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WHAT CAN AN ANTIPROTON AND A NUCLEUS LEARN FROM EACH OTHER?

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INTRODUCTION

The advent of LEAR in 1983 will bring about an improvement of many orders of magnitude in the characteristics of low-energy antiproton beams, in the intensity, as well as in the longitudinal (energy resolution) and transverse emittances. This allows the opening up of many new fields which could not have been studied with conventional antiproton beams -- detailed study of antiproton-nucleus interactions is one of them.

Now the question is, Why study antiproton-nucleus interactions?

Firstly, the fact that this field is almost unexplored makes it interesting since new phenomena may show up which cannot be predicted now.

Secondly, I will try to show that the $\bar{p}$-nucleus interaction may provide very useful information, both about the elementary $\bar{N}N$ interaction and about nuclear structure.

I want to stress that this paper is not intended to be a review of well-established facts. Some of the points mentioned here are preliminary ideas which may look either very naïve or totally unrealistic, but the purpose is to stimulate discussions.

Basic and simple features that characterize the low-energy $\bar{N}N$ interaction, and a few points that make a nucleus interesting for use as a target, will first be pointed out. Then, different reactions involving an antiproton and a nucleus will be reviewed and analysed with the aim of providing answers to the question: "What can an antiproton and a nucleus learn from each other?" Finally, I will include a brief reminder of what will be measured in the experiment PS184 at LEAR.

SIMPLE FEATURES WHICH MAKE A LOW-ENERGY ANTIPROTON AN INTERESTING PROBE OF THE NUCLEUS

- *Short mean free path in nuclear matter*

The main characteristics of a low-energy antiproton are certainly its very large total and annihilation cross-sections. This leads to a very short mean free path in nuclear matter -- as low as 1 fm and 0.5 fm for 0.6 GeV/c and 0.3 GeV/c antiprotons, respectively. The only other elementary probe with such a short mean free path is a pion near the Δ resonance, but there the cross-section is mostly elastic and the pion can undergo several scatterings before being detected. This is not the case for an antiproton, where the large annihilation cross-section greatly reduces the probability of rescattering. The $\bar{p}$ scattering from a nucleus is likely to be described by simple reaction mechanisms without the complication of a multiple scattering process, which makes it a very "clean" way to study the nuclear surface.

- *Large energy released in the annihilation*

The large energy (almost 2 GeV) released in a small volume with very little momentum transfer during the annihilation is also a characteristic specific to antiprotons. It allows the study of the nucleus in a highly excited condition, which is very different from the one provided in heavy ion collisions[1]: How does the nucleus react to this sudden release of large energy? Can this lead to any unusual phenomena? These are questions which can probably be answered only in future experiments.

- *The antiproton is distinguishable from the constituents of the nucleus*

Although the existence of a nucleon-antinucleon pair in a nucleus is not impossible, the probability of finding such a pair should be extremely small. Then, when an antiproton is detected in the $\bar{p}$-nucleus interaction, it is most likely the same object as the projectile. This is not true in the case of the other commonly used hadronic probes, such as protons and pions. The exchange mechanism and the antisymmetrization between the projectile and the target constituents are not relevant in the $\bar{p}$-nucleus interaction.

- *The antiproton is the antiparticle of the proton*

The NN and $\bar{N}N$ interactions are related through the G-parity transformation (with the additional complication of annihilation in the latter case). Thus, if the same nuclear reaction can be induced by both the proton and the antiproton, and if the mechanism can be interpreted in terms of boson exchange models, then a test of these models can be made by requiring that the two sets of experimental data can be simultaneously explained by taking into account the G-parity transformation.

SIMPLE FEATURES WHICH MAKE A NUCLEUS
AN INTERESTING TARGET FOR AN ANTIPROTON

- A nucleus is made of a collection of nucleons close to one another, the distance between them being smaller than the range of strong interaction. Their density distribution is rather well known and there are possibilities for two- or three-body short-range correlations. This provides the possibility, when an antiproton has interacted with a nucleon, for the reaction products to interact coherently with neighbouring nucleons.

- The ground state and excited states of a nucleus have well-defined quantum numbers (spin, isospin, and parity). Inducing transitions between such states by inelastic scattering will provide information about the different spin and isospin components of the $\bar{p}N$ interaction.

- The average $\bar{p}$-nucleus field is built from the elementary $\bar{N}N$ interaction. The sensitivity to some features of this interaction might be greatly enhanced in the experimental measurements of the $\bar{p}$-nucleus one. For example, it seems that present $\bar{N}N$ data can be about equally well fitted with a long-range[2] or short-range[3] imaginary potential, whilst the $\bar{p}$ elastic scattering from nuclei might be very sensitive to the range of annihilation[4].

- In the range of the average nuclear field created by a heavy nucleus, it is possible to have the antiproton in a state of high angular momentum.

ANTIPROTON-NUCLEUS ELASTIC SCATTERING

The first goal of this kind of experiment is obviously to provide information about the $\bar{p}$-nucleus interaction complementary to that extracted from antiprotonic atom data.

At present, three types of $\bar{p}$-nucleus optical potential predictions exist:

The first one[5] -- purely phenomenological, although able to fit the existing antiprotonic atom data with only two adjustable parameters -- is very unlikely to reproduce data which involve short-range and medium-range parts of the interaction.

The second kind of prediction is characterized by its ability to relate, in a very simple manner, the real parts of the N-nucleus and $\bar{N}$-nucleus optical potentials. It is based on a relativistic treatment of the N-nucleus interaction, and is in principle totally self-consistent[6] since the only input is a one-boson exchange NN interaction. Together with the real part of the optical potential, the properties of the ground state of the target nucleus are also predicted. Actually, many authors[7-9] also use as an input the matter density distributions of the target nucleus taken from electron scattering. The nice feature of this model is that the real part of the $\bar{N}$-nucleus optical potential is directly deduced from the N-nucleus one by reversing, because of G-parity, the sign of the vector-boson contribution. It is a case where the same model simultaneously predicts the N-nucleus and the $\bar{N}$-nucleus elastic scattering data. Checking the quality of the fit to both sets of data will be a very good test of the model. This statement is unfortunately weakened because annihilation is treated in a more or less phenomenological way. Nevertheless, this model has also the interesting property of being applicable over a wide range of energies (up to about 500 MeV). The mean features of the predicted real potential are that it is energy-dependent and strongly attractive (of the order of -700 MeV). Such a strong attraction is used by DiGiacomo[10] to calculate $\bar{p}$-nucleus reaction cross-sections; it seems to be responsible for the fast rise at low energy, but this is only supported by a single experimental measurement on copper with poor accuracy.

The third type of calculation essentially involves the folding of the $\bar{N}N$ interaction with the matter density distribution of the nucleus[4,11-14]. It is therefore likely to provide information about these two quantities.

For example, the calculation of Ref. 4, although partly phenomenological since an "effective" $\bar{N}N$ interaction is used, predicts resonant effects in the backward elastic scattering which are very sensitive to the range of annihilation.

In the Kerman-MacManus-Thaler (KMT) or Glauber-type calculations (only valid at intermediate energies) of Refs. 11 to 13, the free $\bar{N}N$ scattering amplitudes are used. In particular, $\bar{p}n$ scattering amplitudes are involved, which is interesting since they cannot be measured directly. These calculations are also (at least in principle) sensitive to the q dependence of the phases of the $\bar{N}N$

amplitudes[11,12]. Free $\bar{N}N$ data are sensitive to this phase only in the Coulomb interference region.

Furthermore, using the proton density distributions deduced from electron scattering, a simultaneous analysis of intermediate energy K^+, p, and $\bar{p}$ elastic-scattering data, corresponding to probes with long, medium, and short mean free paths in nuclear matter, should provide very reliable neutron density distributions of nuclei.

Calculations of Ref. 14 predict a $\bar{p}$-nucleus potential composed of two attractive regions separated by a repulsive barrier. This suggests that, by looking at the energy dependence of elastic scattering at very low energy (a few MeV), one might observe resonant states of the $\bar{p}$-nucleus system. The width of these possible resonances should not be too much broadened by annihilation, for the same reason as that which makes quasi-atomic bound states rather narrow.

ANTIPROTON-NUCLEUS INELASTIC SCATTERING

The inelastic excitation to levels with any of the four combinations of $\Delta S = 0,1$, $\Delta T = 0,1$ are allowed in the $(\bar{p},\bar{p}')$ scattering, just as in the case of (p,p′) scattering. The poor knowledge of the $\bar{N}N$ interaction makes it difficult to predict the relative strength of these various transitions. However, it is quite plausible that the large annihilation cross-section would force the inelastic excitation to occur at relatively large distances between the antiproton and the nucleon, where the interaction is dominated by one-pion exchange. Therefore, the spin and isospin flip states, such as the 15.1 MeV 1^+ state of ^{12}C, are likely to be strongly excited in the $(\bar{p},\bar{p}')$ reaction.

As mentioned previously, the large annihilation cross-section of the antiproton inhibits the multiple scattering process. One implication is that the multiple-particle multiple-hole states are only weakly excited in the $(\bar{p},\bar{p}')$ reaction. This would greatly reduce the background in the giant-resonance region and would allow very reliable extraction of various giant-resonance strengths. If this prediction is verified, $(\bar{p},\bar{p}')$ will be a very powerful tool for studying giant resonances, since background subtraction is still the major cause of uncertainty[15].

Strong absorption also implies that the low-lying collective states will be strongly excited.

From these considerations we can say that $(\bar{p},\bar{p}')$ excitation spectra are expected to be made of a few peaks showing up on the top of a background that is much reduced compared to the (p,p′)

case. The interpretation of the reaction mechanisms will be simplified because of the inhibition of the multiple scattering process and the absence of exchange terms.

PROTON KNOCK-OUT REACTIONS ON NUCLEI

Proton knock-out reaction at forward angles seems to be well suited to the production of antiprotonic exotic nuclei if they exist, because it leaves the antiproton with a small momentum inside the residual nucleus. In this respect it is comparable to the (K^-,π) reaction for recoilless production of hypernuclei. But two major problems make the experimental observation of such states rather uncertain. First, theoretical calculations[16] based on the $\bar{p}$-nucleus optical potential of Ref. 14 predict $\bar{p}$-nucleus bound states with widths of the order of 100 to 200 MeV -- therefore virtually unobservable. However, one should keep in mind that these predictions for $\bar{p}$-nuclear states are, as pointed out by Wyceh[16], very sensitive to many badly controlled factors, and that with the same kind of calculation Σ^- hypernuclei were predicted to have widths of the order of 10-100 MeV [14]. The second problem is the presence of a strong continuous proton background produced by rescattering of pions coming from annihilation and already observed in the reaction $\bar{p}(d,p)X$ [17].

However, speculative as the existence of such antiprotonic exotic nuclei might be, their observation would provide very useful information not only for the determination of the inner part of the $\bar{p}$-nucleus potential but also for the knowledge of $\bar{N}N$ interaction inside a nucleus.

Another interesting point is that in the reaction $A_Z(\bar{p},p)A_{Z-1,\bar{p}}$, the residual antiprotonic nucleus has a baryon number A-2 (A is now the total number of baryons and antibaryons). This can be considered as a (very exotic) excited state of the nucleus $(A-2)_{Z-2}$ containing a $N\bar{N}$ pair. It could be very interesting to determine what is the probability for such a configuration to be mixed in the low-lying states of this nucleus, although the 2 GeV energy factor will certainly reduce this probability very strongly. Complementary information along these lines could be provided by an experiment being performed at LNS, Saclay, by Radvanyi and collaborators[18]. In order to search for coherent $N\bar{N}$ pair production on a nucleus below threshold (on a free nucleon), they bombard a ^{9}Be target with 2.9 GeV protons and try to detect and identify mass-10 nuclei with a kinetic energy of about 1 GeV at forward angles. If a $N\bar{N}$ pair exists in the ground state of ^{9}Be, it could show up in producing a cross-section larger than what can be estimated in a conventional model.

ANNIHILATION OF THE ANTIPROTON IN NUCLEI

When an antiproton annihilates on a nucleon, the fact that it is surrounded by other nucleons at short distances may have interesting consequences.

A practical application of this situation is proposed in experiment PS177 at LEAR[19] when K^- production (from $\bar{p}$ annihilation) and (K^-,π) strangeness exchange reactions are performed in the same nucleus leading to heavy hypernuclei production with interesting counting rates.

The possibility of using $\bar{p}$ annihilation in nuclei to study the equation of state of nuclear matter in a density and temperature domain different from what is provided by heavy ion collisions has been mentioned by Rafelski[1,20] and Strottman[21].

The reaction mechanism studied in Ref. 20 is the formation of a fireball made of a large quark bag with a baryon number larger than zero. It leads to no appreciable compression but to a high temperature of 160 MeV (which is the "magic" maximum temperature appearing in the thermodynamics of strong interaction[22]) and a relative enhancement of strangeness production. It seems to be supported by the results of an experiment[23] where, detecting the annihilation products of antiprotons in deuterium, the momentum distribution of the "spectator" protons, detected in coincidence with a $K\bar{K}$ pair, shows a T = 160 MeV slope.

The hydrodynamical calculations of Ref. 21 arrive at somewhat different conclusions. They predict a compression factor of the order of 2, a low temperature, and a small entropy production (0.06 per nucleon compared to 3-6 in relativistic heavy ion collisions). They also predict the formation of a sound wave which produces peaks in the angular distribution of the emitted nucleons at angles depending on the compressibility of nuclear matter.

The cascade calculation of Cahay et al.[24] also predicts the formation of a sound wave but no appreciable compression. An interesting point is that the momentum distributions of the nucleons and pions both exhibit a thermal shape corresponding to the same temperature of about 40 MeV (except for the high-energy part of the latter corresponding to the almost non-interacting pions), showing that some kind of thermal equilibrium is reached between nucleons and pions mainly due to the Δ resonance.

Another interesting possibility that might occur with the annihilation of the antiproton in a nucleus is that the 2 GeV produced in the annihilation could be directly transferred to neighbouring nucleons by means of virtual pions. In the extreme case, where only two nucleons are concerned, this will produce two 1 GeV nucleons going in opposite directions, which is a clear signal that such an event has taken place -- since if the same thing occurs via two real pions, the maximum energy transferred to the nucleons will be less than 700 MeV. Since the virtual pions are very far off-shell, short-range three-body correlations are required in the nucleus. This would be similar to the internal conversion process where the de-excitation energy of a nucleus inside an atom can be directly transferred to an electron of the atom.

EXPERIMENT PS184 [12]

The aim of the experiment PS184 at LEAR is to provide accurate data in a few simple and well-defined channels of the $\bar{p}$-nucleus interaction where experimental data is at present totally absent, namely:

i) $A(\bar{p},\bar{p})A$. Angular distribution of antiprotons elastically scattered from ^{12}C, ^{40}Ca, and ^{208}Pb.

ii) $A(\bar{p},\bar{p}')A^*$. Excitation energy spectra and some angular distributions of antiprotons inelastically scattered from ^{12}C, ^{40}Ca, and ^{208}Pb.

iii) $A(\bar{p},p)A_{Z-1,\bar{p}}$. Excitation energy spectra for proton knock-out reaction on ^{6}Li, ^{45}Sc, ^{123}Sb, and ^{209}Bi at forward angles.

The high-resolution, large-solid-angle and large-momentum-acceptance magnetic spectrometer SPES II will be used to detect the scattered particles.

Elastic- and inelastic-scattering measurements will be performed simultaneously using the large momentum acceptance of the spectrometer at the two $\bar{p}$ incident momenta of 300 MeV/c and 600 MeV/c. By varying the incident energy, the strength of the annihilation can be changed.

The elastic data on various target nuclei will be compared with various $\bar{p}$-nucleus optical potential predictions. For the inelastic scattering it will be very interesting to compare the excitation spectra with those obtained from other probes.

In addition to these measurements we are also considering the possibility of measuring elastic scattering from ^{12}C at 300 MeV/c at a few backward angles and detecting charged particles produced by the annihilation of antiprotons. These measurements and the ones using SPES II would be performed simultaneously.

Antiprotons scattered at backward angles would be detected and identified in a set of scintillator counters placed at fixed angles at a distance from the target of about 3 m. Time-of-flight measurement with a time resolution of 1 ns will provide an energy resolution of 3 MeV for antiprotons of 300 MeV/c: this is enough in the case of ^{12}C to separate elastic from inelastic scattering. The aim of this measurement is to observe the possible enhancement of backward elastic scattering due to orbiting effects discussed in Ref. 4.

Charged particles emitted in the $\bar{p}$ annihilation would be detected and identified in a set of ($\Delta E.E$) telescopes placed around the target in the scattering chamber. Proton energy spectra and their angular distribution would allow cascade and hydrodynamical calculations to be tested; the latter predicts peaks in the angular distribution at angles which depend on the nuclear compressibility[21]. The ratio of deuteron to proton would also provide information on the entropy produced in $\bar{p}$ annihilation.

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