

# $\eta$ Production on Carbon and Tungsten Targets by Proton at $T_P \leq 1500$ MeV

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The production of  $\eta$  meson induced on carbon and tungsten targets by protons of kinetic energies from 800 to 1500 MeV has been studied at the Laboratoire National Saturne at Saclay.  $\eta$  mesons of mean kinetic energies 55 MeV and 125 MeV have been detected by positioning the PINOT spectrometer in two different configurations. The results are presented and discussed in the framework of a recent theoretical model.

## I Introduction

The study of the inclusive  $\eta$  meson production by protons on nuclei near the threshold of the  $\eta$  production in N-N collisions ( $T_p=1.265$  GeV) has been, in recent years, an important part of the low energy  $\eta$  meson physics research program performed at the Laboratoire National Saturne at Saclay. As in other inclusive particle production experiments, the main goal of the study was to investigate the  $\eta$  production dependence on various nuclear phenomena such as internal nuclear Fermi motion, baryonic resonance production and/or more exotic phenomena like collective effects and variation of meson masses with nuclear density.

The peculiarities of the  $\eta$  meson, compared to the other mesons belonging to the same SU(3) multiplet, are many. First of all it exists only in the neutral state and it has an extremely short ( $10^{-18}$  s) mean life, making it impossible to build suitable  $\eta$  meson beams for direct scattering experiments. Secondly, being an isoscalar meson ( $I = 0$ ), it couples only to  $N^*$  resonances ( $I = 1/2$ ) and not to the  $\Delta$  ones ( $I = 3/2$ ). In particular, at the threshold of the  $\eta$  production in N-N collisions, the  $N^*(1535)$  plays a dominant role; in this respect the  $\eta$  meson is considered a good  $N^*(1535)$  marker. In addition, because of its higher mass, com-

pared for example with that of the pion, its production involves large momentum transfer.

To perform the program, a variety of proton beam energies, from 800 MeV to 1500 MeV, and nuclear targets, from  ${}^6\text{Li}$  to  ${}^{197}\text{Au}$ , have been used and many results have already been published [1, 2, 3, 4].

In this article we report on the measurement of the  $pC \rightarrow \eta X$  and the  $pW \rightarrow \eta X$  reactions, performed with protons of energies between 800 MeV and 1500 MeV, and we compare the experimental results with the predictions from recent calculations [5].

## II Experimental method

The experiment has been carried out at the beam line 10 of the Laboratoire National Saturne in Saclay. Line 10, designed to deliver beams up to the maximum energy of 3 GeV from Saturne II proton synchrotron, was tuned to transport proton beams at an average intensity of about  $10^9$  p/s. The beam intensity was continuously monitored by three beam monitors, each one consisting of a scintillator telescope. The first one was placed before the target and detected charged particles produced at about 20 degrees on a thin polyethylene foil placed directly in the proton beam path in the vacuum pipe, the second one detected charged particles

produced at about 120 degrees in the target and the third one was used to detect charged particles backscattered by the beam dump. All three monitors were calibrated, from time to time, by using of the carbon activation method [6, 7]. Carbon and tungsten targets, respectively 1 cm. and 0.08 cm. thick, were placed and operated under vacuum. In order to reduce the background due to the interactions of beam particles with air, the vacuum was extended upstream the target till the end of the beam pipe and downstream the target for a length of about two meters.  $\eta$  mesons were detected by means of the PINOT spectrometer.

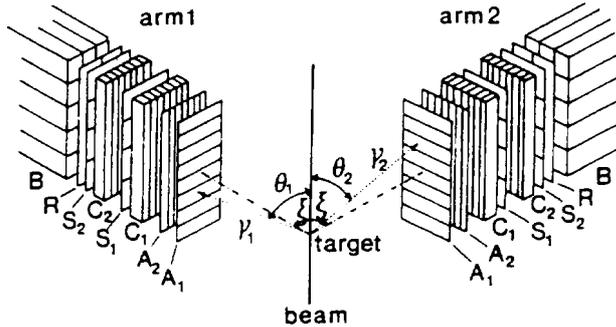


Figure 1. Schematic view of the PINOT spectrometer when the two arms are symmetrically positioned at an angle  $\xi$  with respect to the beam line. In the present experiment the angle  $\xi$  was  $55^\circ$  and  $66^\circ$  and the distance from the target to the first converter was 138 cm.

Details of the spectrometer can be found in reference [1]. Here we simply recall that it consists of two identical arms (see Fig. 1) and can measure simultaneously energy and direction of the two  $\gamma$  rays originating from the instantaneous decay of the  $\eta$  meson. The  $\eta$  mesons are then identified since they fall in a peak in the distribution of the  $\gamma$  pair invariant mass, defined

as:

$$M_{\gamma\gamma} = 2\sqrt{E_1 E_2} \sin(\psi/2) \quad (1)$$

where  $E_1$  and  $E_2$  are the energies of the two  $\gamma$  rays and  $\psi$  ( $\psi = \theta_1 + \theta_2$ , see Fig. 1) is their opening angle.

The Fig. 2 shows a  $\gamma\gamma$  invariant mass spectrum obtained for the two nuclear targets discussed in this paper and for one specific geometrical configuration of the PINOT spectrometer. The  $2\xi$  angles between the two arms were set at two different values,  $110$  and  $132$  degrees. The corresponding  $\eta$  meson kinetic energy ranges were roughly in the intervals  $70$ - $200$  MeV and  $30$ - $100$  MeV, respectively. The acceptances of the spectrometer, as calculated by a Monte Carlo program, for the two settings, are shown in Fig. 3. The  $\gamma\gamma$  opening angle was determined using the information from converter bars and scintillators. The value for the parameter  $X = (E_1 - E_2)/(E_1 + E_2)$ , which determines the asymmetry between the energies  $E_1$  and  $E_2$  of the two gamma rays and consequently the energy resolution of the spectrometer, was chosen in the interval  $\pm 0.3$ . With this choice the energy resolution, which is not so relevant for the experiment, was about  $10$  MeV.  $E_1$  and  $E_2$  were measured adding up the signals in each arm arising from the converter bars and from the blocks, which constitute the calorimeters. Converter bars, for a total thickness of two radiation lengths, and calorimeter blocks, fourteen radiation lengths thick, were both made of scintillating glasses. Target-in to target-out ratios, were on average about 20 making almost unnecessary empty target runs, since the targets were placed under vacuum. Signals from the anticoincidence counters were recorded in a large time window, 250 ns wide and centered at the trigger time, in order to reject pile-up events in the off-line analysis since scintillating glasses have a scintillating decay time as long as  $80$  ns.

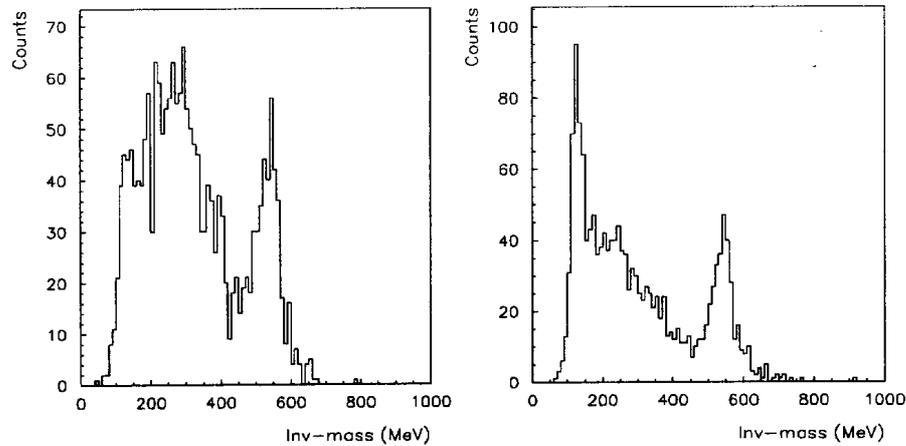


Figure 2.  $M_{\gamma\gamma}$  invariant mass spectrum for the reaction: (left)  $p^{12}\text{C} \rightarrow \eta X$  at  $T_p=1.3$  GeV and (right)  $p^{184}\text{W} \rightarrow \eta X$  at  $T_p=1.4$  GeV. In both cases the spectrometer was set to  $2\xi=110^\circ$ .

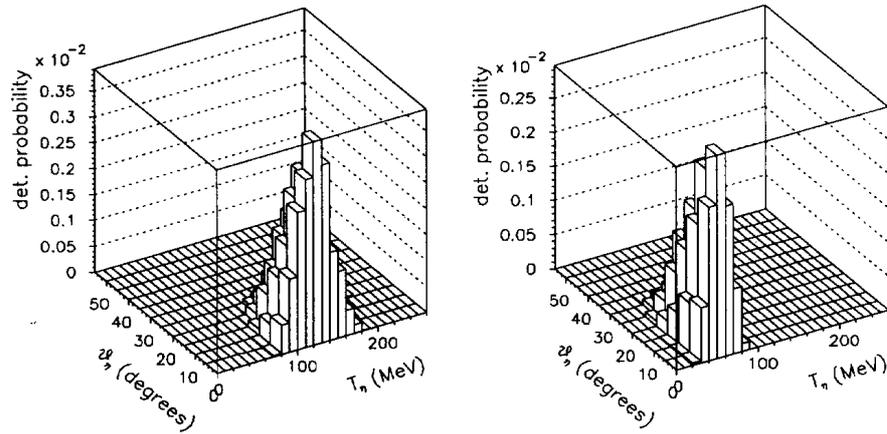


Figure 3.  $\eta$  detection probability calculated by means of a Monte Carlo code for the spectrometer positioned at an opening angle  $2\xi=110^\circ$  (left) and  $2\xi=132^\circ$  (right) at a target-converter distance of 138 cm.

### III Data taking and analysis

For the setting corresponding to the opening angle  $2\xi$  of 110 degrees, the data have been collected for both targets at five incident proton kinetic energies: 900, 1100, 1300, 1400 and 1500 MeV. For the configuration with opening angle  $2\xi = 132^\circ$ , the tungsten target has been studied also at 800 MeV, the same energy where a carbon target has been previously used (see ref[3]). The number of  $\eta$  mesons was extracted from the invariant mass spectrum, filled with events that passed the off-line filters, by fitting the  $\eta$  meson peak with a Gaussian curve superimposed to an exponential curve. This latter accounts for background events which are due to multiple  $\pi^0$  production. Fitted mean values and standard deviations from the Gaussian curve were found to be in good agreement, within 10%, with those obtained in the Monte Carlo simulation. The number of collected  $\eta$ 's depends strongly on the beam energy. After all the corrections for the dead time losses (typically of the order  $30\pm 1\%$ ), for the efficiency of the individual detectors ( $0.90\pm 0.02$ ) and for the  $\gamma$  conversions in the material between the production target and the detectors ( $0.18\pm 0.0005$ ), we were left with the numbers of  $\eta$ 's reported in table 1 and table 2. The data for the carbon target at the opening angle of 132 degrees were previously collected in a separate experiment [3]. The errors quoted in the table are statistical and are due to the fitting procedure and background subtraction.

$T_p$ (MeV)	$^{12}\text{C}$ target	$^{187}\text{W}$ target
900	$158\pm 24$	$44\pm 8$
1100	$423\pm 55$	$377\pm 37$
1300	$319\pm 42$	$289\pm 25$
1400	$536\pm 39$	$240\pm 21$
1500	$419\pm 32$	$229\pm 20$

Table 1. Collected  $\eta$ 's as a function of  $T_p$  for the  $^{12}\text{C}$  and the  $^{187}\text{W}$  at  $2\xi=110^\circ$ .

$T_p$ (MeV)	$^{187}\text{W}$ target
800	$18\pm 8$
900	$50\pm 11$
1100	$253\pm 26$
1300	$183\pm 18$
1400	$157\pm 21$
1500	$113\pm 17$

Table 2: Collected  $\eta$ 's as a function of  $T_p$  for the  $^{187}\text{W}$  at  $2\xi=132^\circ$ .

### IV Results and discussion

The experimental data are presented in Fig. 4 (full circles) in form of doubly differential cross-sections. The quoted errors are purely statistical and inside of the marker dimension; the systematic errors have been estimated to be not higher than 20%.

In order to perform the interpretation of the experimental data, a calculation of the  $\eta$  production process in pA interactions has been carried out, using the code developed by W. Cassing *et al.* [5]. This model takes into account two  $\eta$  production mechanisms in the nucleus: the direct production  $pN \rightarrow pN\eta$  and the two-step process  $pN \rightarrow NN\pi$ , followed by  $\pi N \rightarrow N\eta$ . It also takes into account the nucleon Fermi motion and the effect of the  $\eta$  reabsorption in nuclear matter.

To perform the calculation we have introduced into the code the cuts due to our experimental apparatus and we have modified some original assumptions in the light of new experimental results. In particular the values of the  $pp \rightarrow pp\eta$ ,  $pn \rightarrow pn\eta$  and  $pn \rightarrow d\eta$  total cross-sections have been chosen according to the new experimental data [8, 9, 10, 11, 12] and the  $\eta$  reabsorption has been treated in a more realistic way using a semi-classical model [13]; a  $\eta$ -nucleon cross-section of 30 mb has been chosen according to recent experimental results[14].

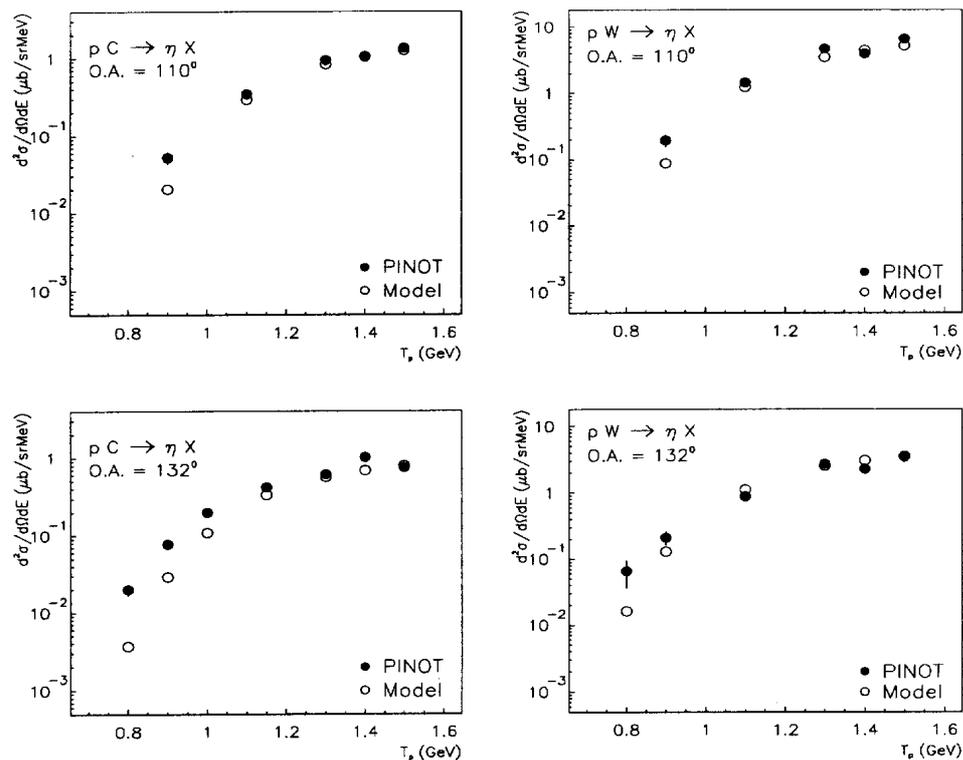


Figure 4. Doubly differential  $\eta$  cross sections  $d^2\sigma/d\Omega_\eta dT_\eta$  as a function of incoming proton energy. Full circles: Experimental data; open circles: predictions from the theoretical model of ref [5].

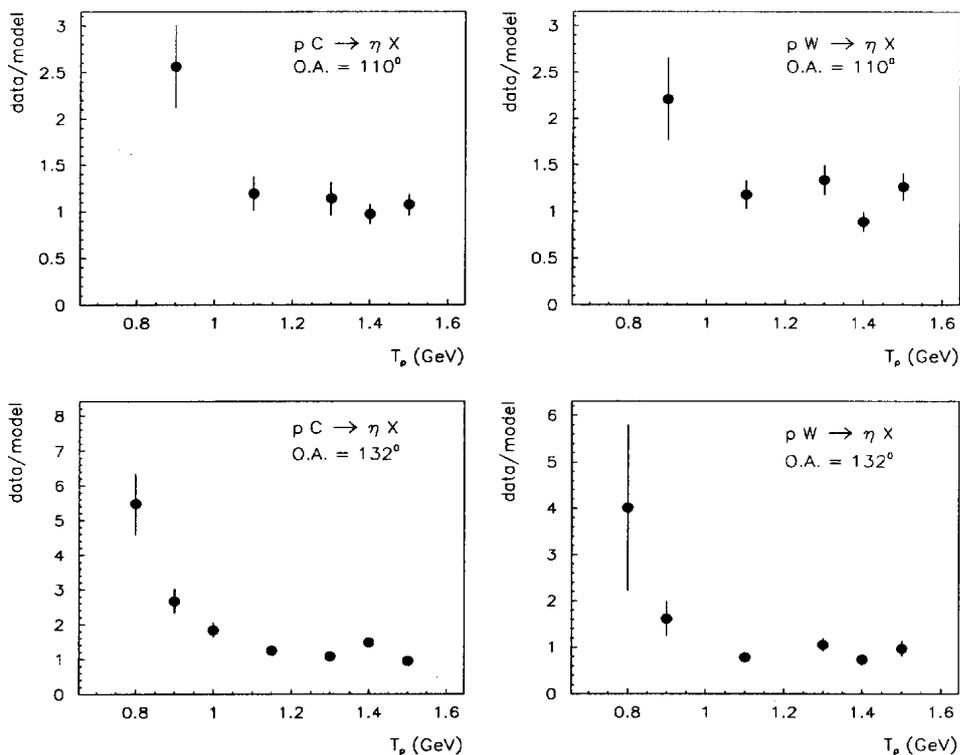


Figure 5. Ratios of doubly differential  $\eta$  cross sections  $(d^2\sigma/d\Omega_\eta dT_\eta)_{exp}$  and  $(d^2\sigma/d\Omega_\eta dT_\eta)_{model}$  for the targets and spectrometer configurations discussed in the text.

The results of the calculation are shown in Fig. 4 (open circles). Fig. 5 shows the ratio between experimental and theoretical values of the doubly differential cross section for the two geometrical setting and nuclear targets discussed in the text.

The model clearly underestimates the measured cross-sections in the region below the free  $NN \rightarrow NN\eta$  threshold ( $T_p=1.265$  GeV) by a factor 2 - 2.5 for  $\eta$ 's of mean kinetic energy,  $\langle T_\eta \rangle$ , equal to 125 MeV and by a factor 4 - 5.5 for  $\eta$ 's of  $\langle T_\eta \rangle=55$  MeV. The model gradually approaches the experimental data as the incident proton energy increases. Such a behaviour suggests that, in the subthreshold region other unknown reaction mechanisms and/or genuine collective nuclear effects could play a role.

## V Conclusions

We have presented new data on the inclusive  $(p, \eta)$  reaction on nuclei in the line of the experimental program which has been undertaken at Saturne in the last years.

We have measured the doubly differential cross section for the reaction  $pA \rightarrow \eta X$  for two nuclear targets and incoming proton kinetic energy ranging from 800 to 1500 MeV at two different settings of the PINOT spectrometer. We have compared the experimental data to the prediction of the folding model developed by Cassing et al [5]. The discrepancy between the data and the theoretical calculation in the subthreshold region seems to indicate the possible existence of different reaction mechanisms and/or the presence of collective nuclear effects.

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## References

- [1] E. Chiavassa *et al.* Z. Phys. **A342**, 107 (1992).
- [2] E. Chiavassa *et al.* Z. Phys. **A344**, 345 (1993).
- [3] E. Chiavassa *et al.* Europhys. Lett. **A41**, 365 (1998).
- [4] E. Chiavassa *et al.* Nuovo Cimento **A107**, 1195 (1994).
- [5] W. Cassing *et al.* Z. Phys. **A340**, 51 (1991).
- [6] H. Quechon Ph.D Thesis Paris (1980).
- [7] Laboratoire National Saturne *Manuel des Utilisateurs* (1991) 120.
- [8] E. Chiavassa *et al.* Phys. Lett. **B322**, 270 (1994).
- [9] E. Chiavassa *et al.* Phys. Lett. **B327**, 192 (1994).
- [10] A. M. Bergdolt *et al.* Phys. Rev. **D48**, 39 (1993).
- [11] H Calen *et al.* Phys. Lett. **B366**, 39 (1996).
- [12] H Calen *et al.* Proceedings of PANIC XIV International Conference on Particles and Nuclei, Williamsburg, USA, 22-28 May 1996, edited by C. E. Carlson and J Domingos, World Scientific, Singapore 1997.
- [13] E. Vercellin *et al.* Nuovo Cimento **A106**, 861 (1993).
- [14] M. Robig-Landau *et al.* Phys. Lett. **B373**, 45 (1996).