	1.78

[1] The ^{22}Na and ^{24}Na yields have been determined disregarding the contributions from the Al monitor samples.

In Table 2: N_T is the total number of the measured yields; N_G is the number of the yields selected to use in comparison with experimental data; N_S is the number of the products whose yields were simulated by a particular code; $N_{C1.3}$ is the number of the comparison events when the simulation-experiment difference does not exceed 30%; $N_{C2.0}$ is the the number of the comparison events when the simulation-experiment difference does not exceed a factor of 2.

Figs 1-4 show the results of the nuclide-by-nuclide comparison of the experimental results with the LAHET, CEM95, CASCADE, INUCL, and YIELDX code-simulated data. From the figures it is seen that all codes (except for YIELDX) can adequately predict the A>170 product yields for 100, 200, and 800 MeV protons and the A>120 product yields for 2600 MeV protons. The yields simulated actually by all the codes in the remaining ranges of masses are very different from experiment, with the most significant differences observed in the 80<A<103 range for the 100 and 200 MeV protons, in the 48<A<130 range for the 800 MeV protons, and in the 28<A<100 range for the 2600 MeV protons.

Figs. 5-8 show the simulated mass yield of the reaction products. Shown for comparison are also the experimental cumulative yields, which are often equal to the mass yields within measurement errors.

The following conclusions may be drawn from the comparison between the experimental and simulated mass yields:

- in the case of 0.1 GeV protons and A>190, all codes predict the mass curve shape quite adequately,
- in the case of 0.2 GeV protons and A>180, all the code-simulated yields are in a good agreement with experiment,
- in the case of 0.8 GeV protons, the best agreement with experiment is given by YIELDX at A>130 and by INUCL at A<130,
- in the case of 2.6 GeV protons and A>100, The CEM95 and CASCADE code-simulated data agree with experiment, while the LAHET results are underestimated and the YIELDX and INUCL code-simulated yields represent the mass curve shape erroneously. None of the codes can represent the experimental curve shape at A<100.

Fig. 9 illustrates the dependence of part of the measured yields on proton energy. The above data will be analyzed after the final release of all the experimental results.

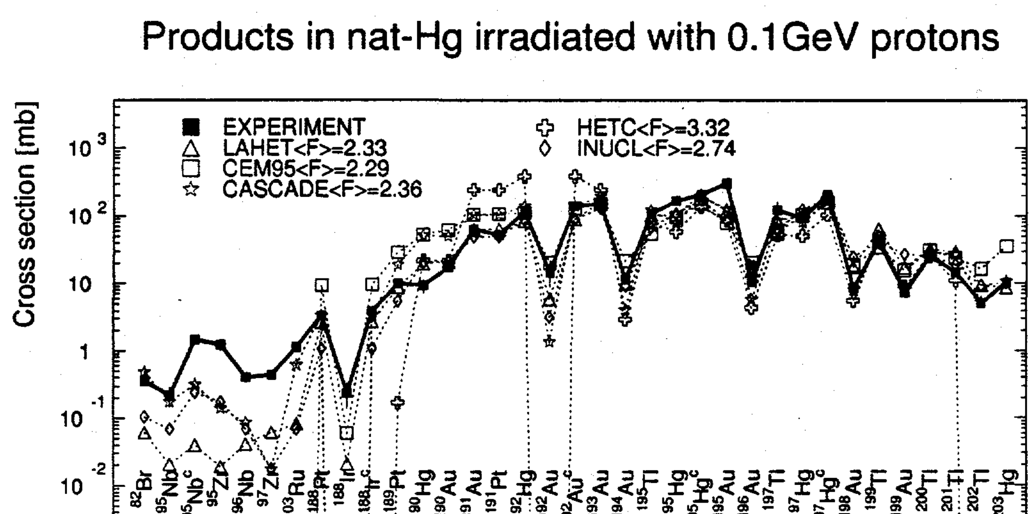

Fig. 1. Nuclide-by-nuclide comparison between the experimental and simulated data for 0.1 GeV protons. The cumulative yields are labeled "c" when respective independent yields are also shown.

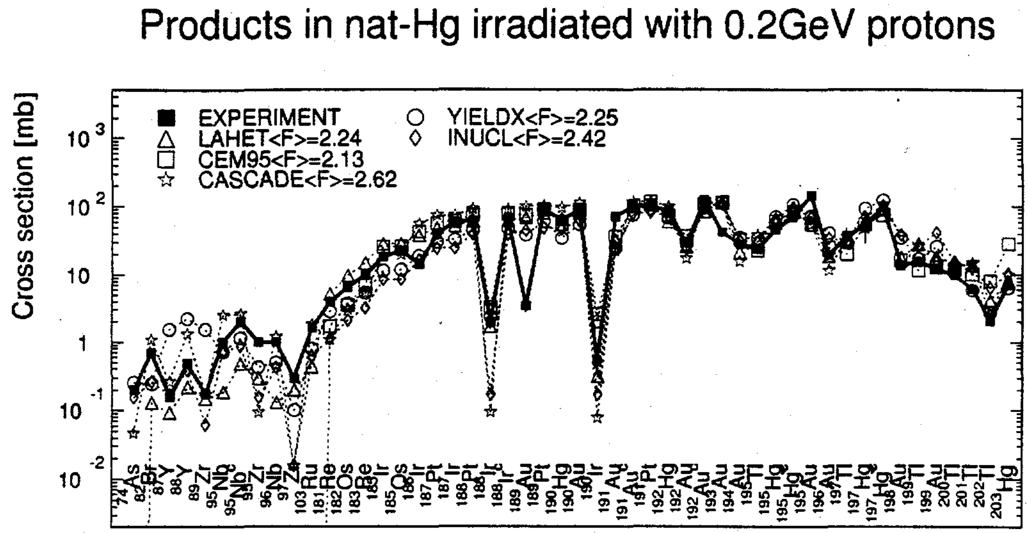

Fig. 2. Product-by-product comparison between the experimental and simulated data for 0.2 GeV protons. The cumulative yields are labeled "c" when respective independent yields are also shown.

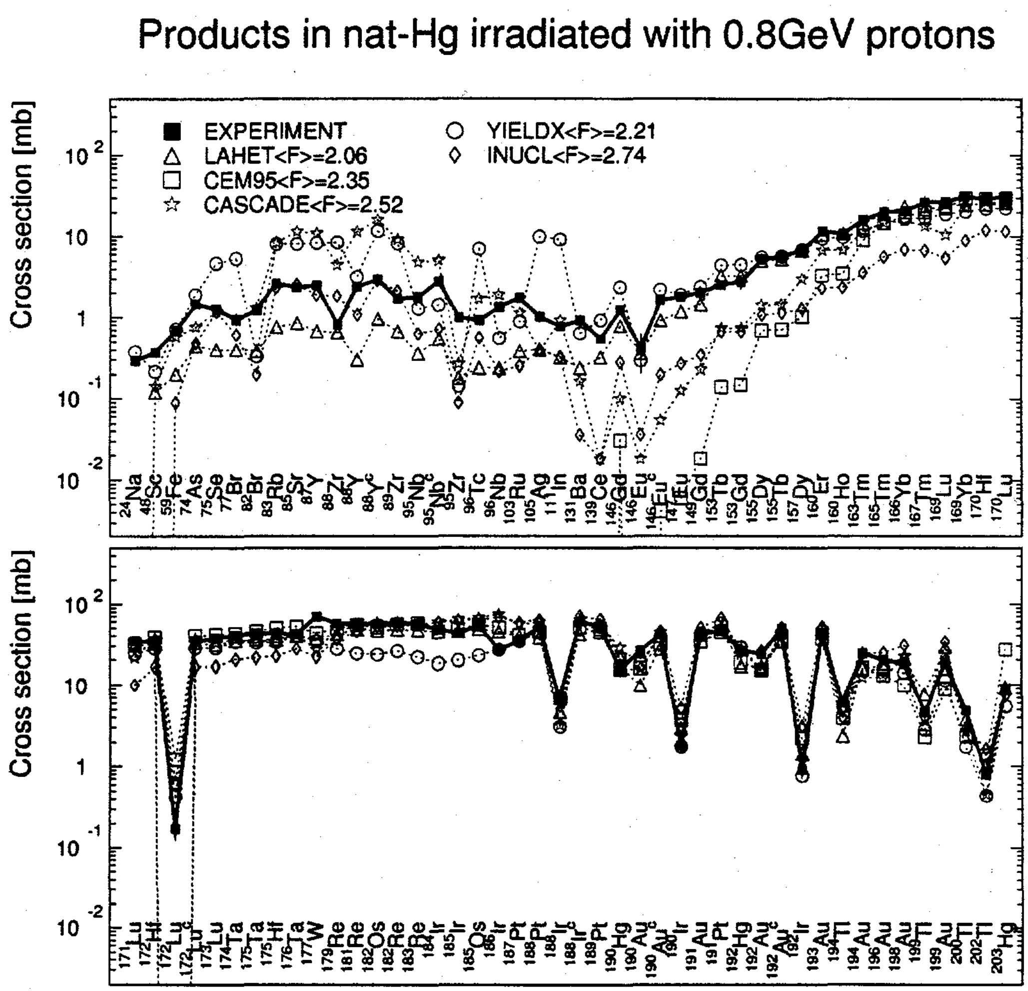

Fig. 3. Nuclide-by-nuclide comparison between the experimental and simulated data for 0.8 GeV protons. The cumulative yields are labeled "c" when respective independent yields are also shown.

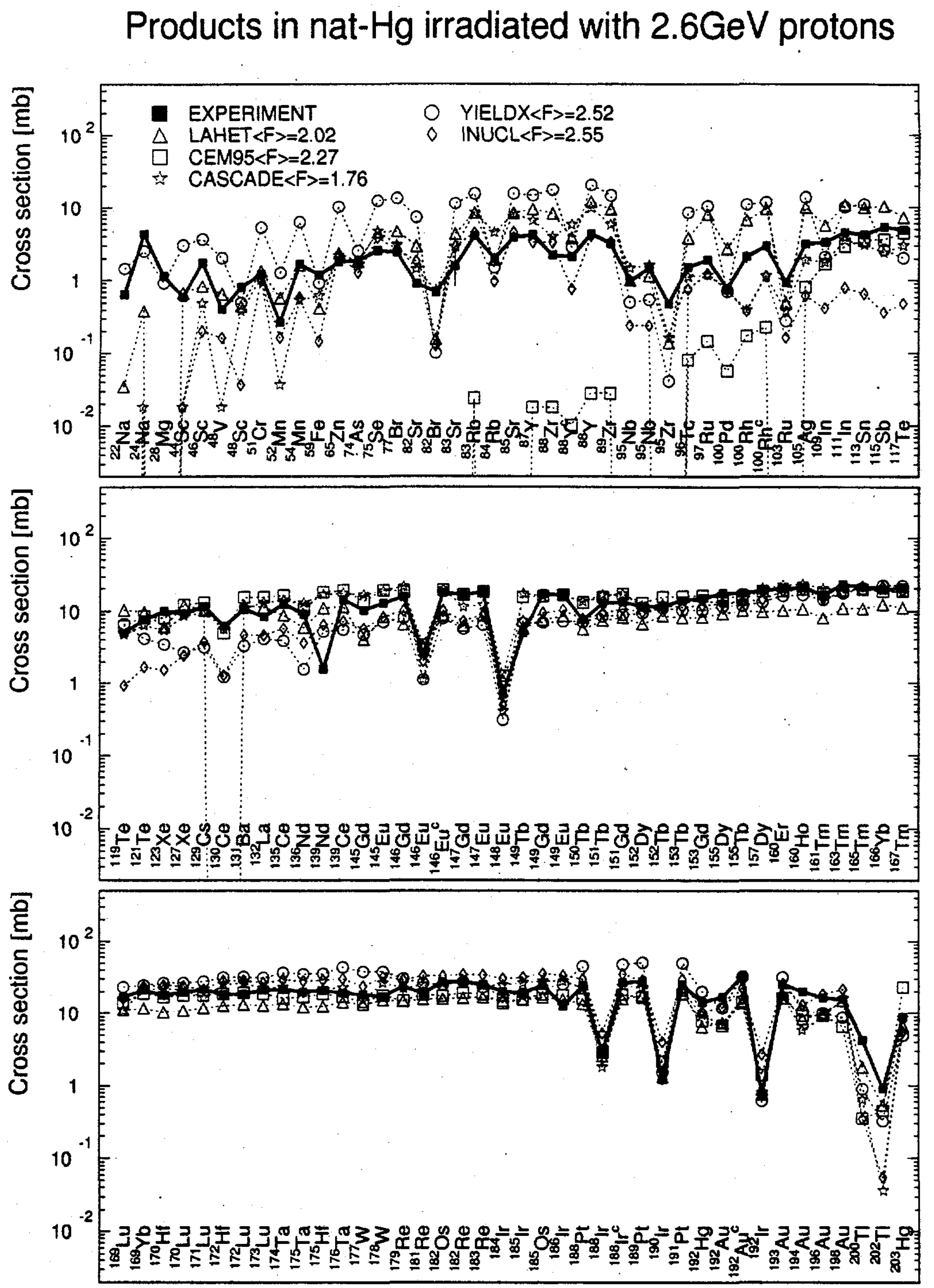

Fig. 4. Nuclide-by-nuclide comparison between the experimental and simulated data for 2.6 GeV protons. The cumulative yields are labeled "c" when respective independent yields are also shown.

Mass yields in nat-Hg irradiated with 0.1GeV protons

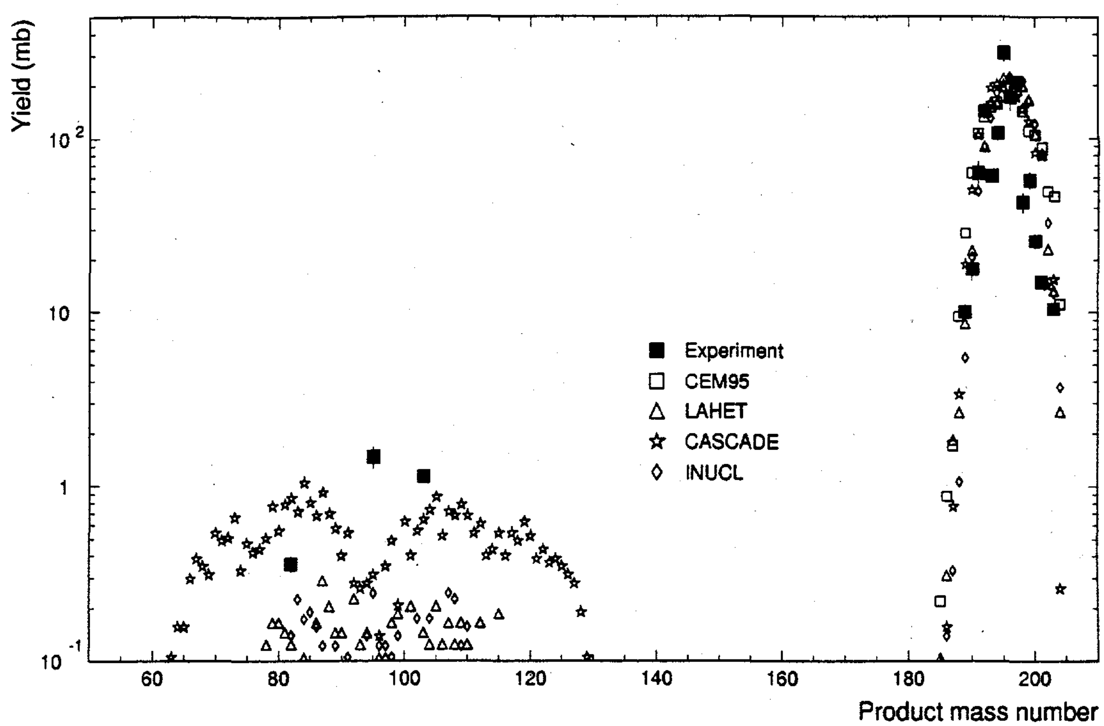

Fig. 5. The simulated and experimental mass yields at 0.1 GeV.

Mass yields in nat-Hg irradiated with 0.2GeV protons

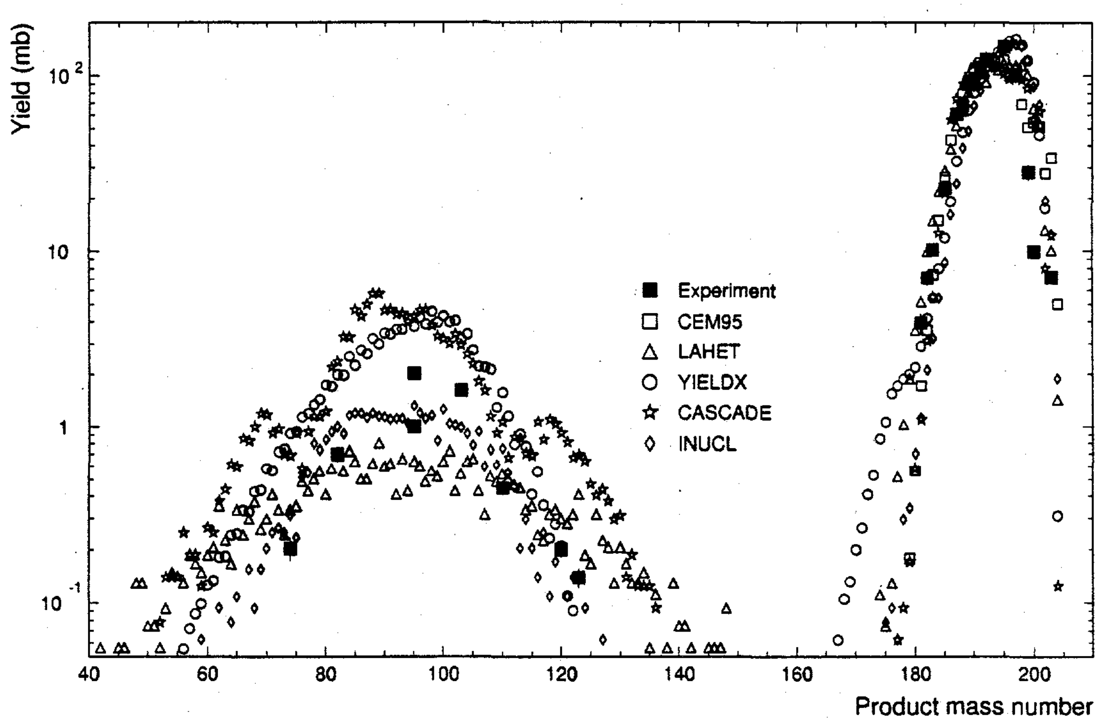

Fig. 6. The simulated and experimental mass yields at 0.2 GeV.

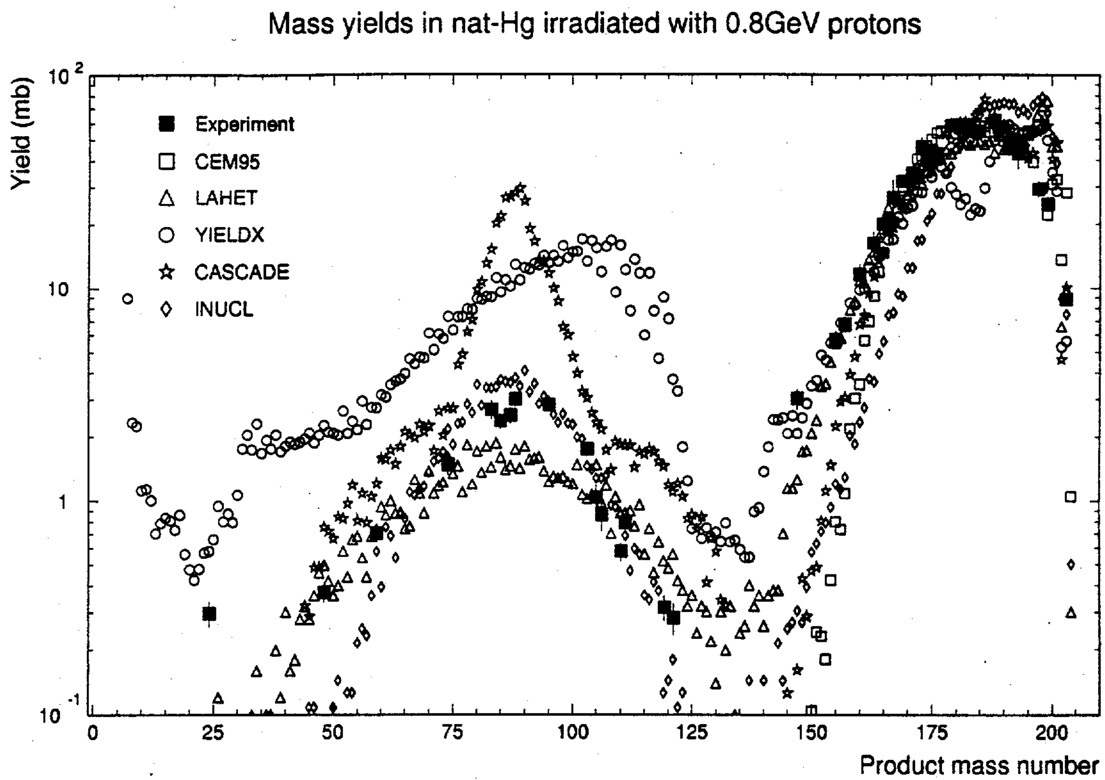

Fig. 7. The simulated and experimental mass yields at 0.8 GeV.

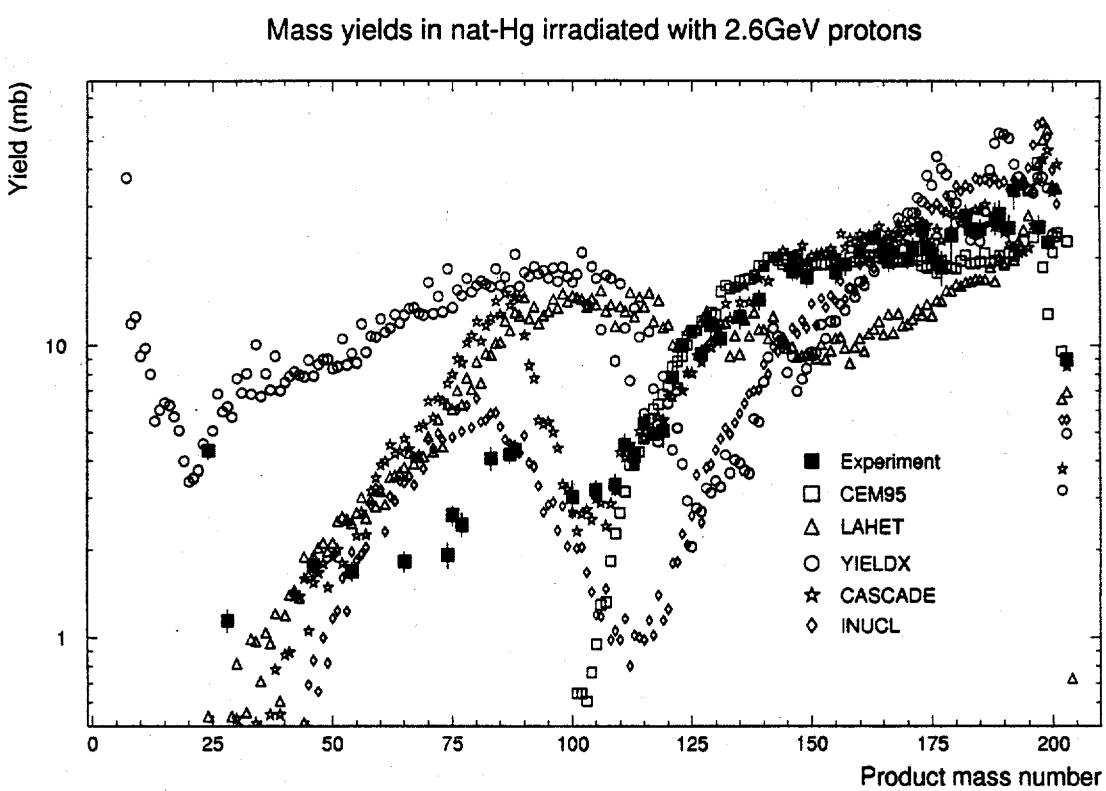

Fig. 8. The simulated and experimental mass yields at 2.6 GeV.

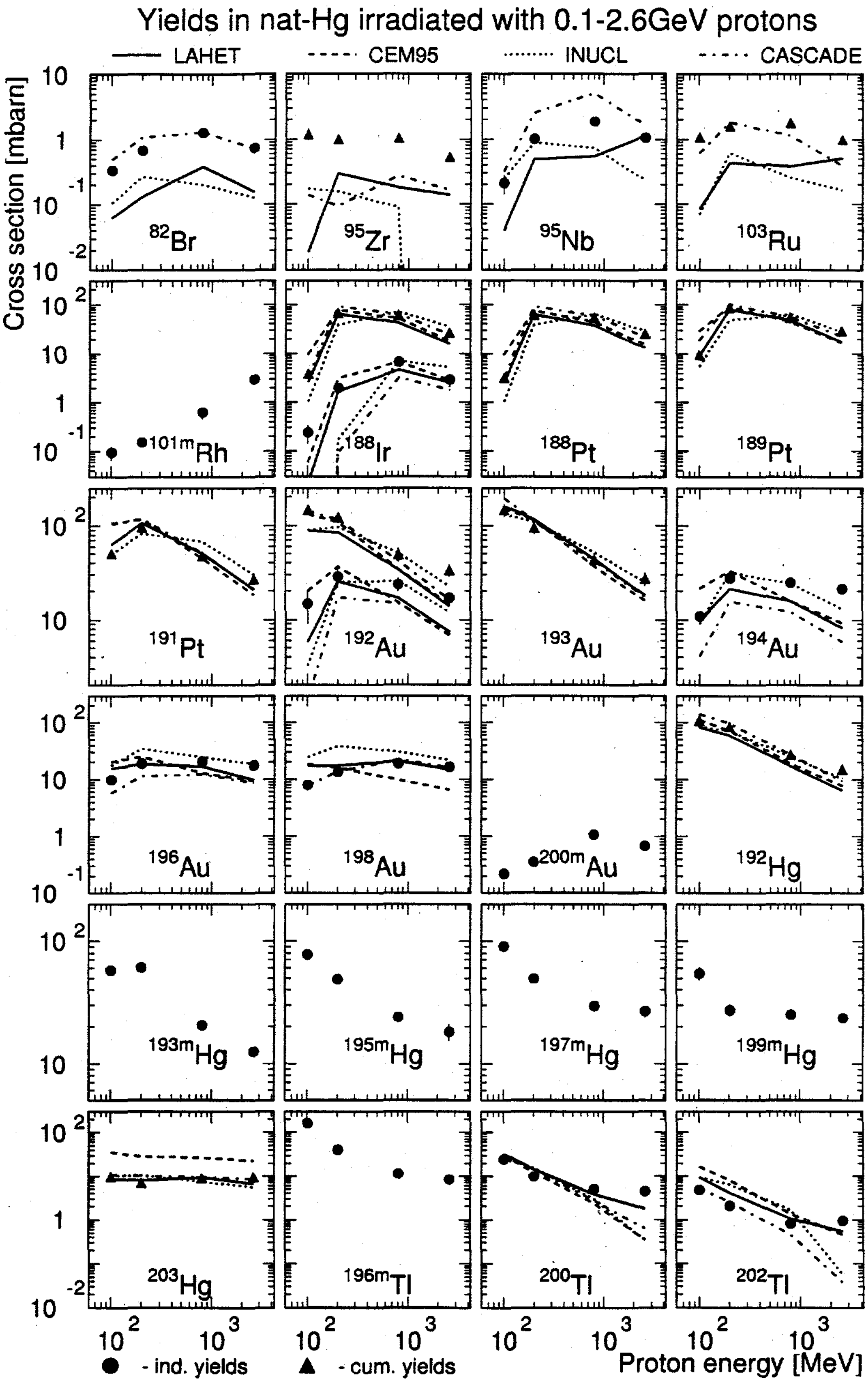

Fig. 9. Some experimental yields versus proton energy and their calculated values.

Conclusion

The experiment-to-simulation comparison has shown that, on the whole, the simulation codes can but poorly predict the experimental results. In some cases, the differences reach an order and even more. This means that the nuclear data must be accumulated persistently in the above-mentioned ranges of energies and masses with a view to modifying the hadron-nucleus interaction models that underlie the codes.

Acknowledgement

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