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Coherent Production and Decay Modes of a Pseudoscalar Partner of the ψ(3105) Boson

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ABSTRACT

Various decay modes and the photoproduction of the pseudoscalar partner of the recently discovered narrow resonances are discussed within the context of a model based upon charm.

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I. INTRODUCTION

If we accept the view that the recently discovered resonance[1] $\psi(3105)$ is a $c\bar{c}$ bound state of $J^{PC} = 1^{--}$, ϕ_c, in the charm scheme[2,3,4] then it is imperative that there exists a $c\bar{c}$ bound state of $J^{PC} = 0^{-+}(\eta_c)$. The following is a brief discussion of its mass, decay modes and widths, and production. In particular we point out that the photoproduction in a Coulomb field (Primakoff effect) and decay into $p\bar{p}$ has some promise for detection of the η_c.

II. MASS

In Gaillard, Lee and Rosner (G. L. R.)[5], a mixing scheme was proposed for neutral pseudoscalar mesons on the basis of a Gell-Mann, Okubo-type mass formula, according to which η, X^0 and η_c were predicted to have the following compositions:

$$\begin{aligned} \eta &= \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}, \\ X^0 &= \frac{u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c}}{2}, \\ \eta_c &= \frac{u\bar{u} + d\bar{d} + s\bar{s} - 3c\bar{c}}{\sqrt{12}} \end{aligned} \tag{1}$$

However, this scheme now appears very unlikely, in view of the recent developments. For, if it were true, the decay $\psi \to X^0\gamma$ would proceed analogously to $\phi \to \eta\gamma$, and its rate would be

$$\Gamma(\psi \rightarrow X^0\gamma) \simeq \frac{3}{8}\left(\frac{M_\psi}{M_\phi}\right)^3 \Gamma(\phi \rightarrow \eta\gamma)$$
$$\simeq 1.3 \text{ MeV} . \tag{2}$$

Another mixing scheme which emerges from the same mass formula is

$$\begin{aligned} \eta &\simeq 0.80\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right) - 0.60 s\bar{s}, & M_\eta &= 508 \text{ MeV} \\ X^0 &\simeq 0.60\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right) + 0.80 s\bar{s}, & M_{X^0} &= 969 \text{ MeV} \\ \eta_c &\simeq 1.00 c\bar{c}, & M_{\eta_c} &= 3122 \text{ MeV} \end{aligned} \tag{3}$$

to within a few tenth of a percent. In G. L. R., this solution was rejected on the grounds that the postdicted η mass deviated somewhat more than one should allow. In retrospect, we feel that this judgment was a little too hasty, and given the questionable treatment of SU(4) breaking in lowest order, M_η = 508 MeV is not a bad fit to the actual mass 548.8 MeV.

We find that another curious solution is obtained if we identify (η, E(1416), η_c) as neutral members of a pseudoscalar 16-plet:

$$\begin{aligned} \eta &\cong 0.662\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right) - 0.747\, s\bar{s}; & M_\eta &= 551 \text{ MeV} \\ E &\cong 0.747\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right) + 0.662\, s\bar{s}; & M_E &= 1398 \text{ MeV} \\ \eta_c &= 1.000\, c\bar{c}; & M_{\eta_c} &= 3.066 \text{ MeV} \end{aligned} \tag{4}$$

We shall not offer any explanation as to where X^0 belongs in such a scheme as this; the idea that E(1416) belongs to the pseudoscalar 16-plet may deserve further attention, nevertheless.

In any case, the mass formula of G. L. R. suggest that if η_c is almost pure $c\bar{c}$, then η_c must be almost degenerate with ψ in mass. Appelquist and Politzer[3] predict that the mass difference of the ortho- and para-"charmonium" to be about 30 MeV. In any case, the $\phi_c - \eta_c$ mass difference is predicted to be very small, perhaps less than 100 MeV, and perhaps ϕ_c is heavier.

III. DECAY MODES

The decay rate $\Gamma(\psi \to \eta_c\gamma)$ is very small, because the magnetic moment of the charmed quark is very small, being inversely proportional to the charmed quark mass, and there isn't much phase space. However, $\Gamma(\psi'(3.695) \to \eta_c\gamma)$ may offer some possibility of detection eventually.

The decay of η_c into hadrons is likely inhibited just as the decay of ψ is. According to Appelquist and Politzer,[3]

$$\frac{\Gamma(\eta_c \to \text{hadrons})}{\Gamma(\psi \to \text{hadrons})} = \left(\frac{10}{54}\,\alpha\,\frac{\pi^2-9}{\pi}\right)^{-1} \tag{5}$$

[In this estimate, the Coulombic nature of the $c\bar{c}$ system need not be assumed.] This gives, with $\alpha \simeq 0.3$,

$$\Gamma(\eta_c \to \text{hadrons}) \simeq \text{a few MeV}. \tag{6}$$

The hadronic final states must have the quantum numbers $J^{PC} = 0^{-+}$,

$G = +1$, $I = 0$. Some of the final channels that are relatively easy to detect are $K^+K_s\pi^-$, $K^-K_s\pi^+$, $\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$ and baryon-antibaryon.

The rate for $\eta_c \to \gamma\gamma$ may be estimated in a number of ways; scaling up the $\pi \to \gamma\gamma$ rate we have

$$\Gamma(\eta_c \to \gamma\gamma) \cong \frac{32}{9}\left(\frac{M_{\eta_c}}{M_\pi}\right)^3 \Gamma(\pi^0 \to \gamma\gamma) = 260\ \mathrm{keV}. \qquad (7)$$

C. G. Callan, et al.,[4] give various estimates based on the known $\eta_c \to \gamma\gamma$ rate. In all $\Gamma(\eta_c \to \gamma\gamma) \simeq 10^2$ keV appears likely. That is, the branching ratio for $\gamma\gamma$ may amount to as much as 10%. In the particular charmonium scheme of Appelquist and Politzer, the rate for $\eta_c \to \gamma\gamma$ is lower and of the order of 10 keV.

IV. PRODUCTION

As alluded to earlier, η_c may be an important product of the ψ' disintegration:

$$\begin{array}{l} \psi' \to \gamma + \eta_c \\ \qquad\qquad\quad \hookrightarrow \gamma + \gamma \\ \qquad\qquad\quad \hookrightarrow \text{hadrons} \end{array} \qquad (8)$$

As pointed out many times, one γ must be monochromatic.

In hadronic reactions, η_c production cross section is presumably not too different from that of ψ.

An intriguing possibility is the Primakoff production of η_c.

Unlike the π^0 and η^0 production by the same process, it is expected that there is very little nuclear interference in this case; it would arise mainly from the exchange of heavy objects like the ψ or ψ', which have low Regge intercepts.

The general formula for the coherent production in a nuclear Coulomb field (Ze/r) of states with the quantum numbers of two photons is given by:[6]

$$\frac{d\sigma}{dt\,ds} = \frac{\alpha Z^2}{\pi} \frac{\sigma^{\gamma\gamma}(s)}{s} \left(\frac{t_{min} - t}{t^2}\right) (F(t))^2 , \tag{9}$$

where t is the momentum transfer to the target with form factor $F(t)$ and s is the square of the total c. m. energy of the photon-photon channel with cross-section $\sigma_{\gamma\gamma}(s)$, and t_{min} is the minimum momentum transfer given to a very good accuracy by

$$t_{min} \approx -\left(\frac{s}{2E_\gamma}\right)^2 , \; (E_\gamma = \text{lab momentum of photon}) \tag{10}$$

The integral over the resonant $\gamma\gamma$ cross section due to the η_c is given by

$$\int \frac{ds}{s} \sigma_{\gamma\gamma}(s) = \frac{8\pi^2}{M^2} \frac{\Gamma(\eta_c \to \gamma\gamma)}{M} \frac{\Gamma_i}{\Gamma} , \tag{11}$$

where $M = M_{\eta_c}$ and $\frac{\Gamma_i}{\Gamma}$ is the branching ratio into a decay mode of good experimental signature (more on this later). We then obtain from Eqs. 10 and 11 the differential cross section with the familiar Primakoff peak:

$$\frac{d\sigma}{dt} = \frac{8\pi Z^2\alpha}{M^2}\,\frac{\Gamma(\eta_c \to \gamma\gamma)\Gamma_i}{M\Gamma}\,\frac{t_{min} - t}{t^2}\,(F(t))^2 \tag{12}$$

The cross-section for a heavy nucleus like lead with $Z = 82$ and a form factor $F(t) = \exp t \frac{\langle r^2\rangle}{6}$, where $\frac{\langle r^2\rangle}{6}$ is approximately 130 GeV^{-2}, is plotted in Fig. 1 for $E_\gamma = 100$ GeV. At $E_\gamma = 100$ GeV and 200 GeV typical energies accessible at Fermilab, $t_{min} = -0.002\,GeV^2$ and $-0.005\,GeV^2$ for $M = 3$ GeV, well within the coherence requirements for lead. From Eq. (12) the total integrated production cross-sections are for $\Gamma(\eta_c \to \gamma\gamma) = 100$ keV:

$$\begin{aligned} \sigma(\gamma \to \eta_c) &\approx 380 \text{ nb at } 100 \text{ GeV.} \\ \sigma(\gamma \to \eta_c) &\approx 1.6\ \mu\text{b at } 200 \text{ GeV.} \end{aligned} \tag{13}$$

The total cross section as a function of Lab energy for various nuclei is plotted in Fig. 2. Of course if the radiative decay width of $\eta_c \to \gamma\gamma$ is much smaller than 100 keV these cross-sections have to be scaled down accordingly. Also the observed cross-section into some decay channel i of good signature has to be corrected by the branching ratio for this mode, Eq. (12), this may decrease the rates also. One particular favorable mode might be the two body mode $p\bar{p}$. The signature for the reaction

$$\gamma + Z \to Z + \eta_c \quad \eta_c \to p\bar{p}$$

would be a $p\bar{p}$ pair with longitudinal momentum of the order of 50 Gev and transverse energy $(p_\perp^2 + m^2)^{\frac{1}{2}}$ of the order of $\frac{M}{2} \approx 1.5$ Gev which come out peaked around the beam direction and isotropic in the rest system of the η_c. Such energetic antiprotons should be a striking effect and the cross-section should be reasonable if the branching ratio $\Gamma_{p\bar{p}}/\Gamma$ is not too small. By examining cross-sections on different nuclei, one can distinguish the coherent Primakoff production from other processes such as $\gamma + Z \to \psi + Z$, $\psi \to p + \bar{p}$.

Another possible production mechanism for η_c is the two photon process in

$$e^- e^+ \to e^- e^+ + \eta_c \ .$$

From the standard formulas[7] for this process, these cross-sections are of the order $10^{-35}\ \mathrm{cm}^2$ and $5 \times 10^{-33}\ \mathrm{cm}^2$ for SPEAR II and PEP.

In conclusion we hope that these remarks are useful for experimentalist planning future endeavors in this field. We would also like to stress the utility of the Primakoff process in general even for hadron beams in scanning for states that might have dominant radiative decay modes.

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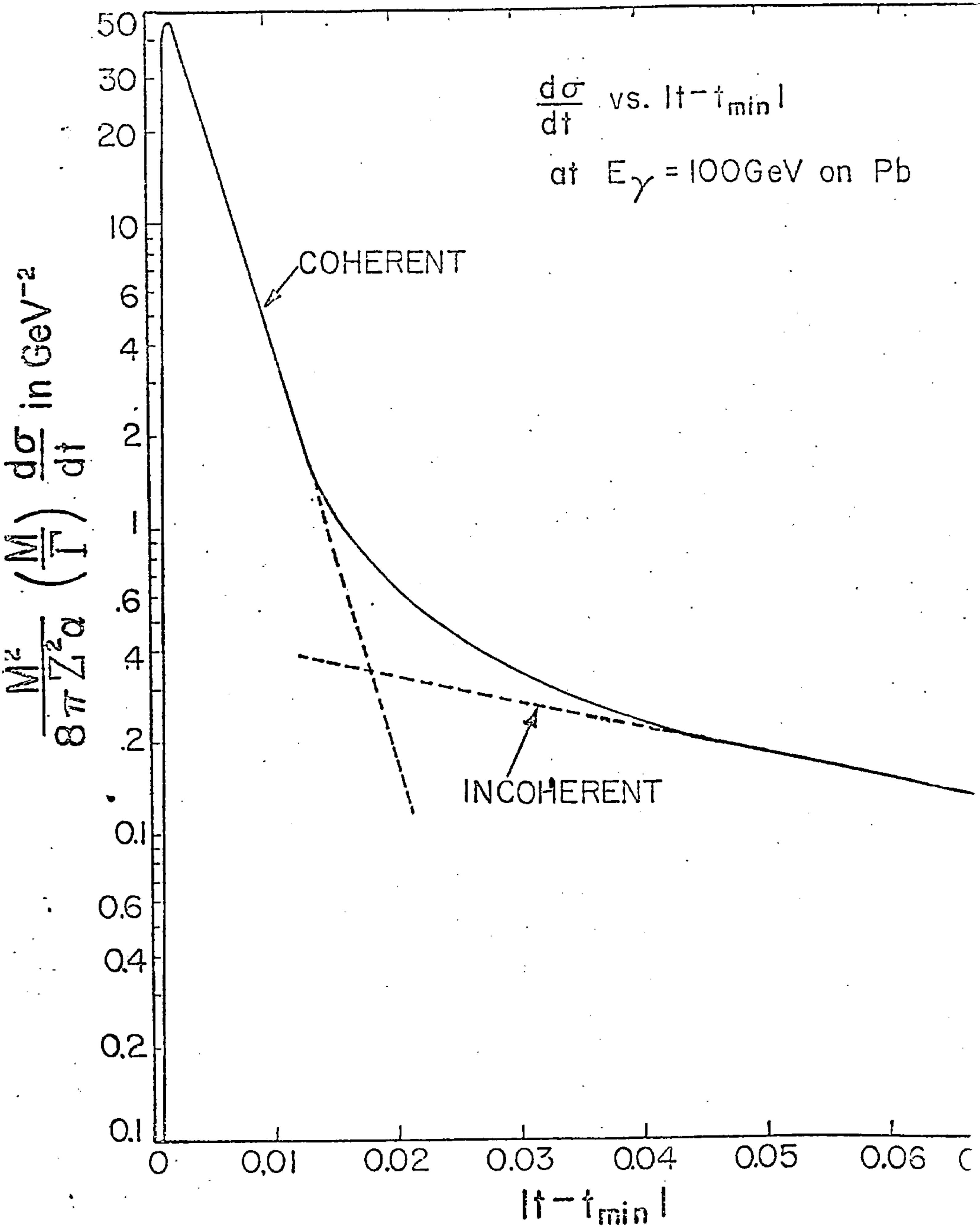
FIGURE CAPTIONS

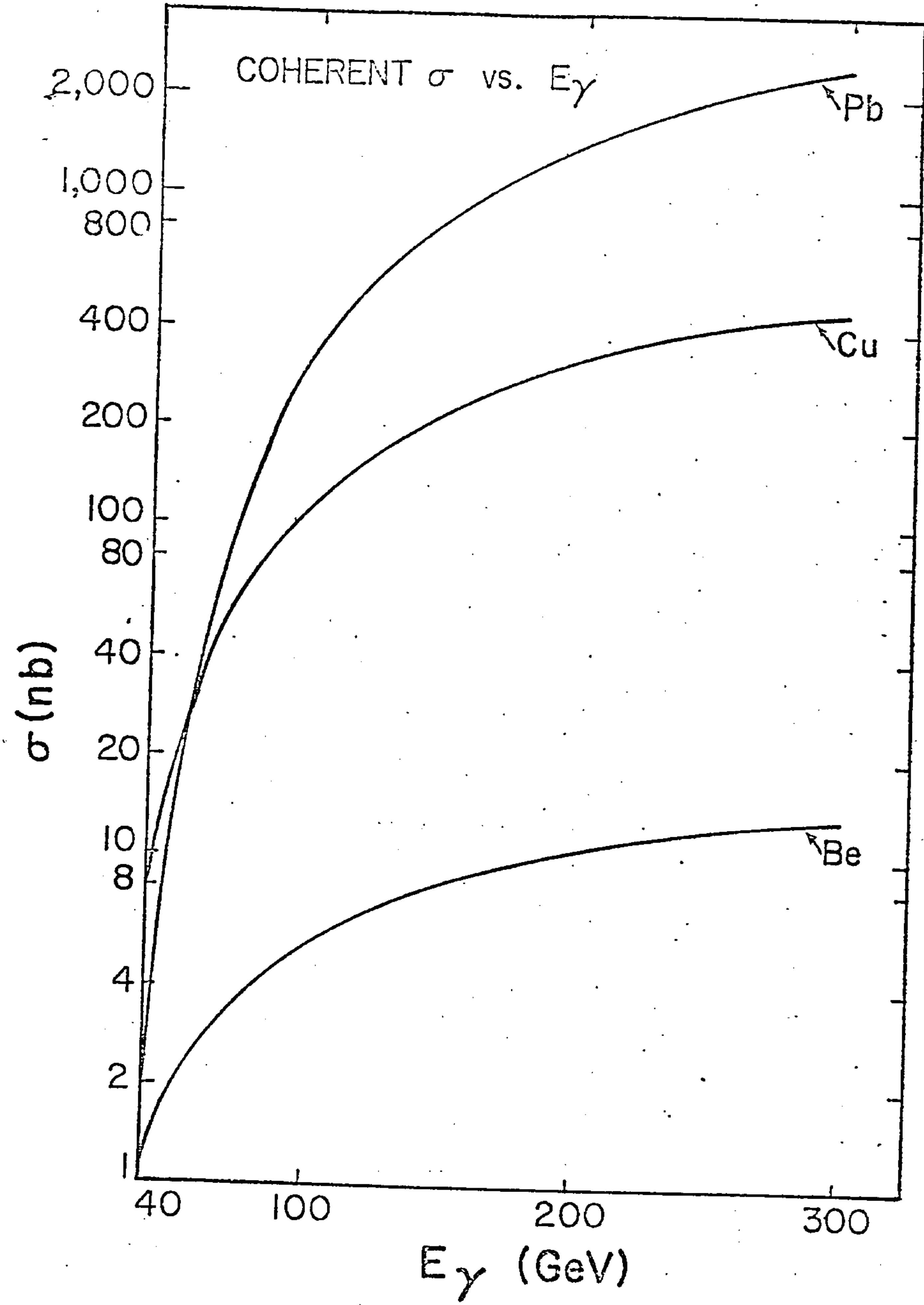
Fig. 1 - $\frac{d\sigma}{dt}$ plotted against $(t - t_{min})$ at E_γ = 100 GeV on Pb .

Fig. 2 - Energy dependence of the total integrated cross-section for various nuclei.



$\frac{d\sigma}{dt}$ vs. $|t-t_{min}|$
at $E_\gamma = 100$ GeV on Pb
COHERENT
INCOHERENT
$\frac{M^2}{8\pi Z^2 \alpha}\left(\frac{M}{\Gamma}\right)\frac{d\sigma}{dt}$ in GeV^{-2}
$|t-t_{min}|$
50
30
20
10
6
4
2
1
.6
.4
.2
0.1
0.6
0.4
0.2
0.1
0
0.01
0.02
0.03
0.04
0.05
0.06

FIG. 2


COHERENT σ vs. Eγ
2,000
1,000
800
400
200
100
80
40
20
10
8
4
2
1
Pb
Cu
Be
σ (nb)
40
100
200
300
Eγ (GeV)