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EXPERIMENTS WITH MONOCHROMATIC AND POLARIZED PHOTON BEAMS

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Introduction.

A great deal of interest has born during the last few years about the use of monochromatic photon beams with high degree of polarization and low background.

One of the main motivations for this interest was undoubtedly the successful results the Frascati /1/ and SLAC /2/ laboratories obtained by making laser photons to collide with high energy electrons. The photon beam at SLAC was obtained with a ruby laser (1.78 eV) and the 20 GeV electron linear accelerator providing photons up to several GeV, whereas the Ladon beam at Frascati operates with an Argon Ion Laser (2.41 eV) and the Adone storage ring in the energy region between 5 MeV and 80 MeV /1/.

By limiting myself to consider this second case, I can summarize here the results obtained so far in the following table

Energy (MeV)	Intensity γ / s	Resolution %	Polarization
5	2×10^4	~ 1	~ 1
80	2×10^5	~ 8	~ 1

letting the reader refer to the published papers of the LADON group for any complementary details on this subject (see refs. quoted in ref. /1/). These numbers are now planned to be improved both in intensity and monochromaticity by modifying the laser arrangement on the machine /3/. In any case they appear extremely encouraging to initiate good experimental research in the photonuclear reactions studies. This beam came into operation in 1979 and the first experimental results on deuterium photodisintegration by polarized photons are now available /4/.

The use of storage rings is clearly favourite with respect to Linacs where the duty-cycle is in general very poor. Moreover the new generation of storage rings, completely dedicated to synchrotron radiation studies, are now planned to be built both in Europe and in USA and the general technical requirement advanced for them is to have very good emittance together with a very high stored current /5/. In order to extend the wavelength region available from a synchrotron radiation source, special components will be foreseen such as superconducting "wigglers" and "undulators". In this second case, the objective of optimum source brightness leads to the criterium to keep the horizontal and vertical angular divergency down to $\sim 10^{-5}$ rad /5/. This fulfils the needs for a good synchrotron radiation beam but at the same time optimizes the conditions for having also a good backscattered photon beam. These two merging interests lead to the consideration of having a nuclear facility like that installed on different machines /6/. Quantitative predictions have been treated with some details by the LADON group. Here different lasers and different methods have been discussed and the results can be summarized as follows :

Machine	E_e (GeV)	Laser (Power)	Beam spot sizes and divergencies horizontal		vertical		I_e (mA)	Photon energy (MeV)	I_γ (γ/sec)	$\Delta E/E$ (%)
			(mm)	(mrad)	(mm)	(mrad)				
NSLS	2.5	Ar (100 W)	0.29	1×10^{-2}	0.045	6×10^{-3}	500	~ 210	10^7	1
ALFA 3	3.5	Ar (100 W)	0.28	2.5×10^{-2}	0.04	1.5×10^{-2}	280	~ 400	$\sim 2 \times 10^6$	1
ESRF	5.0	Ar (100 W)	0.58	2×10^{-2}	0.09	1.2×10^{-2}	500	~ 780	$\sim 4 \times 10^6$	1.5
LEP	50	CO_2 (1 KW)	2.5	5×10^{-3} (?)	0.25	2.5×10^{-3} (?)	10	~ 100 (16°) ~ 4.000 (160°)	2×10^5	22
LEP	50	YAGx4 (3MW)	2.5	5×10^{-3} (?)	0.25	2.5×10^{-3} (?)	10	~ 10.000 (32°) ~ 40.000 (160°)	100/burst at 20 b/sec	12

The case of LEP must be considered separately. The beam emittance in the case of LEP is not as good as one would have. Nevertheless, as a pure exercise, it has been included in the list with an hypothetical angular divergency 4-times better than what is the designed number /7/. Should this be considered feasible, the LEP case would become one of the most exciting facilities since it could provide photon beams tunable from ~ 100 MeV up to ~ 40 GeV, with reasonable monochromaticity and good polarization.

Over the landscape of these different possibilities other considerations must be done. The expenses for a Laser installation on a storage ring are modest with respect to the total investement for the machine itself, and moreover this activity can be conceived to run in parasitic mode without affecting the life of the synchrotron radiation community. Thus there are serious reasons to think that several of these possibilities will become really available in the years to come. If we include LEP in this list, we could imagine a situation for the next decade, where polarized photon beams from few MeV up to several GeV will be operating at the same time. This means that the scientific problems we could investigate will range from the low up to the very high energy region where the typical problematic of the high energy physics will be heavily involved.

A common feature of all these possibilities will be that the intensity will never be greater than $(10^7 - 10^8)$ γ/s at best. This necessarily will require apparatus with very big solid angle, that mainly means (4π) detectors.

At this point the correct way to proceed this discussion would be to display the main topics where the polarization is very useful in the understanding of the physics implied. For obvious reasons, this attempt can not be systematic and thus I will limit myself to the proposition of few significative examples where the importance of the problems and the role of the polarization can easily be appreciated. The exposition will scan the entire energy interval and is very far from being exhaustive. The topics discussed are a selection among others and the choice that has been made is only fruit of my personal feeling on what is going to be an exciting future development in intermediate and high energy nuclear physics.

1. - The low energy region ($E\gamma \leq 100$ MeV)

1. 1. - The dynamic collective model

The first flash I would like to give is on the old problem of the validity of the Dynamic collective model in the description of the nuclear giant resonances /8/. Undoubtedly this is one of the most interesting topic where with a monochromatic and polarized photon beam one can really settle the problem of the coupling between the giant dipole resonance and the surface degrees of freedom. This coupling is the direct signature for the DCM whose qualitative success spread quite far and wide since the pioneer work of Fuller and Hayward /9/ on deformed nuclei.

The underlying idea of the model is to describe the photon scattering on nuclei as given by the sum of the contributions coming from the expansion of the electromagnetic field according to the total angular momentum transfer j and the angular momentum transfers L and L' at the two vertices of the Fig. 1 /10/, where

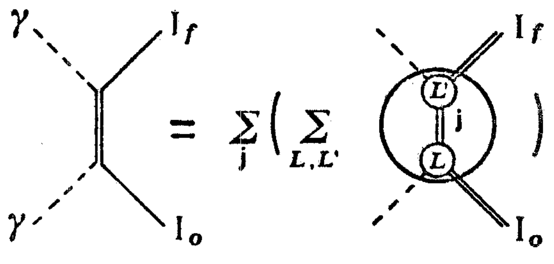


FIG. 1 - Decomposition of the scattering amplitude according to angular momentum transfer.

$$\left| I_f - I_o \right| \leq j \leq I_f + I_o , \qquad \left| L - L' \right| \leq j \leq L + L' .$$

In the region of the GDR where pure dipole radiation contributes, $L = L' = 1$ and $j = 0, 1, 2$. Consequently, the differential cross section for an unoriented scattering target, can be written as

$$\frac{d\sigma}{d\Omega} = \sum_{0}^{2}{}_{j} \frac{|A_j|^2}{2j+1} g_j(\theta) , \qquad (1)$$

where $g_j(\theta)$ are known angular distribution functions depending only upon the relative orientation of the polarization vectors of the incident and scattered photons. The scattering amplitude A_j are directly related to the nuclear polarizabilities (0-scalar, 1-vector, 2-tensor) and are the quantities which contain the information about the nuclear structure /10/. The scalar polarizability describes the isotropic part of the scattering amplitude, the vector polarizability measures the "optical activity" of the nucleus while the tensor polarizability measures the optical anisotropy of the nucleus /10/. These are quantities accessible to photon scattering experiments and thus serve as a common meeting ground with theory. For example, in the framework of the usual hydrodynamic model a spherical nucleus has three degenerate GDR-states. Therefore, vector and tensor polarizabilities vanish since the nucleus is optically isotropic. No inelastic scattering will occur. But if a coupling is conceived between the volume GDR-oscillations and the quadrupole surface vibrations, as suggested in the DCM, the nucleus, due to the instantaneous deformation, becomes optically anisotropic and inelastic scattering into the 2^+-vibrational states will happen.

This inelastic tensor component of the scattering amplitude has been calculated in detail and, for a spherical vibrational nucleus typically as much as 30% of scattering at backward angles is predicted to the first excited 2^+ state /11/. But recent experiments performed with the bremsstrahlung beam obtained with MUSL-2 at the Illinois University seem to contradict quite remarkably this prediction /12/. No more than 15% of the elastic scattering has been found to go to the first excited state in ^{60}Ni, as shown in Fig. 2. And even worse is the case of the heavy deformed ^{166}Er where the inelastic transitions have been found drastically smaller (by a factor $\simeq$ 3-5) than the prediction of the DCM /13/ (see Fig. 3).

In conclusion something seems to be wrong either in the experiments or in theory. A definite way out could be the knowledge of the polarization of the incoming photon beam. In fact, in that case, expression (1) specializes in the two following /14/:

$$\frac{d\sigma^{\perp}}{\ } = \frac{1}{\ } |A\ |^2 + \frac{7}{\ } |A\ |^2 \qquad \frac{d\sigma^{\parallel}}{\ } = \frac{1}{\ } |A\ |^2 \cos^2\theta + \frac{1}{\ } |A\ |^2 (1 + \frac{1}{\ } \cos^2\theta) . \qquad (2)$$

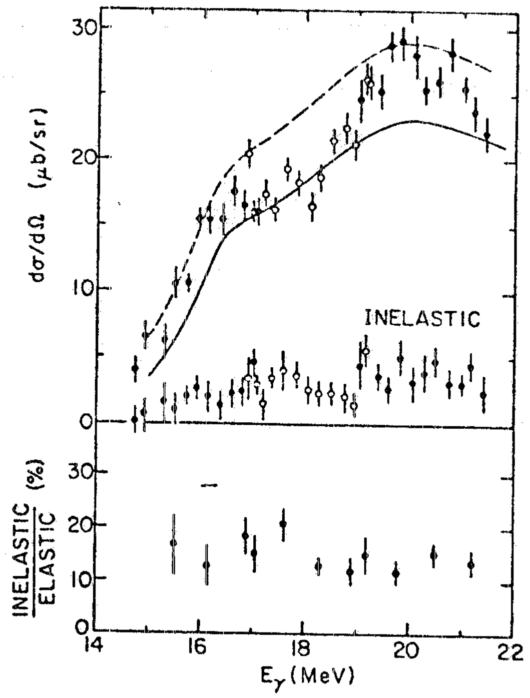


FIG. 2 - The ratio of inelastic to elastic scattering in ^{60}Ni as given in ref. /12/.

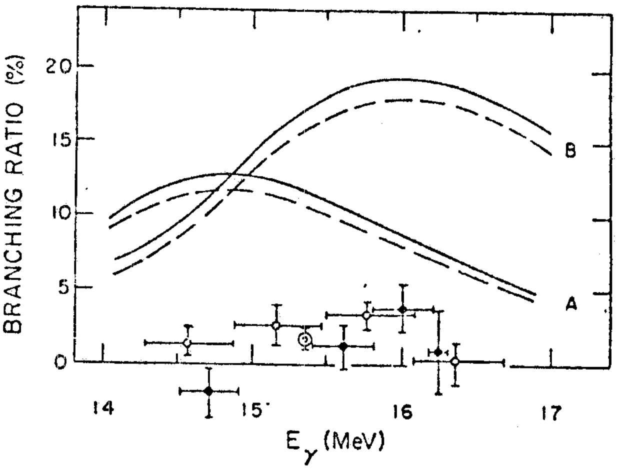


FIG. 3 - The ratio of inelastic to elastic scattering in ^{166}Er as given in ref. /13/.

These say, that the nucleus has no coherent (j = 0) scattering along the polarization vector at $\theta = \pi/2$, so that a measurement of photon scattering in this direction is a direct measure of the incoherent (j = 2) scattering. And this measurement does not depend on the energy resolution of the detectors which could be a serious difficulty when the vibrational levels are so close to the ground state that is not easy to separate the two contributions in the scattering, by γ-ray spectrometry /14/.

1.2. - Proton polarizabilities

Another point where the knowledge of the photon polarization is determinant, is the old question of the measurement of the proton electric and magnetic polarizabilities α and β. These two quantities are fundamental structure parameters which, together with charge and magnetic moment, fully control the behaviour of the proton system in a static or slowly varying electromagnetic field. Therefore they can be obtained by Compton scattering experiments at low energy, where the differential cross section can be expressed in terms of the expansion /15/

$$\left(\frac{d\sigma}{d\Omega}\right)_p = \left(\frac{d\sigma}{d\Omega}\right)_0 - \frac{e^2}{4\pi M_p}\,\omega^2\left\{\alpha(1+\cos^2\theta)+2\beta\cos\theta\left[1-\frac{3\omega}{M_p}(1-\cos\theta)\right]\right\}+O(\omega^4) \qquad (3)$$

ω and M_p being the photon energy and the proton mass respectively. Moreover, $(d\sigma/d\Omega)_0$ is the cross section for the proton thought as structureless and the second term is a structure correction depending on the above mentioned polarizabilities.

The use of monochromatic and polarized photons represents a substantial improvement in the determination of these two quantities. First of all the monochromaticity removes all the usual difficulties one has with bremsstrahlung beams. Moreover, the polarization allows to make the linear combination of the parallel and perpendicular cross section /16/

$$f_1(\theta, \alpha) = \frac{1}{2}\left[\frac{d\sigma^{\perp}}{d\Omega} - \frac{d\sigma^{\parallel}}{d\Omega}\right], \qquad f_2(\theta, \beta) = \frac{1}{2}\left[\frac{d\sigma^{\perp}}{d\Omega}\cos^2\theta - \frac{d\sigma^{\parallel}}{d\Omega}\right],$$

which depend only upon α and β respectively. It is immediate to see how sensitive this method could be in the determination of α and β separately.

According to the present understanding, these two quantities can be related to the structure functions usually defined in the deep inelastic scattering and the following sum rules can be deduced /17/ :

$$\alpha + \beta = \lim_{q^2 \to 0} \frac{1}{2\pi^2} \int_{\nu_{th}}^{\infty} \frac{\sigma_T(q^2, \nu')}{\nu'^2} d\nu' , \tag{4}$$

$$\alpha = \frac{(\lambda e)^2}{16\pi M_p^3} + \lim_{q^2 \to 0} \frac{1}{2\pi^2} \int_{\nu_{th}}^{\infty} \sigma_T(q^2, \nu') \frac{R(q^2, \nu')}{q^2} d\nu' . \tag{5}$$

Besides the usual definitions, the other quantities are defined as follows :

$\sigma_T(q^2, \nu')$ = total photoabsorption cross section , $\quad R(q^2, \nu) = \dfrac{\sigma_L(q^2, \nu)}{\sigma_T(q^2, \nu)}$.

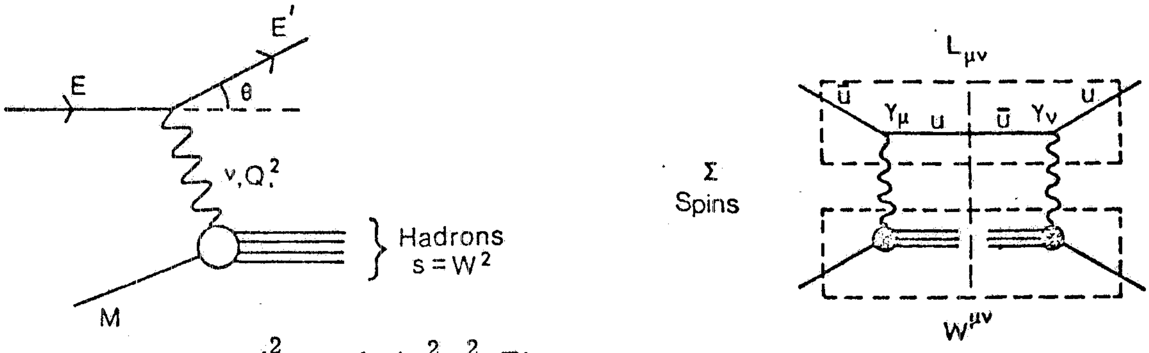
While the first is the very well known Damashek and Gilman sum rule yielding the result /18/

$$\alpha + \beta = (14.2 \pm 0.03) \times 10^{-4}\ \mathrm{fm}^3 , \tag{6}$$

the second one requires R to vanish asymptotically more rapidly than ν^{-1} and fournishes an independent evaluation of α expressed through the experimental determination of $R(q^2, \nu)$ /17/. The relationship between Compton amplitude and deep inelastic scattering can be understood just looking at the topological structure of the electron-proton inelastic cross section (see Fig. 4). The dashed bottom part of the figure ($W^{\mu\nu}$) in the limit of $q^2 \to 0$ describes the Compton scattering of real photons /19/.

According to the quark-parton model, in the scaling region the photon

q^2 (see Fig. 5). In particular if the quarks have spin 1/2, R = 0. Within QCD this picture is modified by the presence of gluons which lead to logarithmic q^2



$$\frac{d^2\sigma}{d\Omega\, dE'} = \frac{1}{2}\,\frac{4\alpha^2 m^2}{q^4}\,\frac{E'}{E}\,\delta(\Sigma E_f - \Sigma E_i) L_{\mu\nu} W^{\mu\nu}$$

FIG. 4 - Tensor structure of electron-proton inelastic cross section with obvious significance of the symbols.

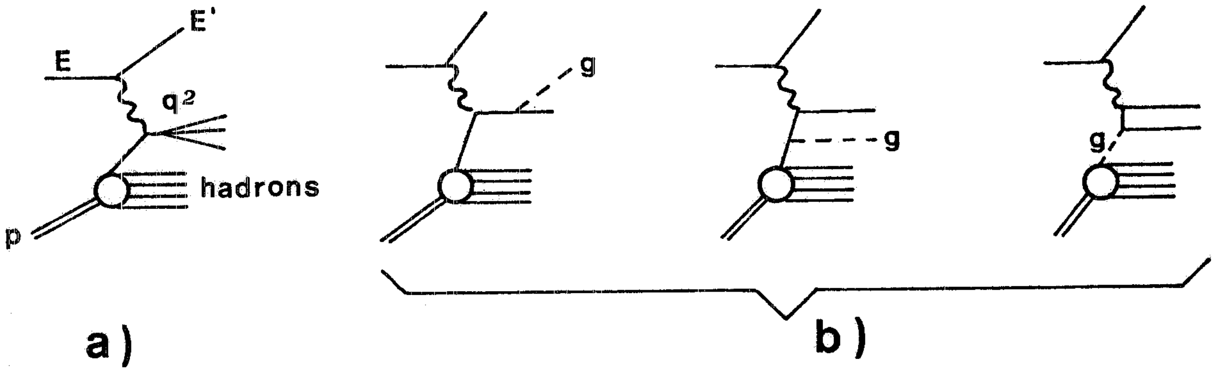


FIG. 5 - a) Parton model picture of deep inelastic scattering;
b) Leading order QCD diagrams involving gluons.

dependence of the structure functions and a well defined behaviour (non-zero) for R (see Fig. 5) /20/.

Thus an unconventional way to look at the second term in the right hand side of eq. (5) could possibly be related to the scaling violation in the deep inelastic scattering. Therefore numerical evaluations within QCD-theory would be highly desiderable.

Taking into account the old experimental determination of R obtained at SLAC and a scaling behaviour in the asymptotic region, a numerical evaluation of this sum rule has been attempted in ref. /17/ yielding the result

$$\alpha = (9.3 \pm 2.0) \times 10^{-4}\ \mathrm{fm}^3 \tag{7}$$

which could now be improved with the new data from the muon experiments at CERN and Fermilab /20/. The present experimental results are the following:

	$\alpha \times 10^4$ (fm^3)	$\beta \times 10^4$ (fm^3)
V. J. Gold'anski et al. (1960) /21, 22/	10 ± 5	4 ± 5
P. Baranov et al. (1974) /23/	10.7 ± 1.1	-0.7 ± 1.6

A fit of these experimental data between 50 MeV and 110 MeV has been made with eq. (3) and the constraint (6) and according to this, the present experimental evidence gives for the proton the following determinations /17/

$$\alpha = (12.4 \pm 0.6) \times 10^{-4}\ \mathrm{fm}^3, \qquad \beta = (1.8 \pm 0.9) \times 10^{-4}\ \mathrm{fm}^3. \qquad (8)$$

It has been already argued how this result has to be considered as a surprising conclusion because one knows that all photoabsorption process on nucleons are dominated by the Δ(1236) resonance whose excitation is of magnetic nature /22/. Moreover this situation is complicated by the presence of the π^0-meson pole contribution /24/ which appears in order $O(\omega^4)$ and higher. This term is quite significant at low energy: at 100 MeV and $\theta = 150^\circ$ it accounts for $\sim$10%. In conclusion a new and more precise experimental determination of α and β is seriously needed.

2. - Medium energy region (100 MeV $\leq E_\gamma \leq$ 1 GeV)

The physics phenomenology in this energy range, has been recently discussed in a dedicated Workshop held at Frascati /25/ under the joint sponsorship of the ESF (European Science Foundation) and INFN (Italian Institute of Nuclear Physics). Being impossible to summarize here the work done on that occasion. I will limit myself to report few ideas that strongly rely to the knowledge of the incoming photon polarization.

It has been known for a long time that the meson exchange currents (MEC) and virtual excitation of the internal nucleon degrees of freedom, must be taken into account in any nuclear electromagnetic and hadronic process. In particular when the energy of the photon is sufficient enough to produce real pions in the region of nuclear isobar excitations, i.e. like Δ's, the dynamics of the pion in nuclear medium must be taken into account through the propagation of the Δ and the subsequent Δ--hole interaction. These models have been developed by different groups and given various generic names (isobar-doorway, isobar-hole, collective N^* resonances, giant (3, 3) resonances) but they contain essentially the same ingredients /26/.

When a bound nucleon is excitated for example, into the (3, 3) resonance in analogy with the Brown-Bolsterli schematic model, a Δ-particle N-hole pair is being created. This Δ decays rapidly ($\tau \sim 10^{-23}$ s) into a nucleon and a pion, where the pion can either leave the nucleus or be absorbed by another bound nucleon, thereby creating a new particle-hole pair. The probability for the resonant reabsorption of the pion is very large inside a complex nucleus; its mean free path is much smaller than the average nucleon-nucleon distance /27/

$$\lambda = 1/\varrho\sigma \ll d \,.$$

Therefore this resonant reabsorption mechanism is expected to be dominant, at least in large nuclei: as it gives rise to a strong ph-ph coupling it has to be discussed in the frame of a RPA-calculation. As a result of such a calculation we expect a coherent superposition of such ph-configurations; that means a collective excitation of the whole nucleus.

This collective mode of excitation corresponds to a resonant pion current which floats through the nucleus and which is characterized by precise set of quantum numbers: it is needless to say that this argument can be qualitatively extended for all baryonic resonances, and in this sense one has to regard the nucleus to consist of baryons rather than of nucleons /27/.

The investigation of these spectra with photons can be particularly interesting when they are polarized. In fact, in this way it should be possible to systematically disintangle the multipole excitation strength distribution, in a way very similar to that used in the low energy region (GDR). Moreover, since the photons are strongly coupled to vector mesons, special mechanism can be investigated, like ϱ propagation in nuclei. The ϱ-meson can either split into two pions giving rise to a double $(\Delta\bar{N})$ configurations $(\Delta\Delta\bar{N}\bar{N})$; or it can excite bound nucleons into the $N^*(1520)$ and create subsequently coherent nuclear N^* excitations. These two modes are mixed and simple and double pion-photoproduction could give information on these two different mechanisms /28/.

To conclude with, if this picture will be shown to be correct, then the next fashinating question to be asked is whether or not this multibaryon concept of the nucleus, as a generalization of the conventional multinucleon model, can be further extended toward a general description of the nucleus as a multiquark system. In this sense Fig. 6, taken from ref. /29/, clarifies substantially the meaning of this concept. At present time very little is known about coherent multiquark excitations and nothing can be really said about

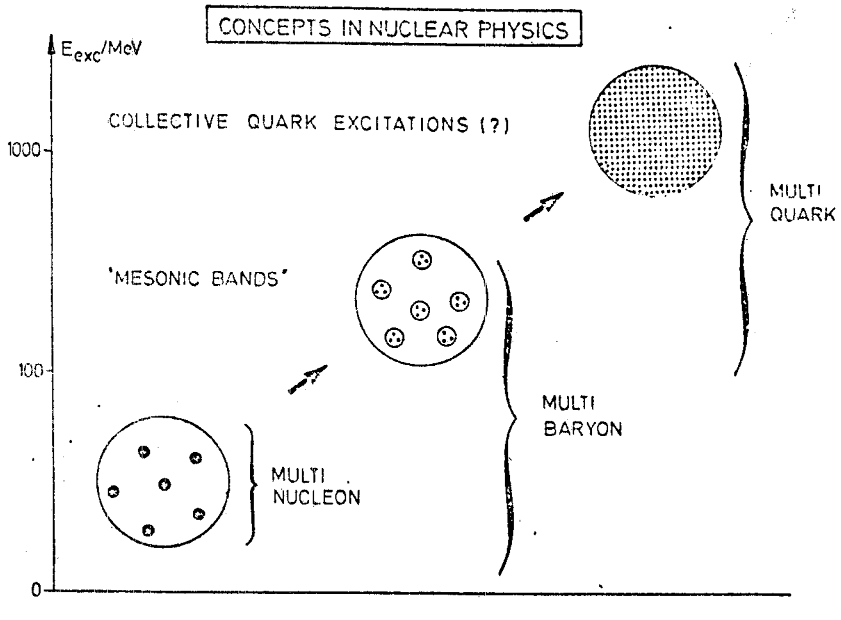


FIG. 6

the applicability of such a quark model. Nevertheless this big "affair" of nucleus as a multiquark system will be one of the most challenging matters for any of us and for the years to come.

3. - High energy region (20 GeV $\lesssim$ E_γ $\lesssim$ 40 GeV)

I will conclude my discussion giving few remarks on the photon physics in the high energy region where a lot of "high energy physics" is still quite a topical subject. With regards to this, it's worthwhile reminding the proposal to move the "SLAC hybrid facility" into the 20 GeV backscattered laser beams at SLAC /30/ or to look through the list of the experiments presently running at CERN (WA57; NA1; NA14; WA4 in ref. /31/ and Fermilab. Electroproduction processes in the limit of $q^2 \rightarrow 0$, usually interpreted as the scattering of an almost real photon, have been extensively discussed also on the occasion of the ECFA-study of an ep facility for Europe /32/.

Nowadays, the main interest of the high energy people for the photon physics lies in the unique property of the photon to have both a hadronic (meson like) and a point-like component. We know that for low transverse momentum photon-hadron physics, the photon can be thought of as a superposition of vector mesons. On the other hand for high transfer momentum, the photon interaction with hadronic matter is predominantly mediated by the bare $q\bar{q}$ component in the photon wave function (when seen in a rapid moving frame).

In a similar way to hadron-hadron scattering, the production at high momentum transfer can reveal the jet structure associated with hard scattering at quark and gluon level. The basic hypothesis of these models are that quark jets arise from a direct hard collision between the quark in the photon and one in the nucleon as shown in Fig. 7 /33/.

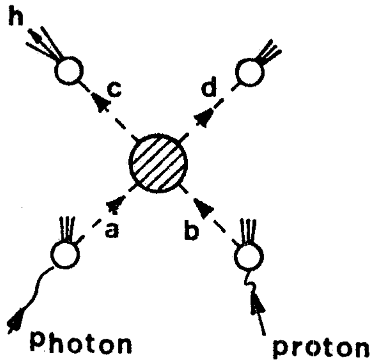


FIG. 7

The large p_T hadron production is assumed to occur as a result of elastic scattering of quarks $a + b \rightarrow c + d$, followed by the fragmentation of c into observed hadron h. In the gluon jet model based on QCD by Fritzsch and Minkowski /34/ the final product of such a photon-quark scattering will be instead a quark and a gluon manifesting themselves still by hadronic jets. These two different dynamical pictures give the idea of the problematic involved in this kind of physics. But this phenomenology can be even more attractive if one thinks that if the photon is polarized, so will be the constituent quarks.

In this sense polarized photon beams can provide polarized quark beams. A very convenient source of polarized quarks turns out to be circularly polarized photon beams. Suaya and Townsend / 31/ have recently shown that fragmentation of polarized quarks into hadrons could yield an independent test of those QCD predictions that rely strongly on the intrinsic angular momentum of quarks and gluons. In their model, the process which should be identified is shown in Fig. 8.

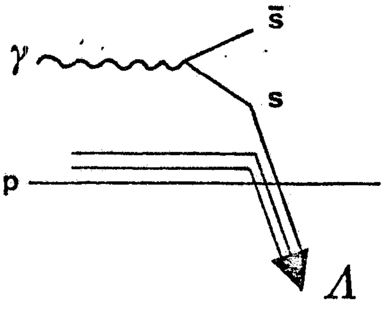


FIG. 8

Fast forward Λ's at high P_T are produced when an s quark from circularly polarized photon fragmentation combines with a -ud- pair from the proton. The fast s quark spin is aligned with the photon helicity direction. Owing to the vector nature of QCD, the s quark helicity in the interaction is preserved and the Λ acquires the original s quark helicity. Suaya and Townsend /35/ have shown that averaging over quark polarization between $x = 0.2$ and $x = 1$ (Feynman variable) gives $P = +0.3$. Similar argument holds for the Σ production where the result is $P_\Sigma = -0.1$.

As it has been discussed previously, the possibility to use the LEP machine as a source for a backscattered photon beam of very high energy, appears to be very problematic because, even accepting to work with a wide-band photon beam, still remains the problem of the bad duty-factor ($\sim 10^{-5}$) which imposes severe limitations. A practical possibility could be to use the bubble-chamber technique as in the SLAC arrangement /30/. The bubble-chamber with its (4π) geometry, excellent detection ability for both high multiplicity events and strange particle decays close to the vertex is the ideal detector, particularly when backed up with good downstream track measurements, particle identification and γ-detection systems.

According to the SLAC estimate /30/ for the counting rate, using 75 cm fiducial volume of hydrogen, 15 expansion/sec and 50 γ/pulse, one obtains

$$\text{events}/\mu\text{b}/\text{day} = \varepsilon_T \times 2.7 \times 10^{-6} N_\gamma/\text{day} \simeq 90 \text{ events}/\mu\text{b}$$

where :

$$N_\gamma/\text{day} = 50\,(\gamma/p) \times 15 \text{ pps} \times 8.6 \times 10^4 \text{ s/day} \simeq 6.5 \times 10^7\, \gamma/\text{day}, \quad \varepsilon_T \simeq 50\,\%,$$

and this number is of a considerable interest not only for the above mentioned possibility but also for other lines of research.

This reference goes mainly to the high mass vector production and the so called "search for charm". In particular (e^+e^-) experiments have not been successful in clearly identifying charmed baryon pairs which suggests that these states are not strongly produced diffractively. Photoproduction could furnish good chances for this recognition.

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