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Division de la Physique
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Service de Physique Nucléaire à Moyenne Energie

QUELQUES CONSIDERATIONS PRELIMINAIRES SUR LES EXPERIENCES ANTIPROTON-NOYAU

par

Avivi I. YAVIN

- Mai 1981 -

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Sommaire.- Des faisceaux d'antiprotons intenses et de bonne qualité seront disponibles en 1983 sur LEAR (Low Energy Antiproton Ring) au CERN et peut-être plus tard dans d'autres laboratoires. On examine, dans ce rapport, les possibilités ainsi offertes d'utiliser l'antiproton comme sonde du noyau. Diverses expériences antiproton-noyau sont proposées et l'on discute la possibilité d'observer des noyaux antiprotoniques et antineutroniques. On montre que, même pour l'étude du système élémentaire nucléon-antinucléon, il pourrait être avantageux d'utiliser comme cible un noyau plutôt qu'un proton. La possibilité d'étudier divers systèmes atomiques incluant un antiproton est aussi brièvement discutée.

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SOME PRELIMINARY CONSIDERATIONS ON ANTIPROTON-NUCLEUS EXPERIMENTS

Summary.- The antiproton as a probe of the atomic nucleus is discussed in the expectation that fairly intense beams of high quality will be available in 1983 at the Low Energy Antiproton Ring (LEAR) facility at CERN and possibly also in some other laboratories at a later date. Several antiproton-nucleus experiments are proposed, and the possibility of observing antiprotonic nuclei as well as antineutronic nuclei is discussed. It is demonstrated that even for the study of the elementary nucleon-antinucleon systems it could be advantageous to use nuclei rather than protons as target. The possibility of investigating several antiprotonic atomic systems is also briefly discussed.

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pions in nuclei, with its dependence on the energy and charge of the pion as well as on the atomic number of the target nucleus, has only recently been carried out $^{4)}$, yielding useful information on the π-A interaction. A similar systematic study of true absorption (annihilation) of $\bar{p}$ in nuclei would be of great value.

3. Nuclei have been studied with leptons ($e^{\pm},\mu^{\pm}$) and mesons ($\pi^{\pm},K^{\pm}$). Whenever an elementary particle has been used as a probe, another particle with some "opposite properties" has also been available. However, the situation with nucleons as probes is different and somewhat less symmetric. Experiments with protons have been compared with experiments with neutrons, but the neutron is not entirely an "opposite probe" to the proton. (It is not negatively charged, for example). We have not been too uncomfortable with the situation, except perhaps whenever we had to detect the non-ionizing neutrons, because the investigated nuclei are basically made up of protons and neutrons. The proton-neutron asymmetry is also carried over to other particles and reactions. The Δ, for instance, can be found or formed in nuclei in four charged states : Δ^{++}(for $p+\pi^{+}$) Δ^{+}, Δ° and Δ^{-} (for $n+\pi^{-}$). There is no Δ with two negative charges. The availability of $\bar{p}$ as a probe somewhat rectifies this asymmetry, as now we can have an "opposite probe" to the proton, a nucleon (or antinucleon) with a negative charge, a negative baryon number, etc. However, as nuclei are what they are, made up of protons and neutrons (and not of protons and antiprotons), and as we do not have antimatter nuclei as targets (in order to compare $\bar{p}$-$\bar{A}$ experiments with p-A experiments), the situation is not fully symmetric even for p and $\bar{p}$ as probes. Still, it is expected that in some cases investigations of nuclei with $\bar{p}$ will be compared with investigations with p in the same sense that experiments with π^{-} are compared with similar experiments with π^{+}. Thus, both $\bar{p}$ and n could now serve as "opposite probes" to p in the study of nuclei, complementing each other. The future might very well see three-way comparisons, such as elastic and inelastic scattering of protons from a nucleus A being related to scattering of both n and $\bar{p}$ from the same nucleus. Pion production presents another interesting case as π^{-} production from both (n,π^{-}) and ($\bar{p},\pi^{-}$) reactions can, in some sense, be compared with π^{+} production from the (p,π^{+}) reaction.

Some properties of the antiproton as a probe of the nucleus will be discussed in this paper and compared with those of the proton and the pion, so as to display the unique features of the $\bar{p}$ as a nuclear probe, and to indicate areas in which $\bar{p}$-A experiments can supplement the information which is obtained from experiments with other probes. Some possible $\bar{p}$-A experiments will be listed and discussed from the point of view of feasibility (an important, thought perhaps not profound, criterion at this early stage of the $\bar{p}$-A field). Whenever possible, it will be shown whether and how those experiments might be used to study the elementary nucleon-antinucleon (N-$\bar{N}$) interaction, or to study some nuclear properties.

II. The antiproton as a probe.

A. Beam.

The plan in CERN 1) is to transfer the antiprotons from the Antiproton Accumulator (AA) into the Proton Synchrotron (PS), where they will be decelerated to 600 MeV/c, and then to inject them into LEAR. Several stages are contemplated. When completed, LEAR will operate in four modes :

1. Extracted beam. Up to 10^6 $\bar{p}$/sec. are expected to be extracted. The available momentum range will be 0.3-2.0 GeV/c, with the lower limit reduced eventually to 0.1 GeV/c. This range is clearly suitable for nuclear physics studies. The momentum resolution could reach a value as low as 10^{-4}. The duty cycle will be 100 % and the beam density high. (The size of the beam spot is expected to be a few mm). The purity of the beam will be high with virtually no π^- or other contaminants.

2. Internal beam. Each antiproton in the circulating beam in the ring can cross an internal target f times each second, where f is the circulating frequency. High interaction rates can thus be achieved even with thin targets (such as gas jets).

3. H^--$\bar{p}$ coasting. Since negative hydrogen ions have the same charge and almost the same mass as antiprotons, they can be stored in the ring, side by side, with almost the same velocity. Neutral protonium ($\bar{p}p$) atoms could be formed and emerge straight out.

4. $\bar{p}$-p collisions. If protons are injected and are allowed to circulate in the opposite direction, colliding $\bar{p}$-p experiments can be performed.

B. Some general characteristics of $\bar{p}$-A reactions.

Only $\bar{p}$-A experiments with $A \geqslant 2$ will be discussed here, although the main goal of many of them will be the study of the nucleon-antinucleon system.

The interaction of $\bar{p}$ with a nucleus A will often result in the disappearance by annihilation of one of the nucleons in A, yielding an A-1 nucleus (from which additional nucleons can also be ejected). In this respect, the $\bar{p}$-initiated reaction bears some resemblance to the quasielastic scattering (p,2p), or to the (p,d) pick-up reaction . The unique feature of the $\bar{p}$-initiated reaction can best be seen in cases in which the $\bar{p}$ stays in the nucleus, as is the case of a knock-out experiment ($\bar{p}$,p). In such a case, if the knocked-out particle "leaves the scene" before annihilation takes place, states of an exotic antiprotonic nucleus can be observed by detecting the knocked-out particle (the proton in our ($\bar{p}$,p) example).

Observing the result of the annihilation can also be interesting. A ($\bar{p}$, annihilation) reaction is characterized by a very high Q value (close to 2 GeV !) and a low (possibly even zero) momentum transfer. The annihilation takes place in a very small volume, smaller than that of a nucleon ($\hbar/mc \sim 0.2$ fermi), and is expected to set up shock waves whenever adequate hydrodynamical conditions are satisfied. As the mean free path is small the annihilation will happen, on the average, close to the surface, and it is expected that violent surface motion could result following the ejection of a few particles. The residual nucleus would thus be left in a state of high angular momentum, and at high excitation (high temperature). If fission takes place, it is not certain that the familiar spectra of binary fission would still be observed. Some of the big fragments could end up highly excited to hitherto unknown nuclear states (high J surface excitation, new giant resonances, etc.).

Clusters or correlations can be studied via the ($\bar{p}$, annihilation) reaction. As an example, let us indicate how three-body correlations can, at least in principle, be studied. Let us imagine that a three-proton cluster exists in the nucleus. The impinging $\bar{p}$ may annihilate one of these protons and the other two will then be ejected with high energy. They may, in some extreme cases, share between them most or even all of the available energy ($\sim$ 2 GeV). The observation of energies and angular correlation of these two ejected protons could yield information on the correlation among the three protons in the cluster. The process is undoubtedly more complicated, with pions and protons scattered and rescattered, and with more than two nucleons, as well as pions, ejected in most cases 5), but the simple picture above serves to illustrate the point that some information on three-body correlations or densities could be obtained by studying reactions such as ($\bar{p}$,2p).

$\bar{p}$-N as well as $\bar{p}$-A annihilation may be of interest in astrophysics and other fields of science. For example, hitherto unknown isotopes, away from the "valley of stability", could be formed as a result of a violent explosion in the nucleus, caused by the annihilation of the $\bar{p}$. It is also possible to speculate on some future applications of the $\bar{p}$-annihilation process. The localized deposition of a large amount of energy due to the annihilation at the end of the $\bar{p}$ range, as well as possible deposition of some energy in the neighbourhood of the end point due to ejected particles (pions, nucleons and clusters), should be investigated in view of possible application of $\bar{p}$ beams for cancer therapy. It is also intriguing to explore the possibility of aiding energy-producing processes such as fission or fusion if it is found that under certain conditions the annihilation could yield a localized high temperature or a large number of neutrons or of heavy hydrogen ions (deuterons and tritons). Antiproton fuel could become a candidate for future space travels because of its high burning efficiency. Special technologies will undoubtely have to be developed and new beam facilities with special characteristics, such as high intensity and density, beam bunching, etc, will have to be constracted.These and other possible applications of $\bar{p}$ beams are highly speculative at this stage, because of the absence of basic data. Further consideration of these prospects is, at any rate, beyond the scope of this paper.

C. Comparison with other probes.

It can be expected that the antiproton would always be inferior to the proton as a probe of the nucleus, at least from the points of view of availability. But the $\bar{p}$ is a *different* probe and information on $\bar{p}$-A experiments can supplement our knowledge about nuclei when compared with similar p-A experiments. Some of the differences are the following : Unlike the proton, the $\bar{p}$ is not identical to any particle in the target nucleus ; its absorption is much stronger and true absorption takes place, emphasizing the imaginary part of the potential ; the interaction with the nucleus takes place near the surface due to the short mean free path; the elementary $\bar{p}$-N interaction, predominantly the short range (three-pion exchange) and long range (one-pion exchange) parts is different from the p-N interaction due to G party, as is the Coulomb-nuclear interference.

It took almost a decade for pion factories to yield valuable information on nuclear structure, such as large proton or neutron components of some wave functions [6]. This was done by comparing π^+ induced reactions (such as inelastic scattering) with similar π^- induced reactions, using the well known difference between the $\pi^- p$ and $\pi^- n$ interactions (or alternatively, the $\pi^+ p$ and $\pi^+ n$ interactions). At this stage, it can only be hoped that differences between the $\bar{p}$-N or $\bar{p}$-A interactions and the respective p-N or p-A interactions, would eventually provide equally useful nuclear information when results of similar experiments are compared.

In comparison with the pion, the antiproton has one clear advantage, namely its stability. Long beam paths as well as storage rings can, therefore, be used. Like the pion in the region of the 3:3 resonance, the $\bar{p}$ is strongly absorbed in the nucleus. Both π and $\bar{p}$ undergo true absorption, in which case they do not emerge from the nucleus. But whereas the pion cannot be absorbed by one free nucleon and is mostly absorbed in the nucleus by a correlated pair of nucleons, the antiproton can be absorbed by one free (or bound) nucleon. In comparing the (π,2N) reaction with the ($\bar{p}$,2N) reaction it should be realized that in the former the π will most likely be absorbed by the two ejected nucleons, whereas in the latter the $\bar{p}$ will be absorbed by a third nucleon, and the annihilation will then cause the two observed nucleons to be ejected. Therefore, (π,2N) reaction investigates mostly two-nucleon densities, while the ($\bar{p}$,2N) reaction could investigate three-nucleon densities.

The $\bar{p}$-N potential is poorly known ; and little, if anything, is known about the p-A potential. Some systematic data, starting with elastic scattering, are needed before even a phenomenological potential can emerge. One of the aims of the early $\bar{p}$-A experiments will have to be the establishment of such a $\bar{p}$-A potential.

III. Proposed experiments

Most of the experiments which will be proposed here will use an external beam, like the one constructed for LEAR, and standard techniques of low as well as intermediate energy physics. Particles will be detected and identified, and their energy (or momentum) determined with a magnetic spectrometer such as SPES II.

Telescopes of solid-state detectors, or of scintillators, will also be used. The following is a proposed list of some such experiments.

1. Elastic scattering -$(\bar{p},\bar{p})$

Elastic scattering, or the reaction

$$\bar{p} + A \rightarrow \bar{p} + A \tag{1}$$

should be one of the first reactions to be studied with a good $\bar{p}$ beam, such as the one proposed for LEAR. One of the main objectives will be to get systematic data which, together with information derived from antiprotonic atoms, will lead to a phenomenological $\bar{p}$-A potential. This potential will, in turn, be used to analyze other reactions (see below). It is expected that these studies will cast some light on the elementary $\bar{p}$-N interaction, provided a microscopic description of the reaction mechanism can be shown to be applicable here. In particular, these studies could provide information on the $\bar{p}$-n interaction, as such information cannot be gotten from studying the interaction of $\bar{p}$ with free neutrons.

The first experiment should be of a survey nature. Angular distributions at several energies and on targets such as H, ^{4}He, ^{12}C, ^{40}Ca, ^{90}Zr and ^{208}Pb, should be measured as soon as possible in order to get systematic data on the dependence of the cross section on the energy and on the atomic number of the target nucleus.

2. Inelastic scattering -$(\bar{p},\bar{p}')$

Angular distributions of the reaction

$$\bar{p} + A \rightarrow \bar{p}' + A^{*} \tag{2}$$

should be studied at an early stage, preferrably on the same targets and at the same energies as those used to investigate the elastic scattering. In fact, in most cases, both elastic and inelastic studies could be carried out simultaneously. One of the goals of the inelastic scattering studies could be to check the optical potential. It will also be of interest to compare the $(\bar{p},\bar{p}')$ studies with (p,p') data obtained with the same targets and at the same energies. It is hard to predict at this stage the result of such comparisons as so little is known about the p-A interaction. However, the strong absorption of the $\bar{p}$ is bound to have a profound effect. For instance, a stronger emphasis of outer-shells excitations could be expected in the $(\bar{p},\bar{p})$ case.

3. Charge exchange - $(\bar{p},\bar{n})$

The elementary charge-exchange process

$$\bar{p} + p \to \bar{n} + n \tag{3}$$

is hard to observe as it requires neutron detection. On the other hand, the reaction

$$\bar{p} + A_Z \to \bar{n} + A_{Z-1} , \tag{4}$$

which is important for the understanding of the $\bar{p}$-A interaction, can in principle be easier to study as the A_{Z-1} recoil can be detected. In order to get reasonable counting rates and resolution and taking into consideration the relatively high specific ionization of ions, the $\bar{p}$ energy should be high and the nucleus light. Intermediate scattering angles (for the $\bar{n}$) will most likely yield the highest counting rates, since the recoil energy is low for small scattering angles, while the cross section is expected to be low for large scattering angles.

The following reactions will serve as examples :

$$\bar{p} + {}^{3}He \to \bar{n} + t \tag{5}$$

$$\bar{p} + {}^{6}Li \to \bar{n} + {}^{6}He . \tag{6}$$

The recoils (t and ${}^{6}He$) will be detected.

In cases in which the recoiling nucleus is radioactive, the radioactivity can be used to measure the sum of cross sections for $(\bar{p},\bar{n})$ transitions leading to all the bound states of the residual nucleus. For example, the 9.45 min activity of ${}^{27}Mg$ can be measured when $\bar{p}$ irradiates ${}^{27}Al$. The reaction is

$$\bar{p} + {}^{27}Al \to \bar{n} + {}^{27}Mg . \tag{7}$$

However, since the reaction

$$\bar{p} + {}^{27}\text{Al} \rightarrow \bar{p} + \pi^{+} + {}^{27}\text{Mg} \qquad (8)$$

also yields ^{27}Mg without involving charge exchange, reaction (7) should be measured below threshold for π^+ production.

4. Knock-out - $(\bar{p},p)$ and $(\bar{p},d)$

Let us look at the reaction

$$\bar{p} + A_Z \rightarrow p + \bar{p} + (A-1)_{Z-1}. \qquad (9)$$

Let us now assume that in some cases the combination $\bar{p}+(A-1)_{Z-1}$ momentarily forms a bound system (or a resonance), which we will call "an antiprotonic nucleus" and will denote it by ${}_{\bar{p}}A_{Z-1}$. (In some cases the antiproton may, instead, be trapped in an atomic orbit, thus forming an antiprotonic atom). This exotic nucleus will, most likely, disintegrate in a short time due to the annihilation of the $\bar{p}$ with one of the A-1 nucleons. However, if the annihilation takes place after the ejected proton is separated, the detection of this proton could yield spectroscopic information on the exotic nucleus ${}_{\bar{p}}A_{Z-1}$, such as binding energy (energies), spins and parities, etc. If separation corresponds to a distance of about 10 fermi, and if $\frac{v}{c} \approx \frac{1}{3}$, separation occurs in $t \approx 10^{-22}$ sec. In other words, if the antiprotonic nuclear state has a width $\Gamma = \frac{\hbar}{t}$ not larger than about 20 MeV, the antiprotonic state will be able to be observed in a $(\bar{p},p)$ knock-out experiment. But will this process take place, and under what conditions will an antiprotonic nucleus be formed ? There have been several speculations concerning these questions. For example, Dover has suggested 7) that if the range of the imaginary part of the $\bar{p}$-nucleus interaction is shorter than that of the real part, conditions can be adequate for a light nucleus like ^{4}He to have a "pocket" in which a $\bar{p}$, with a sufficiently large orbital angular momentum, can orbit around this nucleus. It is felt that at this stage of very limited knowledge of the $\bar{p}$-N and $\bar{p}$-A interactions the subject is sufficiently exciting to merit an experimental exploration.

A preliminary search for an antiprotonic nucleus by a Saclay-Heidelberg collaboration 8) has, in fact, been carried out at the CERN synchrocyclotron for the special case of the deuteron as a target. The studied reaction was

$$\bar{p} + d \rightarrow p + \bar{p} + n. \qquad (10)$$

Proton spectra were observed at forward angles. No peak corresponding to a recoiling bound $\bar{p}n$ system was observed. It is proposed to repeat these measurements at LEAR with better statistics and at various scattering angles and incident $\bar{p}$ energies . A $(\bar{p},p)$ reaction should also be investigated with other targets, such as ^3He, ^6Li, etc. In other words, an attempt should be made to observe proton peaks corresponding to reactions such as :

$$\bar{p} + {}^3He \rightarrow p + {}^3_{\bar{p}}H \qquad (11)$$

$$\bar{p} + {}^6Li \rightarrow p + {}^6_{\bar{p}}He, \qquad (12)$$

where $^3_{\bar{p}}H$ denotes a nucleus with 3 particles: one proton (giving it the symbol H), one anti proton, and one neutron; and $^6_{\bar{p}}He$ denotes a nucleus with two protons, one antiproton, and three neutrons. It should be noted that reaction (10) is distinguished from reactions (11) and (12) in that in the former only one proton will result, whereas in the latters additional protons, as a result of the anihilation of the antiprotonic nuclei $^3_{\bar{p}}H$ or $^6_{\bar{p}}He$, may result. The proton spectra in reaction (10) will, therefore, be cleaner and easier to disentangle.

Let us suppose that the $\bar{p}$ in the ^6Li experiment (reaction 12) has knocked out a $p_{3/2}$ proton and has itself dropped into a $p_{3/2}$ orbit (assuming that the $\bar{p}$-nucleus potential is somewhat similar to the N-nucleus potential). The $\bar{p}$ will now be relatively remote from the ^4He core and may orbit around it for a while, before being annihilated, presumably by the $p_{3/2}$ neutron. If this annihilation is prohibitively fast for the knocked-out proton to be separated, an attempt should be made to observe knocked-out deuterons instead of protons, i.e. to look for the reaction.

$$\bar{p} + {}^6Li \rightarrow d + {}^5_{\bar{p}}He \qquad (13)$$

It should be noted that the nucleus $^5_{\bar{p}}He$ is made up of a ^4He core and a $\bar{p}$ orbiting around it, a picture suggested by Dover 7).

In the ^3He experiment (reaction 11) we can also look for a neutral bound nucleus $(\bar{N}N)_0$ to supplement the search for a $\bar{p}n$ nucleus (reaction 10). This will be done by looking for peaks in the deuteron spectra corresponding to the reaction

$$\bar{p} + {}^3He \rightarrow d + \bar{p}p \qquad (14)$$

(For simplicity, $\bar{p}p$ rather than $(\bar{N}N)_0 = \frac{1}{\sqrt{2}}(\bar{p}p \pm \bar{n}n)$ was used in reaction (14) and throughougt the paper to represent the neutral NN state). Both reactions (11) and (14) (or reactions (12) and (13)) can be studied simultaneously with the standard detection and identification systems mentioned before.

Finally, it should be pointed out that if the recoiling systems in the knock-out experiments are antiprotonic atoms rather than nuclei, the separation of the $\bar{p}$ will be larger and the knocked out proton or deuteron will get a better chance to escape in time. In such cases, energy spectra of antiprotonic atoms will be observed not by detecting X-rays, as is mostly proposed, but by observing the energy spectra of the knocked-out particles.

5. Quasielastic scattering - $(\bar{p},\bar{p}p)$

Quasielastic scattering reactions like (e,e'p) and (p,2p) have been studied extensively. It is proposed to investigate the reaction

$$\bar{p} + A_Z \rightarrow \bar{p} + p + (A-1)_{Z-1}. \qquad (15)$$

Since the charge distribution is known from electron scattering and the momentum distribution from (e,e'p) and (p,2p) studies, the $(\bar{p},\bar{p}p)$ reaction can be used to study the reaction mechanism and the $\bar{p}$-A interaction.

The $\bar{p}$ could be detected by a spectrometer and p, in coincidence, by a solid state detector telescope.

6. Two nucleon knock-out - $(\bar{p},2N)$.

It is proposed to study reactions in which two nucleons are ejected as a result on the annihilation of the $\bar{p}$, and in particular, the reaction

$$\bar{p} + A \rightarrow 2p + X \qquad (16)$$

This reaction has already been mentioned (section II B) as a possible way to study three-body correlations or densities in nuclei. In those possibly rare events in which the two protons are the only particles which are ejected, each of them will have almost 1 GeV of energy or a momentum of about 1500 MeV/c. The observation, in coincidence, of the two protons (or a proton and an alpha in the less symmetric, but perhaps more probable [5] $(\bar{p},p\alpha)$ reaction)) could yield interesting results on multiparticle correlations in nuclei. Of particular interest will be the study of reactions such as :

$$\bar{p} + {}^{3}He \rightarrow p + n \quad (17)$$
$$\bar{p} + {}^{3}He \rightarrow p + p + \pi^{-} \quad (18)$$
$$\bar{p} + {}^{6}Li \rightarrow \alpha + n \quad (19)$$
$$\bar{p} + {}^{6}Li \rightarrow \alpha + p + \pi^{-} \quad (20)$$

7. Pick-up – ($\bar{p}$, $\bar{p}n$) and ($\bar{p}$, $\bar{p}$xN)

The $\bar{p}n$ and $\bar{p}p$ systems can be studied, respectively, by the pick-up reactions:

$$\bar{p} + A_Z \rightarrow \bar{p}n + (A-1)_Z \quad (21)$$

$$\bar{p} + A_Z \rightarrow \bar{p}p + (A-1)_{Z-1} \quad (22)$$

The first reaction has already been discussed (reaction 10) for the special case of the deuteron as a target. The second reaction represents an alternative way to elastic scattering and gamma detection 9) for the study of the $\bar{p}p$ (or $(N\bar{N})_o$) system. The $\bar{p}n$ system, on the other hand, cannot be investigated by free $\bar{p}$-n scattering as there are yet 10) no free neutron targets, and reaction (21) thus represents an attractive way to study this system by observing the $(A-1)_Z$ recoil. Reactions (21) and (22), therefore, present two examples in which the elementary $\bar{p}N$ systems (interactions, resonances or bound states), can be studied by using a nucleus A, rather than a nucleon, as a target.

The following examples will illustrate the point :

$$\bar{p} + {}^{4}He \rightarrow \bar{p}n + {}^{3}He \quad (23)$$

$$\bar{p} + {}^{4}He \rightarrow \bar{p}p + t \ . \quad (24)$$

Both ^{3}He and t will be observed with standard detectors and particle identifiers. Angular distributions should be measured at several energies. An appearance of peaks in the ^{3}He or t spectra will indicate that the $\bar{p}N$ system formed a state, while the comparison of the two cross sections will yield information about the difference between the $\bar{p}$-n and the $\bar{p}$-p interactions.

$\bar{p}N$ systems can also be observed in pick-up reactions on heavier target nuclei such as ^{12}C :

$$\bar{p} + {}^{12}C \rightarrow \bar{p}n + {}^{11}C \qquad (25)$$

$$\bar{p} + {}^{12}C \rightarrow \bar{p}p + {}^{11}B. \qquad (26)$$

But, as higher energies are requires to eject a heavier recoil, the cross section for these reactions could be smaller. Also, the picture in reactions (25) and (26) can be more obscured than in the corresponding reactions (23) and (24), as both ${}^{11}C$ and ${}^{11}B$ have 10 particle-stable states.

The observation of the recoils in pick-up experiments also provides a possible tool for the investigation of more complex antiprotonic systems such as $\bar{p}2N$.

For example, it is proposed to study the following reactions :

$$\bar{p} + {}^{12}C \rightarrow \bar{p}2n + {}^{10}C \qquad (27)$$

$$\bar{p} + {}^{12}C \rightarrow \bar{p}np + {}^{10}B \qquad (28)$$

$$\bar{p} + {}^{12}c \rightarrow \bar{p}2p + {}^{10}Be . \qquad (29)$$

The energy spectrum of the recoiling nucleus in any of these three reactions, which can be studied simultaneously, can indicate whether any $\bar{p}2N$ bound system exists. The $\bar{p}np$ system, or ${}^{3}_{\bar{p}}H$, can be studied, perhaps with more ease than in reaction (28), in the reaction

$${}^{6}Li + \bar{p} \rightarrow {}^{3}_{\bar{p}}H + {}^{4}He, \qquad (30)$$

since now ${}^{4}He$ detection would indicate whether ${}^{3}_{\bar{p}}H$ is bound or not. Instead of picking up a deuteron from ${}^{6}Li$, it might also be possible to pick up a triton from ${}^{7}Li$, i.e. to study the reaction

$${}^{7}Li + \bar{p} \quad {}^{4}_{\bar{p}}H + {}^{4}He. \qquad (31)$$

Alpha particles will again be detected.

In the case of ${}^{10}Be$ as a recoil (reaction 29) an "antiprotonic molecular ion" (i.e. a molecule made up of two protons held together by the $\bar{p}$ via the electromagnetic interaction) may also be observed.

8. Pion production – $(\bar{p},\pi)$

Let us look at the reaction

$$\bar{p} + p \to \bar{p} + n + \pi^+ . \qquad (32)$$

If the $\bar{p}n$ system has a bound state or a resonance (a possibility which has been discussed above following reactions (10), (23) and (25)) it can be observed by measuring the energy spectrum of π^+. If we now apply the C-transformation on eq. (32), we get :

$$\bar{p} + p \to p + \bar{n} + \pi^- . \qquad (33)$$

The cross section for reaction (33) is expected to be identical to that for reaction (32). If the $\bar{p}n$ system has a state, so does the $\bar{n}p$ system. A preliminary search 8) for $\bar{p}n$ and $\bar{n}p$ bound systems, via reactions (32) and (33), has been carried out at the CERN synchrocyclotron by a Saclay-Heidelberg collaboration with negative results. It is proposed to repeat these measurements at LEAR. It will also be interesting to compare these results with pion production at intermediate energies, and in particular with the reaction $p+p \to d+\pi^+$ 11).

Reaction 33 suggests the $(\bar{p},\pi^-)$ process as a means to study a new family of exotic nuclei, the "antineutronic nuclei", $_{\bar{n}}A_Z$, (i.e. a nucleus with Z protons, one antineutron, and A-Z-1 neutrons). For example, it is proposal to look for the antineutronic nucleus $^5_{\bar{n}}\mathrm{He}$ in the reaction :

$$\bar{p} + {}^4\mathrm{He} \to {}^5_{\bar{n}}\mathrm{He} + \pi^- \qquad (34)$$

by measuring the energy spectrum of the π^-. The $^5_{\bar{n}}\mathrm{He}$ is, in some respects, a "mirror antinucleonic nucleus" to $^5_{\bar{p}}\mathrm{He}$, which was discussed in reaction (13), as both have a closed 1S shell of protons and neutrons (a $^4\mathrm{He}$ core) and either a $\bar{p}$ or an $\bar{n}$.

Let us now look at four somewhat similar processes, which can be investigated, at least in principle, and which could result in four "similar" nuclei :

$$p + {}^{12}C \rightarrow {}^{13}C + \pi^{+} \qquad (35)$$

$$\bar{n} + {}^{12}C \rightarrow {}^{13}_{\bar{p}}C + \pi^{+} \qquad (36)$$

$$n + {}^{12}C \rightarrow {}^{13}N + \pi^{-} \qquad (37)$$

$$\bar{p} + {}^{12}C \rightarrow {}^{13}_{\bar{n}}C + \pi^{-} \qquad (38)$$

For the sake of this discussion we will assume that all nuclei exist, including ${}^{13}_{\bar{p}}C$ and ${}^{13}_{\bar{n}}C$ (We did not use ${}^{4}He$ as a target for this discussion as both ${}^{5}He$ and ${}^{5}Li$ are particle unstable). The four final nuclei in reaction 35-38 are similar in that they all are made up of a ${}^{12}C$ and either a nucleon or an antinucleon. The (p,π^{+}) process (reaction 35) has already been studied 11). $\bar{n}$ beams will not be available for quite some time, so that reaction (36) cannot be studied. On the other hand, π^{-} production can be studied by either reaction (37) or reaction (38), and their results can be compared. A comparison can also be made with data from the π^{+} studies (reaction 35). These studies present an example in which reactions initiated by both neutrons and antiprotons can be used in comparison studies with reactions initiated by protons.

It should be noted that the $(\bar{p},\pi^{-})$ reaction presents a challenge to the experimentalist for two reasons : the cross section is small because of the large momentum transfer, as is the case for the (p,π^{+}) reaction ; and the pion background is expected to be large, as several pions could be emitted following the annihilation of the antineutronic nucleus. One possible way to overcome the background difficulty is to observe the $(\bar{p},\pi^{-})$ process by looking for low energy π^{-} slightly above threshold, and comparing the yield of such pions with the expected low yield of low-E pions below threshold.

9. Radiochemical measurements

Radiochemical measurements are relatively easy to perform and usually require less beam time than on-line experiments. However, the measured quantities are often sums of cross sections (to all bound states) rather than a single cross section. Useful preliminary data on π-A interactions were obtained more than 10 years ago from radiochemical measurements 12). One of the pion-induced experiments, which caused a great deal of confusion, but also stimulated new ideas, was the measurements of the excitation function for a neutron knock-out from ${}^{12}C$ with π^{-} and π^{+}. (Simple impulse approximation predicts a cross-section ratio of 3:1 at the 3:3 resonance, while the measured ratio in the first experiments was about 1). A similar study can be carried out with $\bar{p}$:

$$\bar{p} + {}^{12}C \rightarrow \bar{p} + n + {}^{11}C, \qquad (39)$$

by measuring the production yield of the 20.3 min. β^+ activity of ^{11}C. A comparison with the cross section for the reaction

$$p + {}^{12}C \rightarrow p + n + {}^{11}C \qquad (40)$$

could yield information on the $\bar{p}$-n interaction and the way it differs from the p-n interaction when the neutron is bound in a nucleus.

($\bar{p}$, annihilation) or ($\bar{p}$, fission) reactions may yield new isotopes away from the valley of stability, and one way to study them would be by radiochemical methods, including the observation of prompt (ordelayed) gamma rays

10. Formation of antiprotonic atomic systems

The reaction

$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma \qquad (41)$$

does not fall within the scope of $\bar{p}$-A experiments. However, it will be discussed here briefly because it represents an exciting field of research for antiproton beams.

If the $\bar{p}$ beam is allowed to coast in a straight section along an e^+ beam having the same velocity, an antihydrogen atom, $\bar{H}$, can be formed. $\bar{H}$ can be detected, for exmaple, by observing the (anti) hydrogen series. Such a study can check C invariance[13)].

A collision of an $\bar{H}$ with an H atom can result in three kinds of annihilations : e^+-e^-, $\bar{p}$-p, or $\bar{H}$-H (i.e. both e^+-e^- and $\bar{p}$-p). The ratio of these processes should be measured.

Coasting beams of negative hydrogen ions, H^-, and antiprotons may result in the formation of $\bar{p}$-p systems [1)], bound by nuclear or electromagnetic forces (the protonium). Exotic $\bar{p}pe^-$ ions may also be formed. In these ions the e^- serves to pull the p slightly away from the $\bar{p}$, relative to their separation in the protonium.

If a beam of H_2^+ ions is allowed to coast in a straigth section along side the $\bar{p}$ beam having the same velocity, a $\bar{p}$ may replace the electron in the ion and form an antiprotonic molecular ion, which has already been mentioned. (See the discussion following reaction 31). Spectroscopic lines from this exotic molecular ion may be observed before the antiproton annihilates with one of the protons. The same molecular ion may be formed if $\bar{p}$ beams at very low energy is used to irradiate a hydrogen gas. If now the $\bar{p}$ manages to knock-out the 2e and drop into an ionic state, an antiprotonic ion will be formed. If the $\bar{p}$ knocks-out only one electron, a neutral antiprotonic molecule could be formed. Similar systems can be formed with other hydrogen isotopes or with other elements.

IV. Conclusions

Some attrative possibilities for the use of future high quality $\bar{p}$ beams, such as the one proposed at CERN (LEAR), have been pointed out. It has been demonstrated that by using targets with $A \geqslant 2$ rather than protons, new information could be obtained even on the elementary nucleon-antinucleon systems; because the detection of a recoiling nucleus could, in many cases, be easier and may yield more information on these systems than the detection of the products of the $\bar{p}$-N annihilation. It has been proposed here to perform survey experiments such as $(\bar{p},\bar{p})$, $(\bar{p},\bar{p}')$, $(\bar{p},p)$, $(\bar{p},\pi^-)$ etc., at an early stage, in order to explore the $\bar{p}$-A field with all its imponderables. One of the first goals of such survey experiments will be to obtain an interaction potential, even a phenomenological one . Feasibility should be one of the criteria for doing an experiment at this early stage of exploration. It is expected that information on nuclear structure, on quarks in nuclei, on antiprotonic and antineutronic nuclei, etc., will soon follow. Once the difference between the $\bar{p}$-p and $\bar{p}$-n interactions is known, new information on nuclei could emerge from the results of $\bar{p}$-A experiments, and in particular from the comparison with similar p-A experiments. It has been pointed out that some unique information on multiparticle densities, and in particular on three-particle densities, may be obtained from the investigation of $\bar{p}$-A reaction, such as $(\bar{p},2p)$.

Antinucleonic nuclei, ${}_{\bar{p}}A_Z$ and ${}_{\bar{n}}A_Z$, if they can survive for at least 10^{-22} sec. (or if they can form an antinucleon-nucleus resonance with a width not greater than about 20 MeV), are of particular interest to observe and could be studied in reactions such as $(\bar{p},p)$, $(\bar{p},d)$, $(\bar{p},\pi^-)$, etc. Some of the questions which could be asked concerning these exotic nuclei are : Do antinucleonic nuclei exist and can they live long enough to be observed ? Under which conditions and for what nuclei will they, most likely, be formed ? What is their structure ? Where does the annihilation take place, and what happens to the nucleus as a result of the annihilation ? These and other such intriguing questions await experimental answers.

Several antinucleonic complexes as well as experiments designed to search for them and to study ther properties, have been discussed.

1. Antiprotonic nuclei, $_{\bar{p}}A_Z$. Knock-out and pick-up reactions have been suggested for the search of antiprotonic nuclei. In particular, the $\bar{p}N$ nuclei have been discussed as well as some heavier nuclei such as $^{5}_{\bar{p}}He$ (made up of an alpha particle and an antiproton) and $^{13}_{\bar{p}}C$.

It should be stressed that the nucleus $_{\bar{p}}A_Z$,if it exists, has A-1 nucleons (of which Z are protons) and one antiproton. Therefore, the antiprotonic nucleus $^{13}_{\bar{p}}C$, which can also be written as $^{13}_{\bar{p}}C_6$, has 6 protons (thus retaining the symbol C) and one antiproton ; the rest, six, are neutrons. Whereas the number of both particles and antiparticles in $_{\bar{p}}A_Z$ is A, the total baryon number, B, is A-2 and the total charge is Z-1.

2. Antineutronic nuclei, $_{\bar{n}}A_Z$. Antineutronic nuclei, if they exist, could be formed through the $(\bar{p},\pi^-)$ reaction. For example, when hydrogen is used as a target, the $(\bar{p},\pi^-)$ process could form the elementary $\bar{n}p$ system (reaction 33), or if helium or carbon are used as targets, $^{5}_{\bar{n}}He$ or $^{13}_{\bar{n}}C$, can be formed, respectively (reactions (34) and (38)). In $^{13}_{\bar{n}}C$, for example, the number of both particles and antiparticles is 13, the number of protons is 6, the total baryon number is 11 and the total charge is 6.

3. Antiprotonic atoms. The trapping of a $\bar{p}$ at rest in an atomic orbit has been suggested by many for the study of the $\bar{p}$-nucleus interaction. The detection of X-rays is usually applied[14], since line widths and line shifts yield information on the strong component of that interaction. Antiprotonic atoms, which can produced by $\bar{p}$ in flight, have been discussed in this paper. These systems would be observed via the detection of an ejected particle. (For example, see the last paragraph of the discussion of knock-out experiments).

4. Antihydrogen atoms, $\bar{H}$. The attractive possibility of trapping a positron by an antiproton, thus forming an antihydrogen atom, has been pointed out. This atom can, presumably, undergo annihilation in three different ways (e^+-e^-, $\bar{p}$-p, and $\bar{H}$-H). The eventual formation of antihydrogen molecules, $\bar{H}_2$, will be another step towards the production of macroscopic quantities of antimatter.

5. Antiprotonic molecular ions, $p\bar{p}p$. A search for molecular complexes, which

could be formed when a $\bar{p}$ interacts with a hydrogen molecule H_2, has also been suggested. A molecular ion, made up of 2 protons that are held together by a $\bar{p}$ via the electromagnetic interaction, can be formed as a result of the $\bar{p}$-H_2 interaction.

Most of the nuclear experiments, which have been proposed in this paper, will use similar techniques. Therefore, it will be possible in some cases to use the same set-up, and change only the target. Some of the experiments could be performed simultaneously.

Antiprotonic atoms, ions, and molecules are exciting exotic systems, but an elaborate discussion of them is beyond the scope of this paper. They have been introduced here primarily for competences, and because information on them may often be obtained simultaneously with information on the nuclear systems, whenever they both require conventional nuclear scattering techniques for their investigation. Ideas on these atomic systems, as well as on techniques to study them, should be obtained from similar, more familiar, fields such as muonic or pionic atoms.

Some of the ideas which have been presented in this paper may be new, while many have undoubtedly been considered by others. It is hoped that the presentation of these ideas in one paper of preliminary considerations on antiproton-nucleus experiments would serve to stress the attractiveness of this basically new field and will stimulate further considerations and detailed proposals for experiments.

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