EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/85-69
8 May 1985

SEARCH FOR ANTIPROTON-NUCLEUS STATES

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Abstract: The status of the present experimental search for resonant or bound quasi-nuclear $\bar{p}$-states, using the knock-out reaction $A(\bar{p},p)X$ at $p_{\bar{p}}$ = 600 MeV/c is presented. No evidence for such states could be found. Upper limits for the production of such states in ^6Li and in ^{12}C are one order of magnitude lower than theoretically predicted. These observations are consistent with the properties of the $\bar{p}$–nucleus interaction as established from recent elastic and inelastic scattering as well as $\bar{p}$–atom studies at LEAR.

Presented by E. Aslanides at the
Third LEAR Workshop on
Physics in the ACOL Era with Low-Energy Cooled Antiprotons,
Tignes, 19–26 January 1985

The necessary conditions for $\bar{p}$–nucleus states to exist are that the $\bar{p}$–nucleus interaction is attractive and that the real part, V(r), of the $\bar{p}$–nucleus potential, $V^{opt}_{\bar{p}\text{-nucl}}$, must be greater than the imaginary part, W(r), near the nuclear surface, i.e. $V(R) > W(R)$. In the pre-LEAR era, $\bar{p}$-atom data were consistent with a variety of potentials having, in general, a strong absorptive part and a real part ranging from repulsive to strongly attractive with values of several hundreds of MeV. Such a variety of optical potentials could in turn accommodate many resonant[1)] or bound[2–4)] $\bar{p}$–nucleus states. Theoretical predictions for the widths of such states range from a few MeV for unbound, resonant states, to ~ 100 MeV for bound states. The rather scarce theoretical predictions for the production cross-sections of such states are of the order of $d^2\sigma/d\Omega dE \sim 0.25$ mb/sr·MeV [3)].

From a theoretical point of view uncertainties subsist in the derivation of $V^{opt}_{\bar{p}\text{-nucl}}$ from the elementary $\bar{N}N$ potential following folding procedures over the nuclear density; in the calculations of the $\bar{p}$–nucleus eigenstates $E_n - i\Gamma_n/2$ solving the Schrödinger equation for deep-lying states and neglecting higher-lying states requiring a relativistic treatment; and in the calculations of the production cross-section of the $A(\bar{p}, p)$ reaction, in which often only the PWIA is used.

The conclusions of the recent LEAR experiments studying the $\bar{p}$–nucleus interaction through elastic and inelastic scattering[5)], as well as the energy shifts and widths of antiprotonic atoms[6)], indicate rather shallow $\bar{p}$–nucleus potentials with central values for the real part $V_0 \leq 50$ MeV and that near the nuclear surface $W(R) \gtrsim 2V(R)$. The question then arises whether in such an interaction $\bar{p}$–states may be observable or not.

The experimental observation of unexpectedly narrow Σ-hypernuclear states[7)], for which analogies exist with the $\bar{p}$–nucleus system, and the uncertainties in the currently available theoretical models leave a large space for the experimental search of antiproton–nucleus states. Experimentally, such states are easier to identify if their width is ≲ 10 MeV, although experiments with particularly large momentum acceptance could look for broader states. At LEAR one such experiment[8)], with $\Delta p = 200$–1000 MeV/c and resolution between 4% (at ~ 600 MeV/c) and 12% (at 1 GeV/c), was mostly devoted to the study of the dynamics of the $\bar{p}$ annihilation in nuclei. However, in a study of the proton spectra emitted by various targets, no evidence could be found for broad, resonant or bound $\bar{p}$–nucleus states[8)].

The search for narrow $\bar{p}$–nucleus states was carried out at $p_{\bar{p}} \cong 600$ MeV/c using the $A(\bar{p}, p)X$ reaction and the high-resolution magnetic spectrometer SPES II, which has an acceptance of $\Delta p/p = \pm 18\%$ and a large solid angle, $\Delta\Omega = 30$ msr. The energy resolution for the outgoing protons was about 1.5 MeV, essentially due to the energy-loss straggling in the ~ 2 g/cm^2 thick targets and to multiple scattering effects in the target, in the spectrometer windows, and in the detection system. Scintillator (CH), ^{12}C, ^{63}Cu, and ^{209}Bi targets were studied in a first exploratory experiment[9)] but the most statistically significant results were obtained recently on ^6Li ($N_{\bar{p}} = 2.4 \times 10^9$) and on a scintillator target ($N_{\bar{p}} = 2.1 \times 10^9$), for outgoing proton energies between 120 and 290 MeV.

There are two main advantages in using the knock-out reaction: a) the outgoing proton at $\theta_{lab} = 0°$ carries most of the incoming antiproton momentum, $\vec{p}_p \cong \vec{p}_{\bar{p}}$, leaving the antiproton almost 'recoilless' in the target, thus favouring the formation of $\{\bar{p} - (A - 1, Z - 1)\}$ states; b) one can choose the incident $\bar{p}$ momentum close to the maximum of the backward $\bar{p}$–p scattering cross-section[10)], to improve the yield of the $A(\bar{p}, p)X$ reaction.

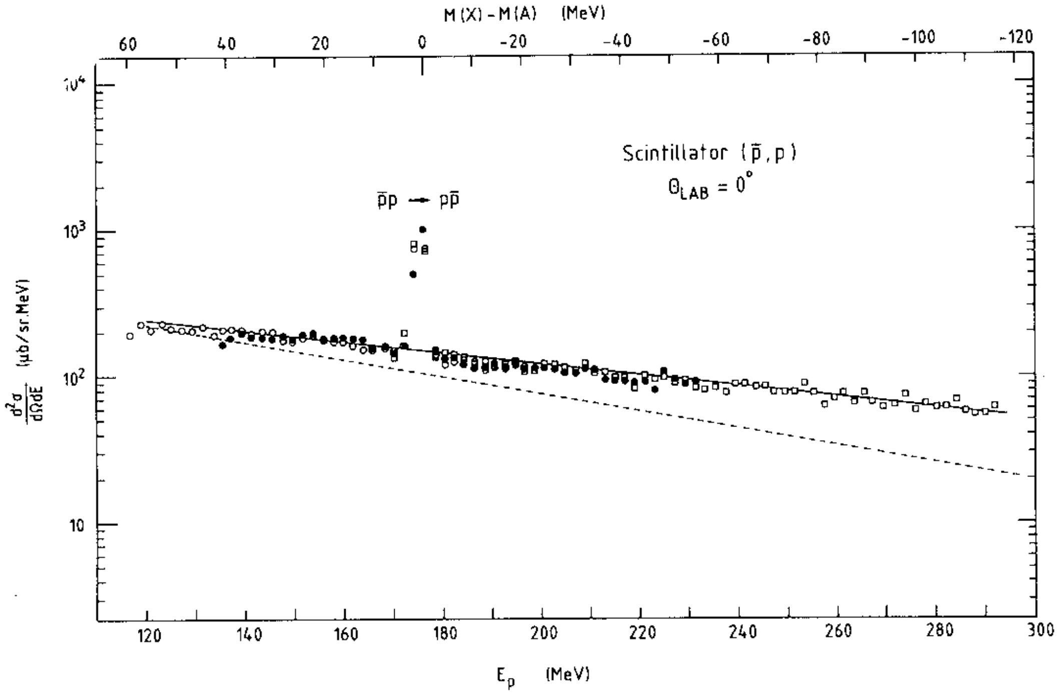

Fig. 1 Double differential cross-sections for the $(\bar{p},p)X$ reaction on the scintillator target at $E_{\bar{p}}$ = 176.5 MeV. The upper energy scale represents the mass difference M(X) − M(A). The sharp peak at M(X) = M(A) corresponds to the backward elastic $\bar{p}p$ scattering. The full line corresponds to an average temperature T = 85 MeV and the dashed line represents an INC calculation with T = 62 MeV.

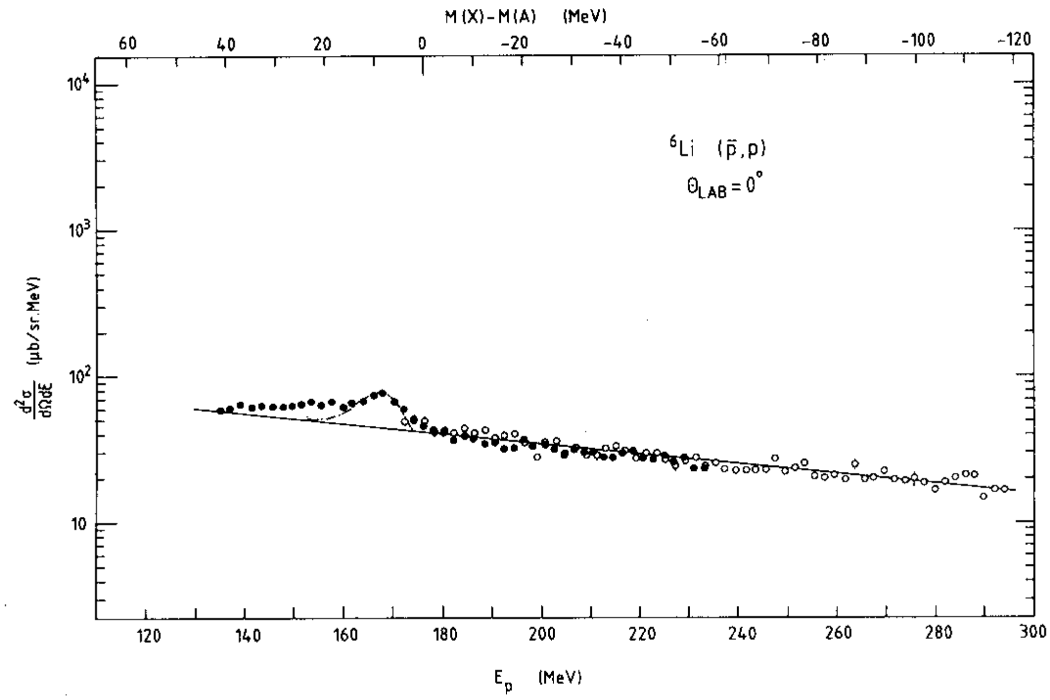

Fig. 2 Double differential cross-sections for the $(\bar{p},p)X$ reaction on the ^{6}Li target at $E_{\bar{p}}$ = 177.9 MeV. The full line corresponds to an average temperature of T = 95 MeV. The dash-dotted line is the result of a quasi-free scattering calculation of the incident $\bar{p}$ on individual protons of ^{6}Li, corresponding to an effective number of protons N_{eff} = 0.12.

Figure 1 shows the proton energy spectrum $d^2\sigma/d\Omega dE$ observed with the scintillator target. Protons are essentially due to the $\bar{p}$ annihilation in the target, where they are knocked out by the emitted pions directly, or indirectly via Δ isobar formation. The spectrum can be described by $d^2\sigma/d\Omega dE = C\sqrt{E}\exp(-E/T)$, where the average temperature T is ~ 85 MeV. Such temperatures are higher than the 62 MeV predicted by intranuclear cascade (INC) calculations. The narrow peak observed at $E_p = E_{\bar{p}}$ is due to backward elastic scattering of the incident $\bar{p}$ on the hydrogen nuclei of the scintillator target. The c.m. differential cross-section for the $\bar{p}p \to p\bar{p}$ reaction deduced from the present data is $d\sigma/d\Omega^*$ (180°) = 0.63 ± 0.01 mb/sr, in good agreement with the previously reported value[10] of $d\sigma/d\Omega^*$ (174°) = 0.65 ± 0.05 mb/sr. The quasi-free backward scattering of the $\bar{p}$ on individual protons of the ^{12}C target nuclei is expected at E_p = 152 MeV, but could not be distinguished above the continuous proton background of about 200 μb/sr MeV.

Figure 2 shows the proton spectrum observed with the ^{6}Li target for which the average temperature is T ~ 95 MeV. Here the background induced by the annihilation pions is lower, making it possible to observe protons from the quasi-free scattering of the incident $\bar{p}$ on individual protons in the ^{6}Li target nuclei, at the expected energy of E_p = 168 MeV.

The dependence of the proton production cross-section on the target mass A, as determined by the measurements on the heavier targets ^{12}C, ^{63}Cu, and ^{209}Bi [9] is ~ $A^{2/3}$, which is the expected A dependence of the antiproton annihilation cross-section. For ^{6}Li, the measured differential cross-sections are a factor of ~ 2 smaller than expected from the above mass dependence. This could be related to the number of protons remaining in a light ($Z \leq 6$) target nucleus after the $\bar{p}$ annihilation. The strong reduction of the annihilation background favours the use of lighter targets in the search for narrow $\bar{p}$–nucleus state.

Calculations of the proton spectra due to backward quasi-free scattering of the antiprotons on the target nucleons have been carried out using the Fermi momenta, $k_{F_{max}}$, values determined from quasi-free electron scattering[11], and assuming for the 1p-shell protons in ^{6}Li and ^{12}C an internal momentum distribution of the form $F(k) \sim \sin^2(\pi k/k_{F_{max}})$. The results confirm the quasi-free peak observed with ^{6}Li. The comparison of the calculated and the observed cross-sections for this reaction leads to an effective number of protons in ^{6}Li, $N_{eff} \cong 0.12$. In ^{12}C, assuming for the quasi-free scattering a differential cross-section limit of 3σ above the proton continuum, an upper limit of $N_{eff} \leqslant 0.13$ can be deduced. Such effective proton numbers are smaller than estimated theoretically[12]: 0.5.

No evidence for narrow peaks corresponding to bound or resonant $\bar{p}$–nucleus states could be found in the proton spectra. Experimental limits for the production of $\{\bar{p}$–$^{5}He\}$ and $\{\bar{p}$–$^{11}B\}$ states on ^{6}Li and ^{12}C, respectively, can be deduced for different outgoing proton energies and level widths. Assuming a width of 2 MeV, and considering proton energies close to the incident antiproton energy, i.e. states in which the $\bar{p}$ binding energy is equal to the binding energy of the ejected proton, such limits (3σ) are ~ 12 μb/sr in ^{6}Li and ~ 40 μb/sr in ^{12}C, about one order of magnitude lower than theoretically predicted[3].

Conclusions and prospects for the future

The upper limits for the production of bound or resonant $\bar{p}$-nucleus states, deduced from the experiment, are one order of magnitude lower than the theoretical predictions. They are however consistent with the conclusions of the elastic and inelastic scattering as well as the $\bar{p}$-atom data on the $\bar{p}$-nucleus interaction.

Future experiments should use lighter targets (liquid helium or deuterium), taking advantage of the expected reduction for the annihilation-induced proton background and aim at higher statistical accuracies, for which about 10^{11} $\bar{p}$'s are required.

Recently[13], the strong spin and/or isospin dependence of the imaginary part of the $\bar{N}N$ interaction was invoked as a possibility for reducing the annihilation probability of antiprotons in the nucleus; this led to the hypothesis that the $\bar{N}NN$ and $\bar{N}NNN$ systems might form relatively narrow bound states. Reactions of the type $\bar{p} + {}^3He \rightarrow p + X$, where $X \equiv \{\bar{p} - (pn)\}$ might be considered. More detailed calculations, taking into account the recent conclusions on the properties of the $\bar{p}$–nucleus interaction as well as the nuclear structure of the involved nuclei, are needed to prepare future, high-statistics experiments.

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