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ANTIPROTON-NUCLEUS EXPERIMENTS AT LEAR AND KAON

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ABSTRACT

Antimatter and matter-antimatter systems are briefly discussed. Results of the antiproton-nucleus scattering experiments at LEAR (PS184) are described, with the emphasis on unfinished experiments and on proposed experiments yet untouched. A few remarks on antiproton and antideuteron experiments at KAON are then presented.

1. Antimatter and matter-antimatter systems

The availability of high intensity, good quality beams of antiprotons such as the one at the LEAR facility suggests a whole line of research with antimatter systems [1]. Antinuclei such as $\bar{d} \equiv \bar{p}\bar{n}$, $\bar{t} \equiv \bar{p}\bar{n}\bar{n}$, $\overline{^3\mathrm{He}} \equiv \bar{p}\bar{p}\bar{n}$ as well as heavier antinuclei have recently been discussed by Forward [2]. The field of antiatoms, whose simplest example is $\bar{\mathrm{H}}$, which is made of an antiproton and a positron, is well understood; however, one cannot rule out surprises. The next system in the complexity hierarchy is the molecule such as $\overline{\mathrm{H}_2}$ or the ion such as the antihydrogen molecular ion (consisting of $\bar{p}$, $\bar{p}$ and a positron), which is easier to handle, because it is charged. The next in line in the way to laboratory construction of antimatter systems is the production of macroscopic (bulk) quantities of solids, liquids and gases made entirely of antimatter particles (antinuclei and positrons). Anticrystals are one such example. Some of the main topics (and difficulties) are the production, the observation, and the preservation of such systems.

Matter-antimatter systems present another fascinating field. Protonium, which is an "atom" made of a proton and an antiproton, held by the electromagnetic interaction, has been the subject of many investigations, and many transitions in protonium have been observed. The main measured quantities are the widths and shifts due to the strong interaction, while the Stark effect distorts the measurements in gas samples, especially of the $2p \to 1s$ transition. Narrow baryonium states, which are bound states (or resonances) of the $N\bar{N}$system, held by the strong interaction, have eluded many experimentalists, and it is commonly agreed now that they do not exist. However, broad $N\bar{N}$resonances, which could also be of the $q^2\bar{q}^2$ type, might still exist. More complex systems, such as $p\bar{p}p$ could also exist, either in a nuclear form, or as molecular ions (similar to the H_2^+ ions), and could be investigated in specific nuclear reactions [1]. Under ordinary conditions, a nucleon and an antinucleon annihilate each other at close proximity (about one fermi), so that no baryonium exists for times longer than about 10^{-22} s. A fascinating challenge is the search for conditions in which a bulk of matter can accommodate an antinucleon in its midst for times longer than that.

Whereas antimatter and matter-antimatter systems are interesting topics of research in many branches of basic physics (atomic, nuclear, and particle physics, solid state physics, astrophysics, etc.), the possible applications present a special exciting challenge . Three examples will illustrate this point: 1) Due to annihilation, antiprotons can produce a larger damage at the end of their path than negative pions. This makes antiprotons, at least in principle, attractive for cancer treatment. 2) A lot of energy (close to 2 GeV) is dissipated when an antiproton is annihilated by a nucleon. Actually, close to 100 percent of the mass is eventually converted into energy, making antiprotons ideal for future space flights. 3) When an antiproton is annihilated by a nucleon, about five pions are produced. This effectively makes a trap [3] of antiprotons a possible effective "pion source" to be used for detector calibration and other applications.

2. Results of $\bar{p}$-nucleus scattering experiments

The study of the antiproton-nucleus interaction is an important part of the antimatter-matter research. Once the interaction is known and understood, it should be possible to study properties of nuclei such as: surface density and excitations, behavior of regions of high density/ high temperature, wave propagation in nuclei, and correlations of three or more nucleons. The unique properties of the antiproton as a nuclear probe are attractive for the study of specific nuclear states. It is also worth noting that the elementary $N\overline{N}$ interaction could at times be best studied in $\bar{p}$-nucleus scattering experiments; whereas for the study of the $n\bar{p}$ interaction, a nucleus is needed.

Little was known on the $\bar{p}$-nucleus interaction prior to the systematic scattering experiments at LEAR (Exp. PS184). Available data consisted mainly of some antiprotonic x-rays measurements. This led to some curious and even conflicting theoretical predictions. The following are three examples: 1) Wong *et al.* [4] claimed that x-rays from antiprotonic atoms could be fitted by an optical potential with either a shallow real part and a deep imaginary part, or *vice versa.* 2) The real potential was predicted [5,6] to be either repulsive, or attractive, while relativistic calculations [7] required it to be very attractive. 3) Under certain conditions (basically a shallow imaginary potential with short range) orbiting resonances could be observed in $\bar{p}$-nucleus scattering [5]. This situation prompted a collaboration from Saclay, Strasbourg, Grenoble and Tel Aviv to launch a series of experiments aiming at probing the antiproton's interaction with the atomic nucleus.

There were basically four goals to the program: 1) to get first accurate measurements of the major antiproton-nucleus scattering channels as functions of $E_{\bar{p}}$, θ, A, and N_n; 2) to determine, or at least set limits on, the antiproton-nucleus potential; 3) to get information on the $\bar{p}$-nucleon interaction from $\bar{p}$-nucleus data; 4) with this acquired knowledge, and taking advantage of the unique characteristics of the antiproton as a nuclear probe, to study some specific nuclear properties.

The basic experimental tool was the split-pole spectrometer SPEC II, built by Saclay. The spectrometer has broad momentum acceptance ($\pm 18\%$), covers scattering-angle range 0°–60° ,with an overall energy resolution of 1.2 MeV. Elastic [8] and inelastic [9] scattering were measured at two energies, 50 and 180 MeV. A spectrum of elastic scattering of 47 MeV antiprotons from ^{12}C at 25° is shown in Fig. 1, while angular distributions for elastic scattering from several nuclides are shown in Fig. 2. Also shown in the figure are optical model fits [10]. We can draw several conclusions from the elastic and inelastic scattering results: The optical potential, which was fitted to the measured elastic cross section, can be determined only near the surface of the nucleus, in the region where the density is only about 10% of that at the center. The

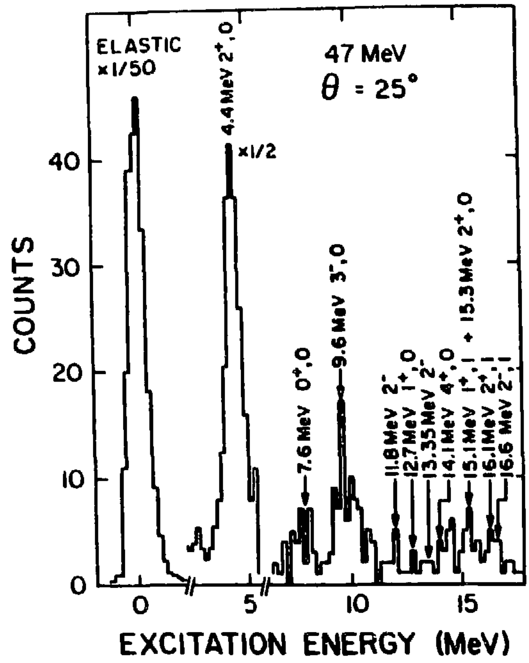

Fig. 1. Excitation-energy spectrum for $\bar{p}+^{12}C$.

depth of both the real and imaginary parts of the Woods-Saxon potential are not well determined; but the imaginary part is deeper than the real part, which is shallower than about 60 MeV. The reaction cross section decreases with energy, indicating an effective increase in the penetration into the nucleus when the $\bar{p}$ energy increases. Finally, the inelastic cross section increases with the antiproton energy in the excitation of collective states with $\Delta S=\Delta I=0$, following the trend of $t_0(E)$. These results show that the requirements for relativistic calculations and for orbiting are not fulfilled. The scattering results are in agreement with the antiprotonic x-rays data [11,12], and the

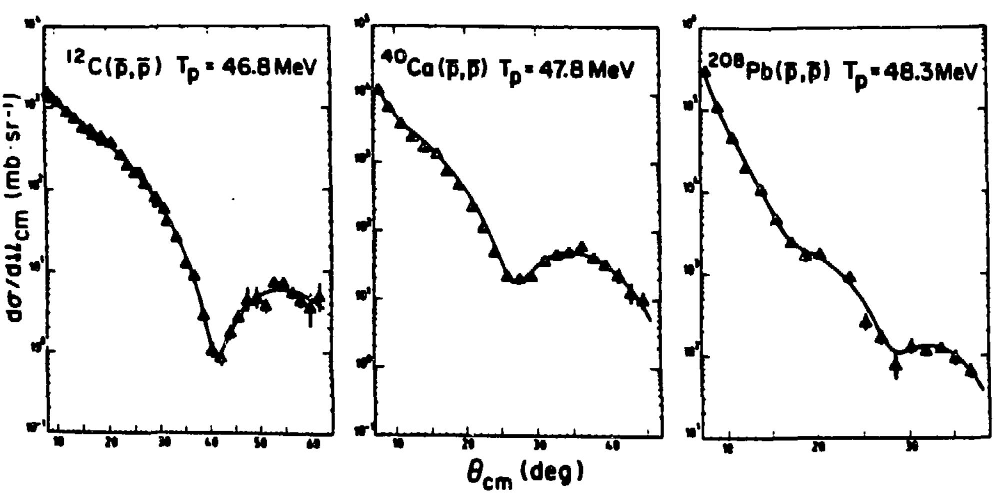

Fig. 2. Angular distribution of $\bar{p}$-nucleus elastic scattering.

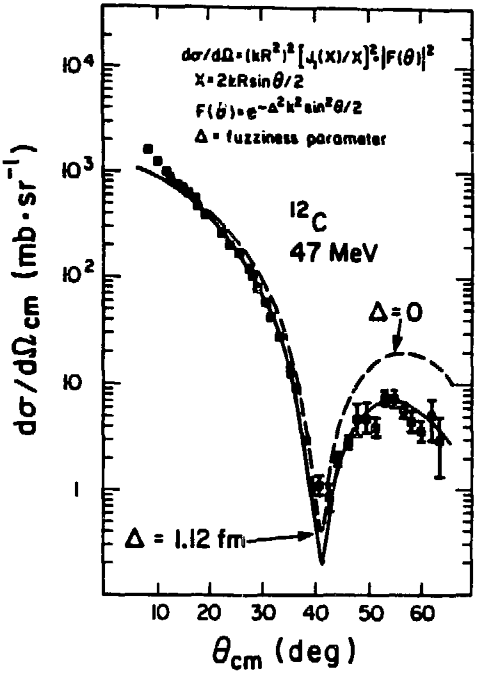

Fig. 3. Angular distribution for elastic scattering of antiprotons on ^{12}C.

apparent ambiguity in the optical potential [4] was removed. It should be noted that no information on the spin/isospin dependence of the antiproton-nucleus interaction was achieved at that stage. An attempt to observe hybrid "nuclear" states made up of an antiproton and a nucleus, with reactions such as $\bar{p}^{12}C \rightarrow p(^{11}B\bar{p})$, has failed, and neither $^{11}B\bar{p}$ nor $^{5}He\bar{p}$ hybrids has been seen [13].

At this point we considered the following questions: Is the nucleus completely black to an antiproton; and if so, can the $\bar{p}$ still be useful for the investigation of the nucleus? Analysis of elastic scattering [14] has shown that by and large the nucleus is black, but as can be seen in Fig. 3, there is also a fuzzy or grey surface. Moreover, the blackness itself could play a constructive role in selectively suppressing the short-range part of the interaction, thus allowing a relatively simple analysis. We also note that elastic and inelastic data do not usually go beyond testing the spin/isospin average $\overline{N}N$ amplitude t_0, while the spin and isospin parts of the interaction are not yet known. We then attempted to obtain information on the spin/isospin dependence of the $\overline{N}N$ interaction by studying inelastic scattering to highly excited, non-collective states. (Naturally, one expects such information to come from $\bar{p}p$ studies, with polarized beams and/or targets, but this was not available.) The 12.7-MeV state in ^{12}C has $I=0$ and $S=1$, while the 15.1-MeV state has $I=S=1$; the ratio of the inelastic cross sections to these two states is therefore a function of the spin/isospin-dependent amplitudes. In fact, predictions by Dover and Richard [15] and by Coté *et al.* [16] differ by a factor of 10. However, the attempt to establish which model for the elementary $\overline{N}N$ amplitude is correct was foiled by the $I=0$ broad state at 15.3 MeV. To alleviate this difficulty, the resolution has to be improved by an order of magnitude; or a reaction which does not excite the $I=0$ state, such as the $(\bar{p},\bar{n})$ reaction to the ground state analog in ^{12}B, should be used. A Tel Aviv-Indiana-Torino-Cagliari-Legnaro collaboration decided to start the investigation of the charge-exchange reactions with an easier case, the reaction $^{13}C\bar{p} \rightarrow ^{13}B(g.s.)\bar{n}$.

3. The charge exchange reaction

The value of the cross section for the elementary $\bar{p}p \rightarrow \bar{n}n$ charge exchange reaction is almost one tenth of that of the total cross section, emphasizing the importance of the study of ($\bar{p}$,$\bar{n}$) reactions. Spin-charge exchange (Gamow-Teller) excitations are predominantly long range (one-pion exchange). They can thus compete with the annihilation, at the diffuse surface, yielding information on the annihilation (especially when compared to (n,p) reactions). This means that the spin and isospin parts of the interaction will be studied [17]. The acquired knowledge of the interaction, together with the specificity of the $\bar{p}$ probe, could then be used to study certain features of the nucleus. In summary, there should be two steps: First, the nucleus will be used as a "filter", during the study of the spin/isospin dependence of the interaction. Isovector excitations of the nucleus will then be investigated.

The antiproton has some attractive features when used as a probe of the nucleus, especially in charge-exchange reactions. Like the nucleon (and the pion) it has a non-zero isospin; charge exchange is thus possible, with no masking background from isoscalar excitations (as in the case of inelastic scattering to the 15.1-MeV state in ^{12}C). It also has a non-zero spin; in charge exchange, both π and ρ can be exchanged. But unlike the nucleon, it is strongly absorbed at a short distance, relatively enhancing the long range (one-pion exchange) excitations. In fact, the ($\bar{p}$,$\bar{n}$) reaction could today be the most selective probe for the study of one-pion exchange transitions in nuclei. Some consequences of the the $\bar{p}$ specificity are: 1) More than in (n,p), and because of the short-range absorption, unnatural-parity ("pionic") states (such as $0^-, 1^+, 2^-, ...$) should be excited preferentially. 2) Gamow-Teller transitions in the β^+ direction should be enhanced, while Fermi transitions should be suppressed. 3) The ($\bar{p}$,$\bar{n}$) reaction is a good candidate for the study of some isovector giant resonances (such as the giant monopole) and of longitudinal spin modes. In summary, for some processes the ($\bar{p}$,$\bar{n}$) reaction could be the most suitable, and the near blackness (short-range absorption) can actually be an asset. Unfortunately, bad weather just before the one-year shutdown prevented us from carrying out the experiment, which is still planned for the future.

4. Future experiments

While a few experiments considered for the original probing-the-probe program have been successfully completed, other studies are yet to be done. Examples of the latter are: 1) The ($\bar{p}$,p) reaction on very light nuclides, such as ^{3}He and ^{4}He, where there could be reasons to believe that the absorption would be somewhat suppressed [18], so that a "hybrid" might be observed. 2) The ($\bar{p}$,d) reaction, which is also a candidate for a search for a light hybrid. 3) The inelastic scattering of antiprotons to the 12.7-MeV and 15.1-MeV states in ^{12}C, to be done with a resolution of less than 200 keV. 4) ($\bar{p}$,$\bar{n}$) on ^{13}C to study the charge exchange reaction and the annihilation, and ($\bar{p}$,$\bar{n}$) on ^{12}C to study the $\Delta S = \Delta I = 1$ transition. 5) ($\bar{p}$,$\bar{n}$)-charge exchange reactions on various nuclei to study Gamow-Teller transitions, isovector giant resonances, and longitudinal spin excitations.

Some experiments were proposed a long time ago [1], but have never been seriously investigated. Detecting recoils of light nuclei could turn out to be an efficient way to investigate very light hybrids such as $\bar{p}p$, $\bar{p}n$ and $\bar{p}np$. This can be done by observing the recoils from reactions such as: $\bar{p}^4\text{He} \rightarrow (\bar{p}p)t$, $\bar{p}^4\text{He} \rightarrow (\bar{p}n)^3\text{He}$, and $\bar{p}^6\text{Li} \rightarrow (\bar{p}np)\alpha$, respectively. A second example is the capture of antiprotons in atomic [1,19] or hybrid- molecular states, such as $p\bar{p}p$ [1]. Pion production could also be used for the search of hybrid nuclei (the $\bar{p}^4\text{He} \rightarrow (^4\text{He}\bar{n})\pi^-$ is such an example), but the observation of a peak in the huge pion background presents a big challenge to the investigator.

KAON, the proposed kaon factory in Vancouver, should have at least two advantages over LEAR: energy and intensity. Energy is needed for the production of heavy pairs such as deuteron-antideuteron, hyperon- antihyperon, heavy meson pairs, etc. The expected high intensity at KAON (up to 10^8 antiprotons per second) will make it possible to use beams of antideuterons [20]. Forward pointed out [2] that at sufficiently high proton energy, the ratio of the number of antideuterons to antiprotons should be about 10^{-4}. This means that beams of thousands of antideuterons per second could be achieved. Similarly, the higher intensity increases the advisability of using antineutron beams. The increased energy also "focuses" the antineutrons in the forward direction, further increasing the flux of (high-energy) antineutrons. A special challenge would be to build an "antiCHARGEX" facility to study the $(\bar{p},\bar{n})$ and $(\bar{n},\bar{p})$ reactions.

The availability of $\bar{d}$ beams opens the possibility for new experiments with "hot" nuclear matter. Two examples will illustrate this point. 1) When both $\bar{p}$ and $\bar{n}$ annihilate in the nucleus, twice as large an energy is deposited as when only $\bar{p}$ annihilates. Also, the energy is deposited over a larger volume, enabling faster equalization with higher energy per nucleon. 2) If the $\bar{p}$ and $\bar{n}$ move toward the nucleus one behind the other, and at low speed, it is possible that the first antinucleon annihilates and heats up the nucleus before the second one interacts, enabling the study of the interaction of antinucleons with "hot" nuclear matter. "Classical" experiments can also be investigated. For instance, if only one $\bar{N}$ annihilates, the other can be used for a clear signature, as is the case of the ${}^4\mathrm{He}\bar{d} \rightarrow ({}^4\mathrm{He}\bar{p})\bar{n}$ stripping reaction, where the $\bar{n}$ is easily observed.

In conclusion: We have discussed briefly the exciting topic of laboratory production of antimatter and matter-antimatter systems, for which beams of low (and even very low), as well as high energy antiprotons are needed. We then summarized the results of scattering experiments at LEAR, where it was shown that the interaction of antiprontons with nuclei is only partially known and understood. When this interaction is better understood, it can be used to study special nuclear properties. However, doing traditional nuclear physics with antiprotons is expensive; this means that the scope of such a program will be limited. The $(\bar{p},\bar{n})$ reaction is an example where the study of nuclear structure can be advantageous. The search for nuclear matter-antimatter hybrids, especially for very light nuclei would and should continue in spite of the hitherto negative results. New methods such as the observation of very light recoils or of pion production could be tried out. The high intensity and high energy make it possible to investigate the production of heavy mesons and of hyperons, as well as of antideuterons. In fact, it would be possible and advisable to build beam facilities for antineutrons and antideuterons, which will open the way to hitherto unexplored research of matter in abnormal conditions.

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