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NUCLEAR TARGETS AS A POWERFUL TOOL IN SELECTING RESONANT STATES

G. Bellini*)

CERN, Geneva, Switzerland

P.L. Frabetti

Istituto di Fisica dell'Università and Sezione INFN, Bologna, Italy

M. di Corato, F. Palombo and J. Pernegr

Dipartimento di Fisica dell'Università and Sezione INFN, Milan, Italy

Yu.I. Ivanshin, L.K. Lytkin, A.A. Tyapkin,
V.V. Vishnyakov and O.A. Zaimidoroga

Joint Institute for Nuclear Research, Dubna, USSR

ABSTRACT

The 0^-S and 1^+S waves have been analysed studying the coherent production of $\pi^-\pi^-\pi^+$ states at 25 and 40 GeV/c with nine different nuclear targets. The absorption in nuclear matter of the meson systems, produced within the nucleus, helps in disentangling the resonant states from the non-resonant background. It was thus possible to analyse the A_1 resonance with a reduced Deck background and to obtain evidence of two new 0^-S resonant states, which can be interpreted as the first and the second radial excitations of the pion.

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*) On leave of absence from the Dipartimento di Fisica dell'Università and INFN, Milan, Italy.

1. INTRODUCTION

In this paper we summarize the main results of the search for resonant states pursued at the Serpukhov accelerator in an experiment carried out by the Dubna-Milan Collaboration[1]. In this experiment the channel $\pi^- A \to \pi^- \pi^- \pi^+ A$ was studied at 40 and 25 GeV incident energies, using different nuclear targets.

A selective effect of the nuclear absorption on the resonant states and on the non-resonant background is studied in detail.

2. PARTIAL-WAVE ANALYSIS OF COHERENT EVENTS

The partial wave analysis (PWA) has been applied to ∿ 120,000 $\pi^-\pi^-\pi^+$ events obtained with a 40 GeV/c π^- beam, using nine nuclear targets (Be, C, Al, Si, Ti, Cu, Ag, Ta and Pb), and to ∿ 22,000 $\pi^-\pi^-\pi^+$ events collected at 25 GeV/c with an Al target. The set-up of the experiment and its performances are described in ref. 1. The results discussed here mostly concern the coherent samples, consisting of events with $t' \leq t'^*$, where t'^* corresponds to the first diffractive minimum of the differential cross-sections for the different nuclear targets. Owing to the steepness of the t' slopes for the coherent interactions on nuclear targets and to the low values of t'^* [e.g. $t'^* \simeq 0.04$ (GeV/c)^2 for Be and $t'^* \simeq 0.008$ (GeV/c)^2 for Pb], the incoherent background is very small in the coherent samples (∿ 12% for Be and ∿ 1.5% for Pb) and most of the events are in a very small t' region. As an example, in more than half of the coherent events obtained with the Pb target, the four-momentum transfer t' is lower than 0.003 (GeV/c)^2.

The PWA, when applied to coherent events, is very much simplified owing to the following reasons:

i) The total number of waves which have to be taken into account is strongly reduced because all the spin-flip amplitudes are suppressed by the coherent mechanism of the production. In our analysis, where we neglect amplitudes with intensities smaller than 1% or consistent with zero within the errors, the set of necessary waves is reduced to five (0^-S, 0^-P, 1^+S, 1^+P, 2^-P) for $M_{3\pi} < 1.1$ GeV and to seven (the previous ones plus 1^+D and 2^-S) above that mass value.

ii) The interference between waves is maximal. Therefore the phase measurements are reliable.

iii) There are no N^* cuts needed.

The PWA program of the Illinois group is used$^{2)}$. In this program the 3π system is assumed to decay into a pion and an intermediate dipion. Whereas the 1^- and 2^+ decay dipions are well described by the ρ and f resonances, respectively, the dipion 0^+ does not find a good description. Neither the ε resonance nor the parametrization using the elastic $(\pi\pi)$ phase shifts corresponds to the reality. Three different parametrizations have been used in our analysis: the ε resonance, and the elastic $\pi^+\pi^-$ $^{3)}$ and $\pi^0\pi^0$ $^{4)}$ phase shifts. The "ε" parametrization gives higher likelihood functions of the fits as well as higher coherence factors. However, the main conclusions are not influenced by the choice of the parametrization.

3. THE 1^+S WAVE

In previous papers concerning this experiment we have shown that the 1^+S amplitude exhibits a clear enhancement in the A_1 region at both the incident energies and the 1^+S phase moves quickly by 110°, at least$^{5-7)}$. This behaviour agrees with the presence of a resonance in the A_1 region, as already found in a previous experiment on nuclei at 15.1 GeV/c$^{8)}$ and confirmed afterwards in an experiment on hydrogen at 63 and 94 GeV/c$^{9)}$.

The 1^+S phase has also been measured separately for the samples obtained with the different nuclear targets. Owing to statistical problems the events were grouped in four samples, as follows: Be + C, Al + Si, Ti + Cu, Ag + Ta + Pb. In the mass region up to $M_{3\pi} \approx 1.4$ GeV the 0^-P wave is used as a reference because its phase is likely to be rather flat, even if it increases by at least 30° with respect to the 2^-P wave$^{6)}$. The results presented in fig. 1 show a systematic increase of the total phase variation with increasing target mass (accompanied by a displacement of the position of the fastest phase motion towards smaller values of $M_{3\pi}$). The phase motion in the sample of the lightest elements is rather similar to that obtained on hydrogen$^{9)}$, while it increases to $\sim$ 130° for the heaviest nuclei.

This dependence of the phase on the target mass is present only in the coherent samples (fig. 2). Whereas in the lightest nuclei the 1^+S phase as a function of t' is rather flat, in the heaviest targets the phase value is ∿ 30° higher in the coherent interval than in the large t' region.

The contribution of the Deck mechanism and resonant states to the $\pi^-\pi^-\pi^+$ channel in the coherent region has been analysed for different nuclear targets. For this purpose, the two-component model has been used, as formulated by Bowler[10]. In this model a coherent Deck contribution (figs. 3a and 3b) is considered in addition to a direct resonance production (fig. 3c). The diffractive amplitudes on nuclei, concerning either the coherent elastic scattering or the coherent production of resonances, are calculated following the Glauber theory[11,12], taking into account the absorption effects.

The fit of the two-component model to the 1^+S intensity and 1^+S - 0^-P relative phase is successful; in fig. 4 the results for silicon are shown as an example.

The contribution of the resonant component compared with the Deck background increases steeply with increasing target mass, from ∿ 0.13 ± 0.04 for Be to 0.19 ± 0.05 for Si and ∿ 0.44 ± 0.11 for Pb. The mass of the A_1 meson, obtained from the fit with the two-component model, is ∿ 1.3 ± 0.02 GeV from the Be data, 1.24 ± 0.02 GeV from Si, and 1.22 ± 0.03 GeV from Pb. Nevertheless, taking into account the errors, this mass shift with increasing resonant component is perhaps not significant, even if the effect is systematic.

From these results of the analysis of the 1^+S wave, we can conclude that the 1^+S resonance production is more and more enhanced as the size of the nuclear target is growing. A possible interpretation is that the absorption in nuclear matter depresses more kinematical effects (such as the Deck mechanism) than the resonant states produced within it.

In the present experiment the A_1 state is produced not masked by the Deck effect, as is the case in the data obtained with hydrogen and light nuclear targets. Therefore the best fit value for the A_1 mass obtained from the data collected on heavy targets is more reliable than the mass found in the hydrogen experiments; and a value below 1.25 GeV seems more likely for the A_1 resonance.

4. THE 0^-S WAVE

In previous papers[5-7] evidence has been presented for two new 0^-S resonances, which can be interpreted as radial excitations of the π.

The first resonance is found at both the incident energies (40 and 25 GeV). The 0^-S amplitude shows a clear enhancement near $M_{3\pi} \simeq 1.2$ GeV and the 0^-S phase exhibits in this mass region a fast motion of $\sim 80°$. In figs. 5a and b the 0^-S amplitude and the $0^-S - 0^-P$ phase difference, obtained at 40 GeV, are compared with the hydrogen data of the ACCMOR Collaboration[9]. The phase motion exhibited by the data on nuclei is very much larger than in the results on hydrogen and is fully consistent with a resonant behaviour of the 0^-S wave.

The intensity of the 0^-S wave and the relative phase $0^-S - 0^-P$ in the first enhancement region have been fitted using the two-component model. The resonant component is ~ 0.25 for the "ε" and the $\pi^+\pi^-$ phase-shift parametrization (the $\pi^0\pi^0$ phase-shift data do not give a good fit) and the resonance parameters are very near to the values obtained from a simpler fit using a Breit-Wigner plus a second-order polynomial background. The resonance mass and width are $M_R \simeq 1.24 \pm 0.03$ GeV and $\Gamma \simeq 0.35 \pm 0.12$ GeV, respectively.

The existence of this resonance is confirmed by the relative phase $0^-S - 1^+S$, which is nearly constant between $M_{3\pi} \simeq 1.0$ and $M_{3\pi} \simeq 1.4$ GeV. It means that in the A_1 region the 0^-S amplitude shows a resonant behaviour similar to the 1^+S wave, with the same parameters.

Evidence for a second 0^-S resonance has been obtained in the 40 GeV data above $M_{3\pi} \simeq 1.6$ GeV. At 25 GeV incident energy the analysis becomes impossible in this mass region, owing to the lack of statistics.

In the analysis of this second resonance the 1^+S wave has been used as a reference wave instead of 0^-P, which becomes negligible. The 1^+S wave, used in this region, as a reference for the 2^-S wave, reproduces well the resonance behaviour of the A_3. The (0^-S - 1^+S) relative phase shows a fast motion across the peak of ∿ 100° (see ref. 6), which is not present at all in the hydrogen data. The contribution of the Deck effect is negligible in this mass range. A fit of a Breit-Wigner resonance and a second-order polynomial background on the mass distribution and on the relative phase gives: $M_R \simeq 1.77 \pm 0.03$ GeV, $\Gamma \simeq 0.31 \pm 0.05$ GeV.

The possible dependence of the 0^-S phase motion on the target atomic weight cannot be investigated in our data, owing to statistical reasons. Nevertheless, the effects of the nuclear targets can be partially understood by the comparison of the data on hydrogen with the compilation of events on different nuclei as in fig. 5b.

5. DISCUSSION AND CONCLUSIONS

The results of the present analysis suggest that the nuclear targets give a good help in disentangling resonant states from non-resonant background. The nuclear matter selects the particle systems produced within it, enhancing the resonant-state contributions in respect of the background.

This effect is pointed out by comparing the phase motion of the 0^-S and 1^+S waves obtained using nuclear targets with the results of the experiments on hydrogen and by studying the dependence of the phase motion on the target atomic weight (the analysis is available for the 1^+S wave only). A possible explanation of this phenomenon is that the nuclear matter absorbs the resonant states more than the non-resonant background.

In a previous analysis$^{1)}$ we have also studied the dependence of the wave amplitudes on the target atomic weight. The results for the 0^-S and 1^+S contributions are summarized in table 1. The 0^-S amplitude tends to decrease with increasing atomic weight in the 0.9-1.2 and 1.2-1.5 GeV $M_{3\pi}$ intervals, while it seems to increase or to be constant, at least, in the highest $M_{3\pi}$ interval. 1^+S is more or less constant in the 0.9-1.2 and 1.5-1.8 GeV regions and tends to grow in the 1.2-1.5 GeV range. The general trend of these data agrees with the conclusion that 0^-S is more absorbed than 1^+S, but no clear conclusion can be reached here for the absorption of the resonant and the non-resonant systems. The only weak indications come from the 1.5-1.8 GeV $M_{3\pi}$ interval, where for both the waves (0^-S and 1^+S) the resonant contribution is weaker and the absorption seems to be decreased.

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Table 1

Partial wave contributions in per cent [0.0 < t' < 0.01 $(\mathrm{GeV}/c)^2$]

$M_{3\pi}$ (GeV)	Be + C	Al + Si	Ti + Cu	Ag + Ta + Pb
0^-S				
0.9-1.2	12.5 ± 1.2	12.5 ± 0.7	11.2 ± 1.6	9.6 ± 1.0
1.2-1.5	17.3 ± 2.2	14.4 ± 1.0	13.5 ± 2.2	9.4 ± 1.3
1.5-1.8	8.0 ± 3.1	10.5 ± 1.6	13.8 ± 4.5	13.3 ± 2.8
1^+S				
0.9-1.2	64.4 ± 3.4	64.8 ± 1.5	68.8 ± 3.6	66.9 ± 2.3
1.2-1.5	38.3 ± 3.1	37.5 ± 1.3	43.7 ± 3.1	50.9 ± 2.0
1.5-1.8	13.5 ± 2.8	15.0 ± 1.4	12.1 ± 3.2	14.9 ± 2.3

Figure captions

Fig. 1 : Relative phase between 1^+S and 0^-P for the $M_{3\pi}$ interval, 0.9-1.4 GeV, and four groups of targets. The data concern the 40 GeV samples and in the fits the "ε" parametrization is used.

Fig. 2 : Relative phase between 1^+S and 0^-P for two $M_{3\pi}$ intervals (1.0-1.2 and 1.2-1.4 GeV) and two groups of targets (light and heavy nuclei). 40 GeV data. "ε" parametrization.

Fig. 3 : Mechanisms which make a contribution to the amplitude in the two-component model: a) pure Deck mechanism; b) Deck mechanism with rescattering through $\rho\pi$ final-state interactions; c) direct A_1 resonance production.

Fig. 4 : 1^+S contribution and 1^+S - 0^-P relative phase for the events collected on the silicon target (filled circles) at 40 GeV "ε" parametrization. The small squares represent the fit obtained with the two-component model.

Fig. 5a : Mass dependence of the 0^-S. Filled circles correspond to the 40 GeV data obtained with the elastic $\pi^+\pi^-$ phase shifts: this plot refers to the left scale on the y axis and includes a compilation. The small triangles represent the data of the ACCMOR Collaboration[9]) with the $\pi^+\pi^-$ phase shifts (scale on the right y axis).

Fig. 5b : 0^-S - 0^-P relative phase: The 40 GeV data (filled squares) are compared with the ACCMOR results on hydrogen[9]) (small triangles); both refer to the $\pi^+\pi^-$ phase shift parametrization. The 40 GeV plot is a compilation of all the data collected with the different nuclear targets.

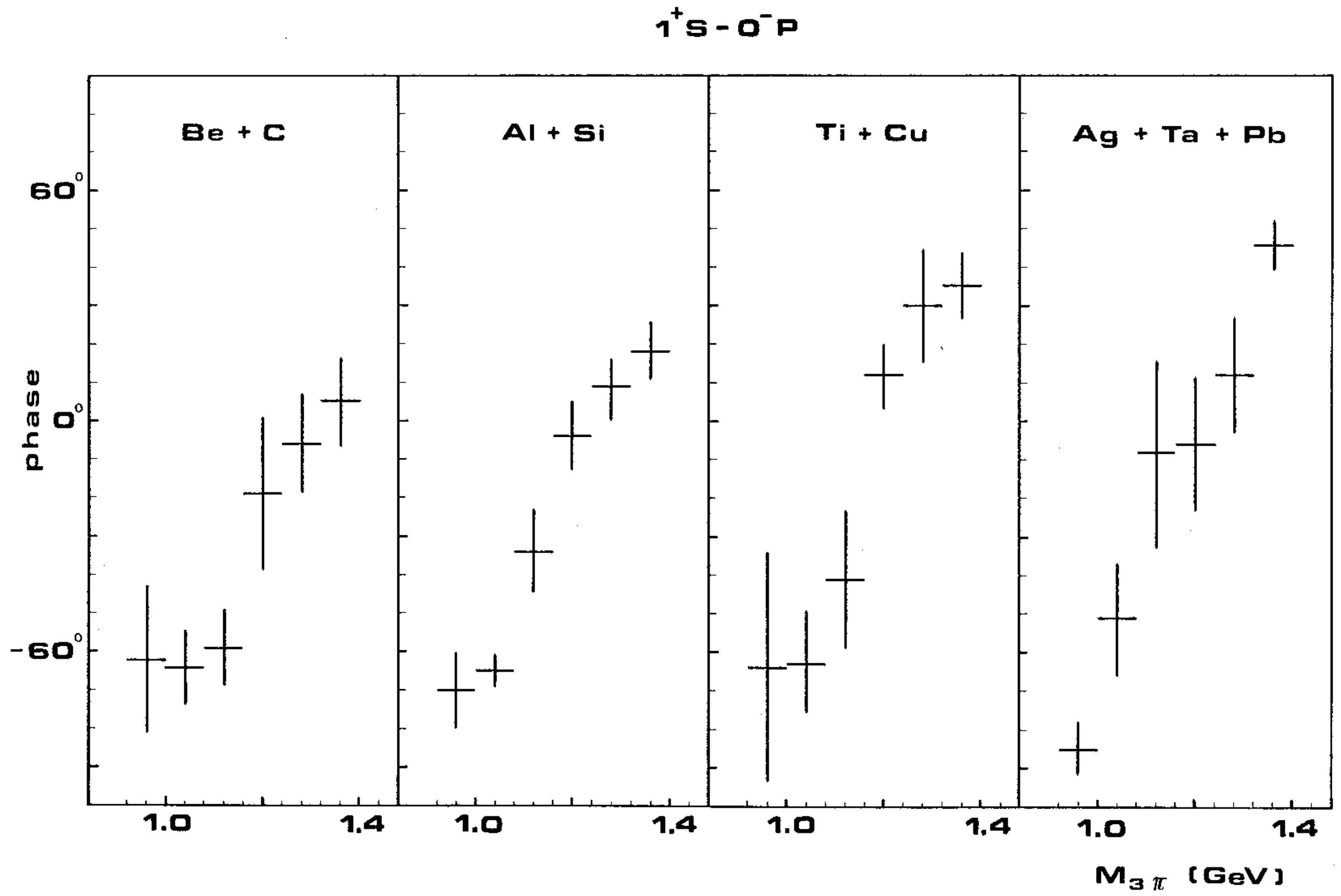

1⁺S - 0⁻P
Be + C
Al + Si
Ti + Cu
Ag + Ta + Pb
60°
0°
-60°
phase
1.0
1.4
1.0
1.4
1.0
1.4
1.0
1.4
M3π (GeV)

Fig. 1

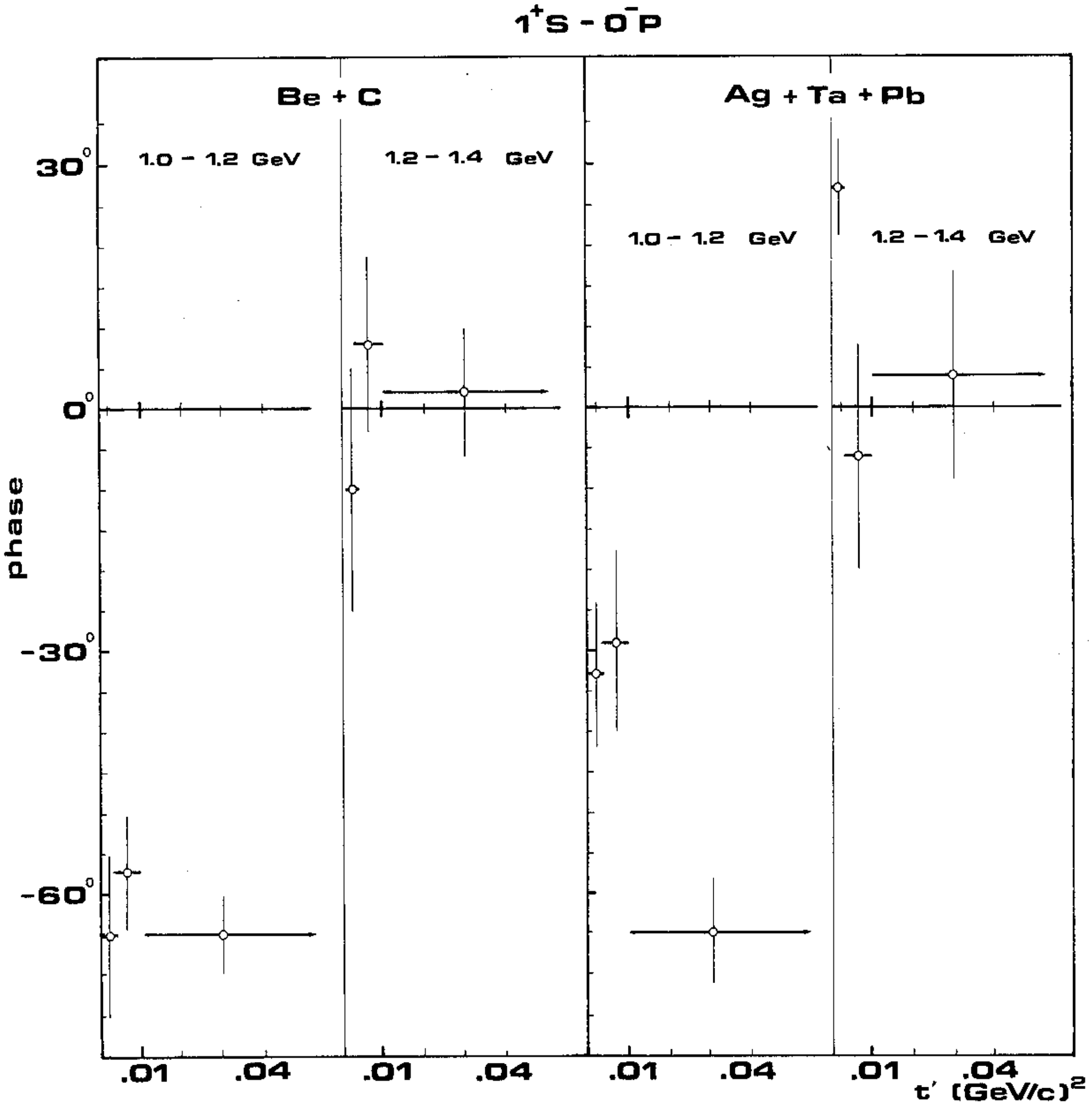
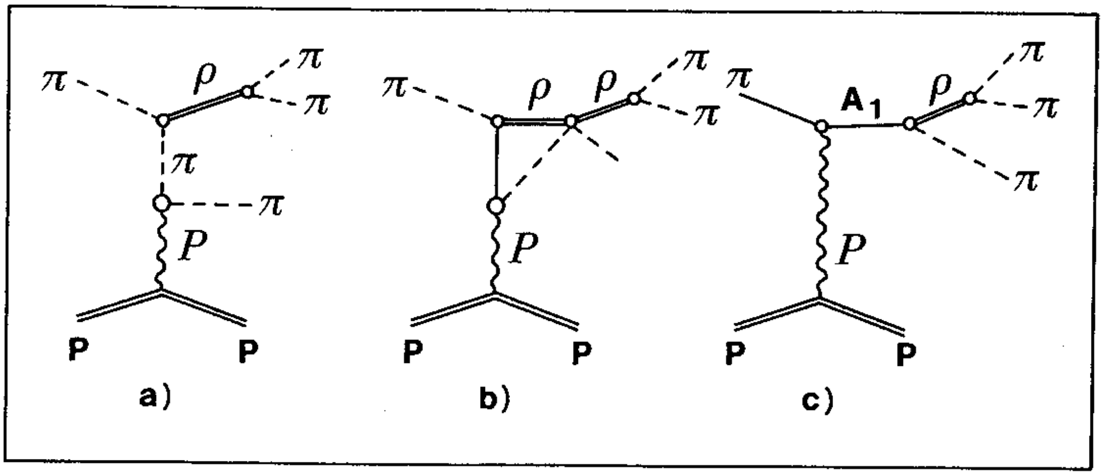

1⁺S - 0⁻P
Be + C
Ag + Ta + Pb
1.0 - 1.2 GeV
1.2 - 1.4 GeV
1.0 - 1.2 GeV
1.2 - 1.4 GeV
30°
0°
-30°
-60°
phase
.01
.04
.01
.04
.01
.04
.01
.04
t' (GeV/c)²

Fig. 2



π
ρ
π
π
π
π
P
P
P
a)
π
ρ
ρ
π
π
P
P
P
b)
π
A₁
ρ
π
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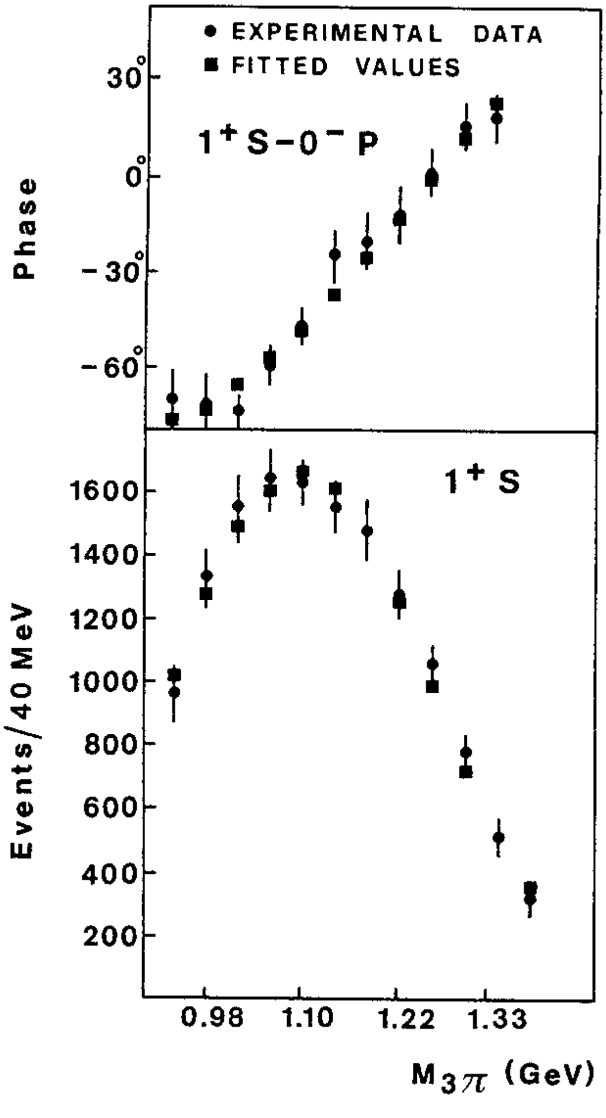
π
P
P
P
c)

Fig. 3



● EXPERIMENTAL DATA
■ FITTED VALUES
30°
0°
-30°
-60°
Phase
1⁺S-0⁻P
1⁺S
1600
1400
1200
1000
800
600
400
200
Events/40 MeV
0.98
1.10
1.22
1.33
M₃π (GeV)

Fig. 4

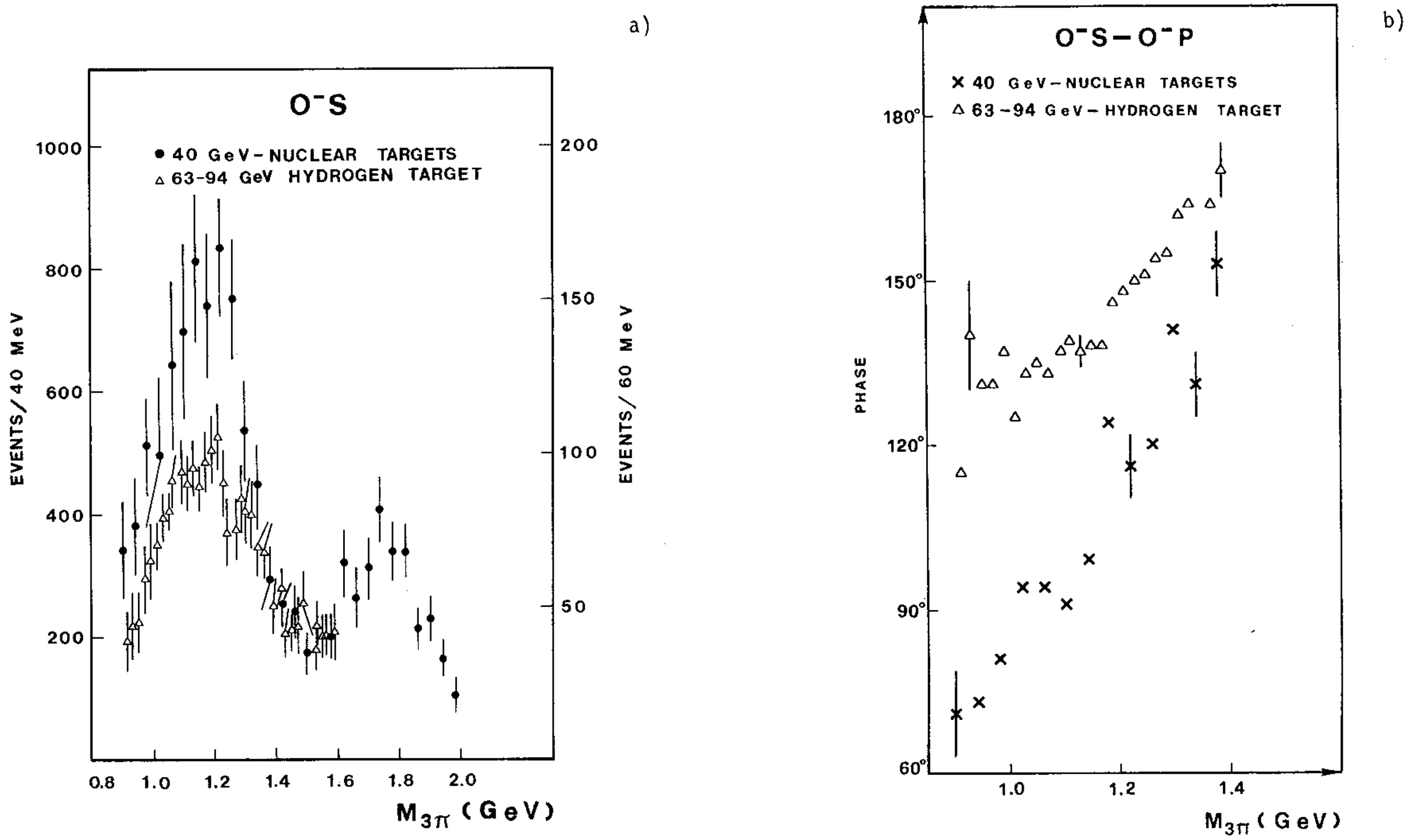

a)
O⁻S
● 40 GeV-NUCLEAR TARGETS
△ 63-94 GeV HYDROGEN TARGET
EVENTS/40 MeV
1000
800
600
400
200
EVENTS/60 MeV
200
150
100
50
0.8
1.0
1.2
1.4
1.6
1.8
2.0
M3π (GeV)
b)
O⁻S–O⁻P
× 40 GeV-NUCLEAR TARGETS
△ 63-94 GeV-HYDROGEN TARGET
PHASE
180°
150°
120°
90°
60°
1.0
1.2
1.4
M3π (GeV)

Fig. 5