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STUDIES OF NUCLEAR STRUCTURE IN ANTINUCLEON CHARGE-EXCHANGE REACTIONS

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ABSTRACT

The antinucleon-nucleus charge exchange reaction is discussed and its use as a probe of isovector excitations in nuclei is described. Attention is drawn to the fact that the $(\bar{p}, \bar{n})$ reaction will predominantly excite "pionic" (i.e., longitudinal spin) modes in nuclei. Comparison between $(\bar{p}, \bar{n})$ and (n, p) reactions is made. Plans for $(\bar{p}, \bar{n})$ experiments in the near future are mentioned.

INTRODUCTION

In recent years charge-exchange reactions have proven to be a very useful means for studying giant isovector resonances in nuclei. The (p, n) reactions at intermediate energies have probed the spin excitations of nuclei and have lead to the observation of the Gamow-Teller (GT) resonance and the study of its properties for a wide range of nuclei.¹ In the pion charge-exchange reactions (π^+, π^0) and (π^-, π^0) , on the other hand, the spin excitations are suppressed and one is able to select the spin-independent electric isovector excitations in nuclei. In this manner the charge-exchange analogs of the giant dipole were observed and the components of the giant isovector monopole were seen for the first time.^{2,3}

The $(\bar{p}, \bar{n})$ reaction combines some of the features of the nucleon and pion charge-exchange processes. In this sense it is a quite unique reaction. On the one hand, it is able to excite strongly spin states in nuclei but as opposed to nucleons and similarly to pions it is, because of absorption channels, a reaction that takes place at the periphery of the nucleus.

We will now discuss several properties of the $(\bar{p}, \bar{n})$ reaction and point out its various applications.

EXCITATION OF UNNATURAL PARITY STATES IN NUCLEI

The most striking feature of the $(\bar{p}, \bar{n})$ reaction is that it will preferentially excite unnatural parity ("pionic") states such as the $J^\pi = 0^-, 1^+, 2^-, 3^+$, etc. The reasons are the following: the natural parity spin excitations ($J^\pi = 0^+, 1^-, 2^+, 3^-, 4^+$, etc.) involve only transverse spin modes (i.e., modes in which the spin vibrations are perpendicular to the momentum transfer) whereas the unnatural parity transitions are composed of both transverse and longitudinal modes (i.e., spin vibrations parallel to momentum transfer). (The 0^- is a purely longitudinal mode.) The longitudinal part of the $N\bar{N}$ interaction is due to one pion-exchange. The transverse part is

caused by the exchange of heavier mesons such as the ρ and therefore the longitudinal part is of longer range than the transverse part of the NN force. Because of the strong absorption of the antinucleon the transverse part will be suppressed and the longitudinal part will dominate. The isovector spin-independent part of the force is also of short-range and will also be considerably weaker than the

Figure 1

isovector longitudinal, spin-dependent coupling. Figure 1 illustrates in a schematic manner the physical picture. As the antinucleon approaches the nucleus and touches the nuclear density it is quickly annihilated. Among the virtual mesons which are exchanged between the approaching $\bar{p}$ and nucleons in the nucleus only the lightest one (i.e., the pion) will reach the nuclear interior and interact with

several nucleons. The exchange of a ρ -meson, for example, will occur only with a very small number of nucleons at the nuclear surface.

These ideas were outlined some time ago in Ref. 4. Also in Ref. 4, cross-sections for the various $(\bar{p}, n)$ transitions in ^{90}Zr were calculated using two common types of NN forces.^{5,6} The DWIA calculations have shown that for $E_{\bar{p}} = 175$ MeV the "pionic" (unnatural parity) states are excited about 10 times more strongly than the corresponding (the same L) natural parity states.

For example,⁴ for an (n, p) reaction with $E_n = 200$ MeV the cross section at $\theta = 0^\circ$ for exciting the 1^- state is 6.8 mb/sr while for the 0^- and 2^- states the cross sections are 3.0 mb/sr and 4.4 mb/sr respectively. On the other hand, for the $(\bar{p}, n)$ at $E_{\bar{p}} = 175$ MeV the cross section for the 1^- is 0.05 mb/sr while for the 0^- and 2^- states the corresponding cross sections are 0.34 mb/sr and 0.57 mb/sr, thus the $L = 1$ unnatural parity states are much more strongly excited than the giant dipole. For more details see Ref. 4.

In a recent model calculation⁷ in which only the $1f \rightarrow 1g$ transition is considered the differential cross sections for the 1^+ and 0^- isovector excitation in $^{90}\text{Zr}(\bar{p}, \bar{p}')$ at 175 MeV were estimated. For the 1^- state only the $L = S = 1$ part was included so that a pure transverse spin transition resulted. The $0^+ \rightarrow 0^-$ transition is a purely longitudinal one. The calculated DWIA cross section at its maximum for the $0^+ \rightarrow 0^-$ transition was 16 times larger than for the $0^+ \rightarrow 1^-$ transition at its maximum. The moduli of the longitudinal and transverse transition potentials for the 0^- and 1^- as calculated in Ref. 7 are shown in Fig. 2. One sees clearly that the longitudinal transition potential dominates the transverse one for distances larger than the strong absorption radius R_{SA} . It was

Figure 2

in nuclei. These effects should show up in the longitudinal response function of nuclear excitations.⁸⁻¹⁰ The $(\bar{p}, \bar{n})$ reaction presents some possibilities to study such effects in nuclei. One should keep in mind however that these effects occur at higher momentum transfer in which case the dominance of the longitudinal transitions in $(\bar{p}, \bar{n})$ will be reduced.

OBSERVATION OF GAMOW-TELLER STRENGTH

The $(\bar{p}, \bar{n})$ reaction induces $\Delta T_z = +1$ transitions in the target nucleus. Therefore it will be possible to measure β^+ strength (S_+) particularly of Gamow-Teller (GT) type.

By measuring the S_+ strength and comparing it to the GT, S_- strength measured¹ in $(\bar{p}, n)$, one may be able to better understand the problem of missing GT strength.¹ Presently two different explanations have been put forward to account for the missing GT strength. The first suggests that the strength is removed to very high energies due to the coupling of the GT to Δ -particle-nucleon hole states.¹¹ In the second approach^{12,13} the missing GT strength is due to the coupling of the $1p-1h$ GT state to $2p-2h$ configurations leading to a fragmentation of GT strength.

By using (n, p) or $(\bar{p}, \bar{n})$ reactions it may be possible to shed light on this problem and provide more direct experimental evidence concerning one of these possibilities. The $(\bar{p}, \bar{n})$ reaction might be even better suited than (n, p) to study GT strength because of the suppression of natural parity excitations.

pointed out⁷⁻ that in light nuclei ($A \sim 20$) the node in the longitudinal transition potential is outside R_{SA} and thus cancellations occur for the $0^+ \rightarrow 0^-$ transition. As a result the dominance of the longitudinal transitions is reduced in light nuclei. One should therefore attempt to measure the pion-like transitions in heavy nuclei.

The dominance of the longitudinal transitions in the antinucleon charge-exchange reaction follows from the very general properties of the $N\bar{N}$ interaction and does not depend on the details of the force. This characteristic feature of the $(\bar{p}, \bar{n})$ reaction, we feel may provide exciting possibilities of research. There has been a longstanding question whether the pionic field is enhanced in nuclei⁸⁻¹⁰ and whether precursor phenomena⁸ to pion condensation

The inclusion of 2p-2h configurations in the configuration space in which the GT is calculated leads not only to a fragmentation of the strength but also to the appearance of new additional strength.¹⁴ For a β_- transition the strength in a nucleus like ^{90}Zr should be

$$S_- = 3(N-Z) + \Delta S$$

where ΔS is the additional GT strength mentioned above. In the β_+ channel the strength ΔS should appear¹⁴ so that the sum rule

$$S_- - S_+ = 3(N-Z)$$

is obeyed. If indeed the second hypothesis about the missing GT is valid, then one should find some of this strength in the $(\bar{p}, \bar{n})$ reaction.

In some light and medium heavy nuclei GT, β^+ transitions of the ohw type are allowed. For example, in ^{60}Ni the transition $f_{7/2} \rightarrow f_{5/2}$ is allowed for both β^- and β^+ . A comparison of the $(p, \bar{n})$ on the one hand and the (n, p) and $(\bar{p}, \bar{n})$ on the other might be of interest. Note that in the case of ^{60}Ni RPA correlations¹⁵ do affect the $f_{7/2} \rightarrow f_{5/2}$ part of the GT transitions. Our DWIA-RPA estimate of the $^{60}\text{Ni}(\bar{p}, \bar{n})^{60}\text{Co}$, $f_{7/2} \rightarrow f_{5/2}$, GT transition gives a forward peaked cross section of about 4.5 mb/sr for $\theta = 0^\circ$.

EXCITATION OF NEW RESONANCES

One will also be able to excite new types of giant resonances in $(\bar{p}, \bar{n})$. In particular there is the possibility that the spin isovector monopole¹⁶ will be detected. The transition density for a monopole excitation has a volume part and a surface part of opposite sign which usually cancels to a large extent the contribution of the volume part in the cross section. However, if the interaction is at the surface as is the case with 160 MeV pions or with antinucleons, then mostly the surface part of the transition density contributes and the cross sections could be measured. One would expect, therefore, to observe the isovector monopole state in $(\bar{p}, \bar{n})$ and because of the relatively strong spin-isospin component in the NN force the spin part of an isovector monopole transition would show up. The cross section for exciting the spin isovector monopole was computed in a DWIA calculation with an RPA transition density. The calculation includes in addition to the $L = 0$, $S = 1$, $J = 1^+$ also the $L = 2$, $S = 1$, $J = 1^+$ component. The forward peaked differential cross section is about 0.8 mb/sr for $\theta = 0^\circ$.

STUDYING THE NN INTERACTION

The $(\bar{p}, \bar{n})$ reaction will help to determine the spin, isospin components of the NN force. In inelastic $(\bar{p}, \bar{p}')$ scattering on ^{12}C an attempt was made to measure¹⁷ the cross sections for the transition to the $J = 1^+$, $T = 0$ at 12.7 MeV and the $J = 1^+$, $T = 1$ state at 15.1 MeV. These measurements should then provide essential information that will help determine¹⁸ the v_σ , and $v_{\sigma\tau}$ parts of the

Figure 3

$\bar{N}\bar{N}$ force. Measurement of the $J = 1^+$, $T = 1$ resonance is strongly impaired however by the closeness of an $J = 2^+$, $T = 0$ (15.3 MeV) level, which because of its isoscalar nature is strongly excited in the reaction. The $(\bar{p}, \bar{n})$ reaction of course is a means of avoiding this difficulty. In this reaction one can excite the $\Delta T_3 = +1$ component of the $J = 1^+$ isotriplet in the $A = 12$ nuclei and obtain the same kind of information as in the $(\bar{p}, \bar{p}')$ measurement of the $J = 1^+$, $T = 1$ state (see Fig. 3).

THE EXPERIMENTAL PROGRAM. OUTLINE

In the first stages of the experimental program¹⁹ at LEAR, the following reactions will be studied.

(A) The transition $^{13}\text{C}(\bar{p}, \bar{n})^{13}\text{B}$ to the $J = 3/2^-$ g.s. of ^{13}B will be measured. The GT, β^- -decay transition between the $J = 3/2^-$ g.s. of ^{13}B and $J = 1/2^-$ g.s. of ^{13}C is well known and its ft value measured. The $^{13}\text{C}(p, n)^{13}\text{N}$ reaction has also been studied.²⁰ By measuring this transition in the $(\bar{p}, \bar{n})$ reaction and combining it with the known GT strength one will be able to assess the distortion effects entering the reaction mechanism. An (n, p) measurement of this transition was performed recently.²¹

(B) The reaction $^{12}\text{C}(\bar{p}, \bar{n})^{12}\text{B}$ (g.s.) will be studied. The ^{12}B ground state ($J = 1^+$, $T = 1$) is the analog of the 15.1 MeV level in ^{12}C . The importance of studying this transition was mentioned in the previous section. In ^{12}B the first excited level at 0.95 MeV is a $J = 2^+$, $T = 1$ state and with the present limited resolution it could in principle obstruct the analysis of the transition to the g.s. We hope, however, that as discussed above the excitation of the natural parity $J = 2^+$ state will be weaker as compared with transition to the g.s.

(C) Also in the first stage of the $(\bar{p}, \bar{n})$ experiments the $^6\text{Li}(\bar{p}, \bar{n})^6\text{He}$ (g.s.) transition will be measured. The ^6Li and ^6He ground states have $J = 1^+$, $T = 0$ and $J = 0^+$, $T = 1$, respectively and thus the transition is a pure GT one. The β^- transition from ^6He to the g.s. of ^6Li is known. All the above reactions will be studied for forward angles.

With these "calibration" experiments in hand one hopes to measure $(\bar{p}, \bar{n})$ transition in medium and heavy mass nuclei such as ^{90}Zr and ^{208}Pb in the near future.

The comparison between the ($\bar{p}, \bar{n}$) and (n,p) results (anticipated from experiments at TRIUMF and LAMPF) should reveal some new interesting features in the structure and nuclear spin excitations. This comparison will tell us more about transverse versus longitudinal components of various nuclear transitions.

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