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$\bar{p}$ ANNIHILATION ON HEAVY NUCLEI

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ABSTRACT

In order to study the properties of nuclear matter at high temperature and/or density, a substantial amount of energy has to be delivered to a heavy nucleus. In this paper we are proposing to employ the annihilation of antiprotons at LEAR momenta of 0.5-1.5 GeV/c on heavy nuclei ; a qualitative discussion of possible interesting reaction channels is presented.

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Since little study 1),2) has been devoted to the annihilation of antiprotons on nuclear targets, our considerations 3) shall be based mainly on the available data on $\bar{p}p$ and $\bar{p}n$ annihilations 4). However, the available fragmentary information on $\bar{p}N$ reactions indicates the presence of very peculiar events in which many nuclear fragments are produced that carry a large part of the annihilation energy. We wish to study such reactions systematically in order to learn about exotic annihilation mechanisms in nuclear matter. Ultimately, our aim is to learn from such reactions about the properties of nuclear matter exposed to high temperatures.

A. - ASPECTS OF $\bar{p}$ ANNIHILATION

When $\bar{p}$ impinges on a heavy nucleus, it will (almost always) eventually annihilate on one of the nucleons. The different $\bar{p}p$ and $\bar{p}n$ cross-sections are shown as a function of $\bar{p}$ momentum P_{lab} in Fig. 1. The annihilation cross-section is very substantial at small P_{lab} and falls to about 50 mb above ~1.5 GeV/c. The range of antiprotons in homogeneous nuclear matter of density $\rho_N = 1/7$ nucleon/fm^3 is

$$\lambda = \frac{1}{\rho_N \bar{\sigma}_a} = 1.4 \text{ fm} \left[\frac{50}{\bar{\sigma}_a [\text{mb}]} \right] \qquad (1)$$

where $\bar{\sigma}_a$ is the averaged $\bar{p}p$ and $\bar{p}n$ annihilation cross-section. λ is a small fraction of the nucleon diameter at small momenta ($\lesssim 200$ MeV/c) : most annihilations will occur at the nuclear surface. This is in fact known from the $\bar{p}$ atomic data 5). For higher momenta ($P_{lab} > 1$ GeV/c) λ reaches the magnitude of one nucleon diameter. Then there is a sizeable chance that an antiproton can penetrate deeply into a heavy nucleus. The exponential absorption law allows about 2% of annihilations to occur four (inelastic) interaction lengths into the nuclear matter which is practically in the middle of heavy nuclei for $P_{lab} \gtrsim 1$ GeV/c.

Many (unknown) reaction channels govern the $\bar{p}p$ and $\bar{p}n$ interaction ; aside from direct annihilations we can also have peripheral reactions in which pions are produced, but the baryon number is not destroyed. Loss of momentum in such reactions assures that the annihilation follows soon in a subsequent reaction in a heavy nucleus. A similar remark is true for the charge-exchange process $\bar{p}p \rightleftarrows \bar{n}n$. A qualitative measure for the reaction channel is the number of pions produced in the annihilation.

In our investigations the total number of mesons in the annihilation is very relevant, including the neutrals. Some information on neutrals can be extracted from the missing mass spectra. In Fig. 2, the normalized total pion multiplicity cross-sections, as obtained at 4.6 GeV/c, are shown 6). Unfortunately data of a similar character are not yet available at lower momenta. A Gaussian fits the relative yield

$$\sigma_n / \sigma = \frac{1}{\sqrt{2\pi}\Gamma} \exp\left[-(n - \langle n \rangle)^2 / 2\Gamma^2\right] \tag{2}$$

quite well, with $\langle n \rangle = 6.8$ and $\Gamma^2 = 2$ at 4.6 GeV/c. At smaller momenta $\langle n \rangle$ seems to decrease slightly, data for annihilation at rest in deuterium 7) indicate three charged mesons on the average. Including about two neutrals we expect that $\langle n \rangle \gtrsim 5$ at rest, averaged over isospin.

Little is known about the momentum distribution of these pions. In annihilations on nuclear targets those in the momentum range of 200-400 MeV/c in the nucleus frame are most interesting to us : such pions would have high reaction cross-sections in the peak of the Δ_{33} resonance of about 200 mb (at $P_\pi = 280$ MeV/c). Such pions have zero range in nuclear matter and we could expect that a substantial part of the annihilation energy is converted into kinetic energy of nucleons. In this context we must also keep in mind the broadening of the momentum distribution of pions by the Doppler effect - the annihilation centre-of-mass moves with $0.2 < \beta < 0.5$ (for $0.4 < P_{lab} < 1.3$ GeV/c) through the nuclear target. Not necessarily all annihilations will yield pions in the desired energy window - we estimate that in about 10% of reactions pions would carry the required energy of 315 ± 70 MeV ($\hat{=}$ 280 ± 100 MeV/c). This estimate is based on the requirement that a sufficient number of pions is available so that their average energy is of the required magnitude.

Further information on reaction channels comes from a recent evaluation of pion correlations in annihilations 8). This indicates that the pion source has a size in space of $r = 1.89 \pm 0.06$ fm and time $c\tau = 1.52 \pm 0.14$ fm, compatible with the intuitive assumption of a very short-lived, hadron-sized, fireball as the intermediate pion emitting state. If baryonium exists as a stable state, a small part of the cross-section could be attributed to the creation of these long-lived states and be compatible with other experimental information. If the width of such a state is smaller than ~50 MeV, it could live long enough to travel through the nucleus at $\beta \lesssim 0.6$; we will not follow here this line of thought.

To summarize the essential figures of the above discussion :

a) few per cent of antiprotons with $0.4\ \mathrm{GeV/c} < P_{\mathrm{lab}} < 1.7\ \mathrm{GeV/c}$ will penetrate deeply into a heavy nucleus ;

b) about 10% will decay into numerous pions with a resonant average energy ;

c) the average annihilation domain in space-time has hadronic sizes.

Consequently we expect that about one to one-half per cent of all annihilations on heavy nuclei should lead to conversion of a large fraction of annihilation energy into the kinetic energy of nucleons.

B. - NUCLEAR EXPLOSIONS

From now on we shall refer to a reaction channel in which a large fraction of the annihilation energy is found in a multiplicity of nuclear fragments as a nuclear explosion. Already some evidence for this reaction channel can be derived from emulsion experiments. In the article of Segrè 1) it is mentioned that among 220 annihilation stars one showed a nuclear multiplicity of 16. Since only 40% of these stars were annihilations in flight, this event corresponds to 1% of all eligible events. In our opinion, this high nuclear multiplicity is the most characteristic signature for the nuclear explosion. Thus the simplest trigger to discriminate against the 100-fold higher background of other events is a charged particle multiplicity counter. We observe that thin targets must be used to allow slow multi-charged nuclear fragments to arrive in the detector - this requires an intense beam of (slow) antiprotons that only the planned LEAR facility 9) at CERN can currently offer. Also the other experimental problems in such counter experiment : rescattering, spallation and pion contamination can then be handled.

There is most likely an optimum antiproton momentum at which a particularly high yield of explosions can be expected. With higher $\bar{p}$ momenta the chance to penetrate deeply into a nucleus increases, but the required condition for pions to be found in the desired energy window restrains the experiment perhaps to less than 2.5 GeV/c. Another very important reason to use as small a P_{lab} as possible is the resulting smaller β for the centre-of-mass of the annihilation fireball. This "hot spot" then travels relatively slowly through the surrounding matter and has significantly more time to undergo reactions, as compared with highly relativistic projectiles.

C. - LARGE QUARK BAGS

Take as an example the possible excitation of a quark matter state. If in $\bar{p}$ annihilation a slow fireball is created, with baryon number zero, it can collide with other neighbouring nucleons and absorb them into a domain of space similar in nature to the interior of a hadron. Repetition of this reaction may lead to the formation of a large quark bag with high baryon number and internal excitation provided by the annihilation energy. The ability of the absorbed hadrons to follow the motion of the condensation point is essential. Thus the likelihood to create quark matter rises when β is of the order of the Fermi motion in the nucleus. The decay of such a large quark bag would certainly lead to large baryon multiplicities and so be counted as a nuclear explosion. The optimum $\bar{p}$ momentum would be about 300 MeV/c.

To consolidate this proposal it is worth repeating here the essentials of the present understanding of hadrons in the bag model 10) : the total mass of a hadron consists of a volume term and the kinetic energy of the enclosed quarks. The energy density inside the hadronic bag is 4B, where the bag parameter B has been fitted to hadronic spectrum and has the value $B = (145\ \text{MeV})^4$. This energy density is roughly 1.8 times higher than that of normal nuclear matter. In excited large bags this factor may be slightly higher ; it is rather independent of the baryon number. Thus it expresses the true barrier between the normal nuclear state and large quark bags. As we outlined above, we see the possibility that this barrier can be overcome in $\bar{p}$ annihilations.

D. - HOT NUCLEAR GAS

Less spectacular but equally interesting is the alternative that the available energy is thermalized among the nuclei in the nucleus in the form of a nuclear fireball. Such objects have been considered recently in the context of relativistic heavy ion collisions 11). While some qualitative features of inclusive particle spectra are reproduced, the need for a more detailed understanding of equations of state of nuclear matter is recognized. In the case of $\bar{p}$ annihilations higher temperatures but lower densities could be most likely achieved than in heavy ion collisions. The high temperature aspects of nuclear matter, in particular the relevance of the limiting temperature 12), has been the subject of intense recent investigations 13). We are looking forward to the possibility of the observation of "thin" and hot nuclear gases.

Perhaps more than one of the above-described channels will be ultimately found - but at present in the absence of a satisfactory understanding of the annihilation process - it is hard to propose specific signatures for such exotic channels. The inclusive particle spectra triggered by high multiplicities would provide us with an enormous amount of information : in particular the particle temperatures, relative yields, rapidity distributions would clearly indicate possible collective action of nuclear or hadronic matter.

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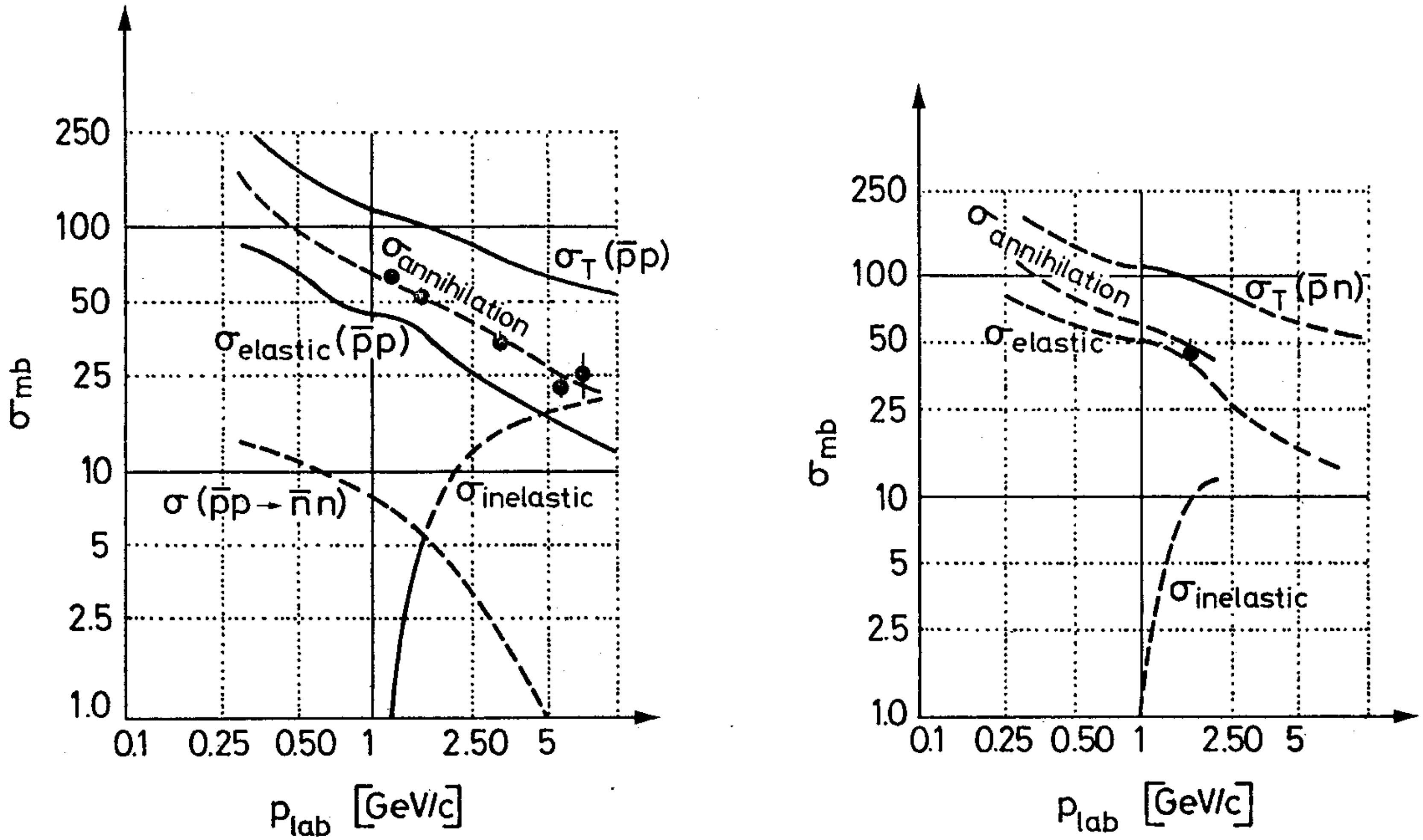
FIGURE CAPTIONS

Fig. 1 a) Cross-sections for the $\bar{p}p$ interaction. Solid lines indicate cross-sections which are reasonably well established. The experimental points represent direct determinations of the annihilation cross-section above 1 GeV/c.

b) Cross-sections for the $\bar{p}n$ interaction. See : H. Muirhead, in Ref. 4b).

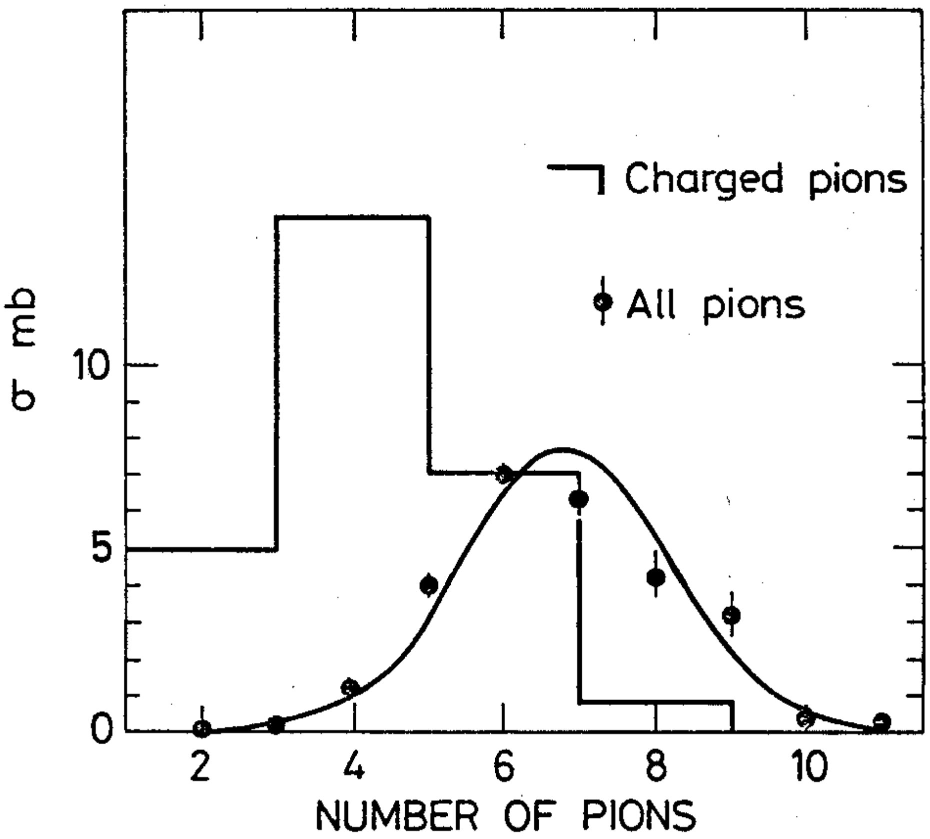
Fig. 2 Charged and true pion multiplicities for $\bar{p}p$ annihilation. See : D. Everett et al. in Ref. 6).



a) $\sigma(\bar{p}p)$

b) $\sigma(\bar{p}n)$

- Figure.1 -



- Figure 2 -