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SOME ASPECTS OF APPLICATIONS OF PHOTOGRAPHIC EMULSIONS

(Invited Paper Presented at the Vth International Conference on Nuclear Photography, Geneva 15.IX-1964)

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The results of the recent Conference on High Energy Physics held in Dubna have shown that in the investigation of such phenomena as elastic p-p scattering, inelastic p-N and π-N interactions at about 20 GeV, the double charge exchange of pions on nuclei, positron asymmetry in $\pi^+ \to \mu^+ \to e^+$ decays, muon polarization in $K^+_{\mu 3}$ decay etc., the emulsion technique proved to be successful to get some experimental data which could not be obtained by other methods or at least the data which have the same degree of accuracy. It should be emphasized that these experiments yielded quantitative results. In the future development of the emulsion technique one has to take into account essentially the progress of other types of nuclear instrumentation, especially that of spark chambers in which the main properties of track detectors and electronic counters are combined. However, there is good reason to believe that the emulsion technique will prove to be successful along many lines of research having in mind some its well-known advantages: 1. high angular (< 1 mrad) resolution and good energy resolution at the same time, 2. possibility to measure small lifetimes ($\approx 10^{-16}$ sec), 3. portability, 4. comparative insensitivity to the background, 5. possibility to use different targets which are put inside the emulsion blocks or are in contact with them, or are located at some distance. As an example, the experiment on the Σ^+ magnetic momentum being just performed at CERN could be mentioned.

In the following we shall discuss three lines of research: 1. the enrichment of emulsions with hydrogen, 2. the use of emulsion stacks with hydrogen targets, 3. some problems of application including the combination of nuclear emulsions with other methods.

1. Hydrogen targets are a reliable means in investigating elementary particle interactions. Successful results have been obtained with liquid hydrogen chambers and by means of electronic counters. However, the discrimination of particles having momenta of more than 1.5 GeV/c is very difficult in bubble chambers, if at all possible. The counter technique is less suitable for investigating interactions in which many particles with different masses, energies, and lifetimes are produced. It is well known, however, that in this field interesting results have been obtained by means of nuclear emulsions. Nevertheless, an essential improvement in the experimental facilities for investigating the interactions in hydrogen with emulsion technique seems necessary and possible. That will allow us to get experimental data which are difficult to be obtained with other techniques.

The emulsion pellicles are enriched in hydrogen being soaked with lithium acetate, ethylenglicol $(CH_2OH)_2$ or water what increases the hydrogen content twofold or even more. An increase in the amount of light nuclei increases the number of interactions on free and quasi-free protons in the emulsions up to ≈ 0.3. This means that in this respect the emulsions are practically equivalent to propane chambers. The freezing of soaked emulsion stacks /1/ makes possible to reduce deformations and to simplify the handling of emulsion stacks in the course of the experiment.

We have worked out an effective method of hydrogen enrichment /2/. Hydrogen is introduced in the emulsion with a certain substance which is washed out in the development. These methods permit us to expose pellicles of about 1000 μ, while their shrinking factor is ≈ 5; hence the observed pellicles have the usual thickness, what simplifies the ionization and multiple scattering measurements. Then the number of particles is increased by a factor of W, whose momenta can be measured. This factor is equal to the following ratio of the corresponding solid angles:

$$W = \frac{\arc\operatorname{Sin}\left(\frac{\operatorname{Sin}\frac{K}{K_0}\alpha}{\operatorname{Sin}\phi}\right)}{\arc\operatorname{Sin}\left(\frac{\operatorname{Sin}\alpha}{\operatorname{Sin}\phi}\right)}$$

where ϕ is the angle with the beam direction, α is the maximum angle of the track inclination with respect to the plane of normal emulsion in which the muliple scattering measurement is possible, K_0 and K being the shrinking factors for normal and impregnated emulsions.

We have found /3/ an appreciable increase of the ratio between the blob densities at the plateau and at the minimum in the NIKFI BR emulsions soaked with ethylenglycol as compared with the normal emulsions. The discriminating properties are improved in this case and the momentum range in which π, K and p are difficult to be distinguished from each other becomes smaller. If not very large emulsion stacks are used, for example, $10 \times 20 \times 30$ cm^3, or one uses stacks of smaller thickness, a certain part of the volume being in a magnetic field of about 100 kgauss, it is possible to measure the momentum and identify the mass of the majority of secondaries produced in p-p and π-p collisions even when the energy of the primary particle exceeds that attained with modern high-energy accelerators. (An increase in the energy of the primary particle leads to a narrowing of the cone of the secondary particles what makes easier to measure the multiple scattering, the magnetic deflection and the ionization).

To summarize: an increase in the hydrogen content, in the thicknesses of pellicles and in the sizes of the stack, the growth of the ratio J_{pl}/J_{min} as well as the application of magnetic fields will allow to obtain, with much less effort, a great number of completely analysed events of multiple particle production in the collisions of fast particles with protons. Moreover, an emulsion stack of the given

dimensions is the so called "strangeness detector": the kaons generated in the primary collision preserve their strangeness in subsequent collisions, and observation of the decays and interactions of secondary particles gives information about the generation of kaons in the primary collisions (see ref. /4/).

It is of interest to investigate the production of strange particles by p, π, e, and γ quanta when the velocities of the corresponding centre-of-mass systems are close to each other. In loaded emulsions the average atomic weight is about 12.5, and the probabilitiy for the kaons to undergo a secondary collisions in the nucleus in which they are produced is about 0.3 /5/. Hence, the strange particle production in this case is not very different from that when pure hydrogen target is used. These experiments can be performed fast enough and give information within a wide range of angles and energies of strange particles.

2. Hydrogen targets, outside or on the surface of the emulsion stack can also be used. Such experiments combine on the one hand the advantages of the hydrogen target and on the other the possibility of using intensive beams, carrying out accurate angular and range measurements, and discriminating between particles in the nuclear emulsion. In investigating the small-angle elastic p-p and p-d scattering good results have been obtained by applying a thin polyethelene film (CH_2) as an internal target and by detecting the recoil protons of 30 MeV/c momentum. In ref. /7/ the effectiveness of this method is proved even for very high energy primary particles.

The method proposed by the author /8/ permits the performance of several precision experiments with a hydrogen jet target which crosses the proton beam at the accelerator orbit. A hydrogen jet having the density of 10^{-6} - 10^{-4} gr/cm^2 may be used in the experiment. For example, at the 10 GeV synchrophasotron in Dubna the accelerated protons will pass through the jet, for about 0.2 sec, more than 10^5 times, and most of them interact with the target protons. The 10^{-6} gr/cm^2 density is reached at the jet diameter of 41 μ. Hence, the jet is a point-like target which creates perfect angular conditions in photoemulsion experiments. The application of this method has the following advantages:

a) in the investigation of elastic p-p and p-D scattering it is possible to measure smaller scattering angles than in ref. /6/ and to remove completely the background of nuclear interactions.

b) the kinematic conditions allow the investigation of proton resonances in p-p collisions by detecting the range and the angle of the secondary protons in the photoemulsion; /9/

c) it is possible to investigate the elastic p-D scattering with a high momentum transfer ($\approx$ 1 GeV/c) to the deuteron as well as to investigate the charge exchange in the $p + D \to n + 2p$ reaction.

d) It is also possible to investigate the spectra of secondary particles including the gamma ray production in direct p-p interaction etc.

A liquid hydrogen target being near or in contact with the emulsion block enables us to investigate thoroughly the spectra of secondary particles given rise in π-p, π-D, γ-p and other collisions. Let the fluxes of strongly interacting particles be equal to $10^8 cm^2$. Denote the beam radius by r, the side of the square target by a, and the length of the target by ℓ $\ell \gg r$. If the length of the emulsion stack is also equal to ℓ, the average number of secondary particles per 1 cm^2 of emulsion is given by:

$$n \approx \frac{\pi r^2 \rho \sigma s}{4a}$$

where ρ is the number of hydrogen atoms in 1 cm^3. If $r = 0.3$, $a = 3$ cm $S = 10^8$ and $\sigma = 10^{-27} cm^2$, then $n = 3.10^3$. The investigation of strange particle production by gamma rays and electrons with $S = 10^{10}$ is possible if the production cross sections are about $10^{-30} cm^2$.

The method permits us also to investigate the momentum distribution of secondary protons as a function of their emission angle. The soft part of the proton spectrum can be detected, if the emulsion is submerged into hydrogen. It is shown in ref./10/ that in Ilford G5 and special NIKFI emulsions the grain density of relativistic particle tracks slightly decreases (about 20%) when these emulsions are cooled down to 0.1°K. Deformations in the emulsion are not too serious and allow to irradiate emulsion stacks embedded in liquid hydrogen and helium or in contact with a solid hydrogen layer on the emulsion surface/11/. In view of this, it seems feasible to do the experiments with polarized protons. The application of polarized pure hydrogen targets requires very low temperature ($< 0.01^{\circ}$K) and strong magnetic fields what is difficult to reach in a considerable volume. Therefore, a polarized hydrogen layer on the surface of the emulsion having a small volume is expedient, especially in the experiment with unstable particles, for example, hyperons.

The dynamic polarization method described in ref./12/ makes possible to accomplish proton polarization of about 70% in the crystal $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$, where about 16% of the total interaction cross section belongs to free protons. Thus, the experiment for the determination of the relative parity of Σ and K in the reactions $\pi^+ + p \to \Sigma^+ + K^+$ which we are now preparing/13/, becomes possible. It is a very convenient method to observe the kaon decays in nuclear emulsions and to detect the right-left asymmetry of the K^+ emission in the reaction. We should note in this connection that a possible CP violation reported at the recent International Conference on High Energy Physics/14/ at Dubna, opens a new chapter in these investigations.

Further on, it was shown in ref./15/ that it is possible to determine the spin and parity of baryon and kaon resonances with polarized protons, for example, in reactions of the type:

$$\pi + p \to Y^* + K, \qquad \pi + p \to \Lambda + K^*$$

It was also shown in our paper/16/ that the dynamic polarization method can be used when emulsion pellicles are put into the cavity in an immediate contact with the crystal in which the protons are polarized.

The emulsion stacks together with the liquid or solid hydrogen targets can be an effective means in investigating the cosmic ray interactions at energies of $> 10^{12}$ eV. The application of hydrogen targets is necessary for the following reasons: the large multiplicity of particles produced in the primary collision with the nucleus leads to the fact that a considerable number of them undergo secondary interactions in the same nucleus, which distort the original properties of the primary interaction. In the superhigh energy region a "tunnel mechanism" of the interaction is possible, but it is difficult to detect this phenomenon if the energy of the primary particle is not known. It is also interesting to investigate the interactions of fast multiply charged particles with protons at rest.

Successful experiments carried out by Powel et al. with large emulsion blocks flown in the stratosphere and similar investigations done at the Physical Institute of the USSR Academy of Sciences with emulsions in liquid hydrogen/17/ provided the possibility for making the following experiments. A cubic emulsion block with an edge of about 30 cm is put inside a solid hydrogen sphere, 1 m in diameter. Solid hydrogen is more preferable than liquid one since no container and emulsion supporting material are required. The weight of emulsion is ≈ 100 kg and that of the hydrogen – about 65 kg. In winter, especially at high latitudes, the sun is absent for more than 16 hours. If the sphere is covered with a thin coating having a reflection factor $K = 0.9$ (larger values are also possible), the heat flux is given by: $Q = \pi r^2 C (1 - K) t$, where $C = 2$ cal. cm^{-2} min^{-1}. In 10 hours of flight $Q = 10^6$ cal (the flux owing to the air thermal conductivity will be less) and only 10 kg of hydrogen will evaporate. According to ref./18/ the flux of particles of energy $\geq 10^{12}$ eV is $S = 3.10^{-5}$ cm^{-2} $sec.^{-1}$ $ster^{-1}$. The average path length of primary particles, whose interaction products penetrate into the emulsion, is in hydrogen $< \ell > \cong r - \frac{a}{2} = 35$ cm. The number of their interactions in hydrogen is given by: $N = 4\pi^2 r^2 \rho \sigma < \ell > s\, t$ where $\rho = 0.5.10^{23}$. If $t = 10$ hours, $\sigma = 30.10^{-27} cm^2$, one obtains $N = 5700$. The number of showers ΔN which enter into the emulsion block, is less than N approximately by the ratio of the surface of the emulsion cube to that of the hydrogen sphere, from where $\Delta N = 10^3$. The average multiplicity of the showers q is, according to ref.[19], $q = 1.2\left(\frac{E}{mc^2}\right)^{1/4} = 22$, and the average angle in radians[20] is $\langle\theta\rangle = \left(\frac{2mc^2}{E}\right)^{1/2}$. The lateral width δ of the shower, if initiated at a distance $\langle l\rangle/2$ from the emulsion, is $\delta = 8$ mm. A knowledge of the above values allows one to calculate the coordinates of the origin of the shower i.e., to prove whether the shower was originated in hydrogen or not (for energies of $> 10^{14}$ eV we have $\Delta N = 10$, $q = 70$, $\langle\theta\rangle = 15'$). Observation of the electromagnetic cascades and nuclear interactions in the emulsion block as well as multiple scattering measurement give us a possibility of studying the primary interactions on protons.

3. Nuclear emulsions were also applied together with other methods. In Grigorov's investigations[21] on cosmic rays of $10^{11} - 10^{14}$ eV energy an arrangement was used which involved ionization chambers, counters, absorber and two pellicles of emulsions with an effective area of 0.6 m^2.

Takibayev[22] suggested to use nuclear emulsion together with a cloud chamber.

In paper[23], reported at the Instrumentation Section of the International Conference on High Energy Physics at Dubna an arrangement was described which consisted of a 125 pellicle emulsion stack (400 microns thick, 3 cm in diameter), a spark chamber as well as of Čerenkov and scintillation counters. This arrangement was irradiated in a beam of positive particles with momentum of 3.2 GeV/c. The contamination of protons was 65%, that of positive pions 34%, and that of kaons 1%. It allowed to separate positive pions and to determine the place of their entering the emulsion. The difference between the track coordinates measured in the emulsion and that calculated by means of spark chamber tracks was, on the average, 0.8 mm.

Successful investigations were carried out recently on neutrino interactions with photoemulsion nuclei at CERN[24].

In Gurevitch's works[25] a pulsed longitudinal (parallel to spin) magnetic field of 140 kgauss was used to eliminate the depolarization of muons coming to rest in the emulsion. This permitted to measure the asymmetry of the positron decay in the reactions $\pi^+ \to \mu^+ \to e^+$. The asymmetry coefficient a in the formula $\frac{d\omega}{d\omega} = 1 - a\cos\theta$ turned out to be: $a = 0.323 \pm 0.009$ which is in good agreement with the "V – A" theory.

The muon polarization in the $K^+_{\mu 3}$ decay at rest was investigated[26] by irradiating a 1-litre emulsion stack with 5.10^5 kaons incident perpendicular onto the surface of the stack. A 6 kgauss magnetic field directed perpendicular to the K^+ beam was used to preserve the pion polarization. The value of the positive muon polarization was found to be $p\,(K^+_{\mu 3}) = 0.68 \pm 0.28$.

The emulsion technique has particularly large advantages in investigating hyperfragments, nuclear fragmentation processes, nuclear reactions when the number of secondaries is great or their energies are low, as well as nuclear reactions occurring via several channels. The loading of nuclear emulsions with suspensions of certain elements makes possible to study reactions on light nuclei with different excitation levels[27].

The application of fine-grain emulsions which improve discriminating properties is very prospective. Using such emulsion Perfilov[28] studied, for example, the angular correlation between fragments in their multiple production.

π^--meson absorption processes and especially double charge exchange $\pi^\pm$ + (nucleus) $\to \pi^\mp$ + (nucleus) reactions enable us, according to ref.[29], to produce and investigate isotopes which cannot be studied otherwise. In papers[30] investigation of the double charge exchange of π^+ and π^- on photoemulsion nuclei is described. The investigation was carried out at the JINR synchrophasotron. The cross section for π^+ + (nucleus) $\to \pi^-$ + (nucleus) was found to be $(5 \pm 1) 10^{-28}$ cm^2. Recently at the Paris Conference it was emphasized that we can obtain further new information on nuclear structure from nuclear reactions.

It should be noted that the study of the complete disintegration of nuclei in collisions with fast particles is important. In our work[5] it was found that 10 DeV/c protons induce in (2.0 ± 0.3)% of events the decay of Ag and Br nuclei accompanied by the emission of more than 28 charged particles. The emission of 40 particles was also observed, i.e., a complete decay of a nucleus predominantly into nucleons. The excitation energy was 2-3 times above the binding energy of the nucleus. The detailed study of such excitation processes should be very interesting. The main problems are the following: by which mechanism and for what time the nucleus acquires the excitation energy, how this energy depends on the mass and energy of the primary particle and what is the dynamics of the complete disintegration of the nucleus.

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