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SEARCH FOR ANTIPROTON-NUCLEUS STATES WITH ($\bar{p}$, p) REACTIONS

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ABSTRACT

We have studied ($\bar{p}$, p) reactions on ^{12}C, ^{63}Cu, and ^{209}Bi to search for possible nuclear states formed by antiprotons and nuclei. The experiments used the 180 MeV antiproton beam from LEAR, and the high-resolution magnetic spectrometer, SPES II, to detect the outgoing protons. No evidence of antiproton–nucleus states was found. The gross features of the proton spectra are reasonably well described by intranuclear cascade model calculations, which consider proton emission following antiproton annihilations in the target nucleus.

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The antiproton beam recently available at the Low Energy Antiproton Ring (LEAR) at CERN has offered a unique opportunity to investigate the interaction of antiprotons with nuclei. An experimental study of antiproton–nucleus scattering is currently under way and first results [1] on $\bar{p}$–^{12}C scattering have already been reported. In this paper, we present the first experimental results of a search for nuclear states formed by antiproton and nucleus, using the ($\bar{p}$, p) reaction.

The states being searched for would be either bound or resonant states formed via the nuclear interaction between the antiproton and the nucleus and are to be distinguised from the well-established $\bar{p}$ atomic states which are bound by the Coulomb interaction. For such nuclear states to exist, it is necessary that the nuclear interaction between the antiproton and the nucleus be attractive. Indeed, analyses of the $\bar{p}$-nucleus scattering data [1] and the $\bar{p}$-atom X-ray data [2] suggest that the real potential is sufficiently attractive to accommodate a wide spectrum of $\bar{p}$-nucleus bound [3–5] or resonant states [6]. In order for these states to be observed experimentally they need to have reasonably narrow widths. The widths depend sensitively on the binding energies of these states and on the details of the interactions, such as the strength and the range of antiproton annihilation in the nucleus. Theoretical calculations show that the width can vary from several hundred MeV for deeply bound states [4, 5] to several MeV for weakly bound [3] quasi–nuclear or unbound resonant states [6].

It might be interesting to compare these hypothesized $\bar{p}$-nucleus nuclear states with the Σ-hypernuclear states [7]. Both $\bar{p}$ and Σ are unstable in a nucleus because of strong-interaction processes, namely antiproton annihilation and $\Sigma + N \rightarrow \Lambda + N$. The discovery of Σ-hypernuclear states with widths of $\sim$5 MeV suggests that current theoretical understanding of the widths of such unstable states is not complete. It remains largely an experimental task to search for evidence of $\bar{p}$-nucleus states. A similar situation also exists in the experimental search for $\bar{N}N$ baryonium states.

To search for $\bar{p}$-nucleus states, we have measured the ($\bar{p}$, p) reaction. Some of the detected protons could come from the A($\bar{p}$, p) $_{\bar{p}}$(A − 1) reaction, where the incident antiproton transfers its momentum to the knocked-out proton and gets trapped in a possible $\bar{p}$-nucleus state. Evidence of $\bar{p}$-nucleus states could then show up as peaks in the energy spectrum of the detected protons. Both bound and resonant states could be reached in this reaction. A 612 MeV/c (180 MeV) antiproton beam from LEAR was used to bombard, ^{12}C, ^{63}Cu, ^{209}Bi, and scintillator targets. This momentum is close to that (500 MeV/c) where the cross section for backward $\bar{p}p$ elastic scattering is maximum [8]. The beam intensity averaged 4×10^4/s. The target thickness varied from 1 g/cm^2 to 2 g/cm^2. The ^{63}Cu and ^{209}Bi targets are of interest because both nuclei have a single proton outside a closed proton shell, and it was hoped that when this proton is "replaced" by an antiproton, this antiproton might survive for a relatively long time before eventually annihilating with the tightly bound nuclear core. A high resolution, large-acceptance spectrometer (SPES II) was used for proton detection. The measured momentum and time of flight provide clear identification of protons. Most measurements were made at 0°, because the angular distributions are likely to be forward peaked if the angular momentum transfer is small. For 0° measurements, the antiproton beam entered the spectrometer and the background caused by annihilation products was efficiently rejected by a large scintillator placed in the beam path.

Figure 1 shows the A($\bar{p}$, p)X spectra measured from scintillator and graphite targets. The error bars are statistical. The spectra are plotted as a function of the proton energy. Also indicated (upper scale) is the difference between the target mass and the mass of the reaction products.

The narrow peak observed in Fig. 1a near 180 MeV comes from the 180° $\bar{p}p$ elastic scattering. The sharpness of this peak reflects the good energy resolution ($\sim$1 MeV) in the present experiment. The c.m. cross-section of this reaction is measured to be 0.67 ± 0.10 mb/sr, in good agreement with a previous experiment [8]. In addition to this peak, the proton spectrum exhibits an exponential-like shape falling with increasing proton energy. This is more clearly seen in Fig. 1b, which is a combination of three separate measurements covering different momentum bites with a graphite target. A very similar spectrum is observed for the measurement of ^{12}C at 40°, as shown in Fig. 2. The ($\bar{p}$, p) spectra measured from ^{63}Cu and ^{209}Bi at 0° are also shown in Fig. 2. Although the shape of these spectra is very similar to that of ^{12}C, the cross-sections are significantly larger.

The spectra of Figs. 1 and 2 offer no clear evidence of any peak which could be attributed to a $\bar{p}$-nucleus state. Although a direct comparison cannot be made with the calculation of Heiselberg et al. [4], their prediction of a peak cross-section of 0.3 mb/sr × MeV for ^{16}O ($\bar{p}$, p)$_{\bar{p}}$ ^{15}N at $E_{\bar{p}} \sim$ 100 MeV appears to be too large and is not supported by the present measurement.

It is evident that other processes contribute to the ($\bar{p}$, p) cross-sections. One of them is the quasi-free p($\bar{p}$, p)$\bar{p}$ reaction with protons of the target nucleus. We calculated the cross-section of this process semiclassically for the $p_{3/2}$ proton shell of ^{12}C assuming that ^{11}B recoils with momentum opposite to the Fermi momentum of the proton before collision. The shape of the momentum distribution of the proton was taken to be a uniform sphere of k_F = 220 MeV/c [9] and the effective number of $p_{3/2}$ shell protons contributing to the quasi-free process was estimated by Bouyssy [10] to be 0.5. The calculated cross-section, as shown by the dotted curve in Fig. 1b, is much smaller than the observed cross-section. It is therefore evident that the ($\bar{p}$, p) spectra are dominated by processes other than the quasi-free reaction.

The dominant process responsible for the ($\bar{p}$, p) spectra is probably proton emission following antiproton annihilation in the target. At this beam energy, an average of 5 pions are produced in $\bar{p}$ N annihilation. These relatively energetic pions could then undergo final-state interactions, such as $\pi + N \rightarrow \pi + N$, $\pi + N \rightarrow \Delta \rightarrow \pi + N$, $\Delta + N \rightarrow N + N$, causing energetic protons to be emitted.

Energy spectra of protons and pions emitted after antiproton annihilation in a nucleus have been calculated by several groups [11–13], using an intranuclear cascade (INC) model. In particlar, Clover et al. [11] have made the calculation for $\bar{p}$ + ^{12}C annihilation at 600 MeV/c. Their result, plotted as the dashed curve in Fig. 1b, is in good agreement with the data in the overall magnitude. However, the predicted slope is somewhat steeper than that of the data. The proton spectra could be described by a Maxwellian distribution, $d^2\sigma/d\Omega dE = C\sqrt{E}\exp(-E/T)$, where T is associated with an "effective temperature". The values of C and T which fit the data are shown in Table 1 for various spectra. Depending on the target mass, T varies between 69 MeV and 86 MeV. This is to be compared with the "effective temperature" of 62 MeV deduced from ref. 11 for $\bar{p}$ + ^{12}C, and 65 MeV predicted [12] for $\bar{p}$ + ^{40}Ca. The nearly isotropic angular dependence in the ^{12}C($\bar{p}$, p) reaction is consistent with the cascade calculation. From the measured ($\bar{p}$, p) cross-section for ^{12}C, ^{63}Cu, and ^{209}Bi at 180 MeV proton energy we deduce a mass dependence $A^{0.63}$, in good agreement with the $A^{0.67}$ dependence we deduce from ref. 11.

In conclusion, we have reported the results of the first ($\bar{p}$, p) experiment intended to search for $\bar{p}$-nucleus states. No evidence of such states has been observed in the present experiment. Further measurements with improved statistics are needed to provide more sensitive limits on the cross-sections of such states. The gross features in the ($\bar{p}$, p) spectra can be explained by INC calculations. Protons emitted after antiproton annihilation are a major source of "background", which complicates the task of finding $\bar{p}$-nucleus states. These background protons would be less abundant if lighter target nuclei such as ^{3}He and ^{6}Li were used, because of the A dependence of the emission cross-section. Other reactions such as $A(\bar{p}, \Lambda)_{\bar{\Lambda}}(A-1)$ could also be contemplated [14] since the cascade background would be absent. Unfortunately the cross-section of the $p(\bar{p}, \Lambda)\bar{\Lambda}$ reaction is small. Finally, one could also consider detecting $\bar{p}$-nucleus resonant states [6] by measuring excitation functions of the $(\bar{p}, \bar{p})$ or $(\bar{p}, \bar{p}')$ reactions. Further experimental efforts are definitely required in order to search for $\bar{p}$-nucleus states.

REFERENCES

[1] D. Garreta et al., Phys. Lett. **135B** (1984) 266.

[2] P. Roberson et al., Phys. Rev. **C 16** (1977) 1945;
H. Poth et al., Nucl. Phys. **A294** (1978) 435.

[3] A.M. Green and S. Wycech, Nucl. Phys. **A377** (1982) 441.

[4] H. Heiselberg, A.S. Jensen, A. Miranda and G.C. Oades, Phys. Lett. **132B** (1983) 279.

[5] C.Y. Wong, A.K. Kerman, G.R. Satchler and A.D. Mackellar, Phys. Rev. **C 29** (1984) 441.

[6] E.H. Auerbach, C.B. Dover and S.H. Kahana, Phys. Rev. Lett. **46** (1981) 702.

[7] Proc. Int. Conf. on Hypernuclear and Kaon Physics, Heidelberg, Germany 1982 (Max-Planck-Institut Für Kernphysik, Heidelberg, 1982);
R. Bertini et al., Phys. Lett. **136B** (1984) 29.

[8] M. Alston–Garrjost et al., Phys. Rev. Lett. **43** (1979) 1901.

[9] E.J. Moniz et al., Phys. Rev. Lett. **26** (1971) 445.

[10] A. Bouyssy, private communication.

[11] M.R. Clover, R.M. DeVries, N.J. DiGiacomo and Y. Yariv, Phys. Rev. **C 26** (1982) 2138.

[12] M. Cahay, J. Cugnon, and J. Vandermeulen, Nucl. Phys. **A393** (1983) 237;
M. Cahay, J. Cugnon, P. Jasselette and J. Vandermeulen, Phys. Lett. **115B** (1982) 7.

[13] A.S. Iljinov, V.I. Nazaruk and S.E. Chigrinov, Nucl. Phys. **A382** (1982) 378.

[14] J.C. Peng, Proc. Third LAMPF II Workshop, Los Almos, July 1983, Report LA–9933–C, p. 531;
C.B. Dover, in Proc. 10th Inte. Conf. on Few Body Problems in Physics, Karlsruhe, 1983 (North Holland, Amsterdam, 1984), vol. 1.

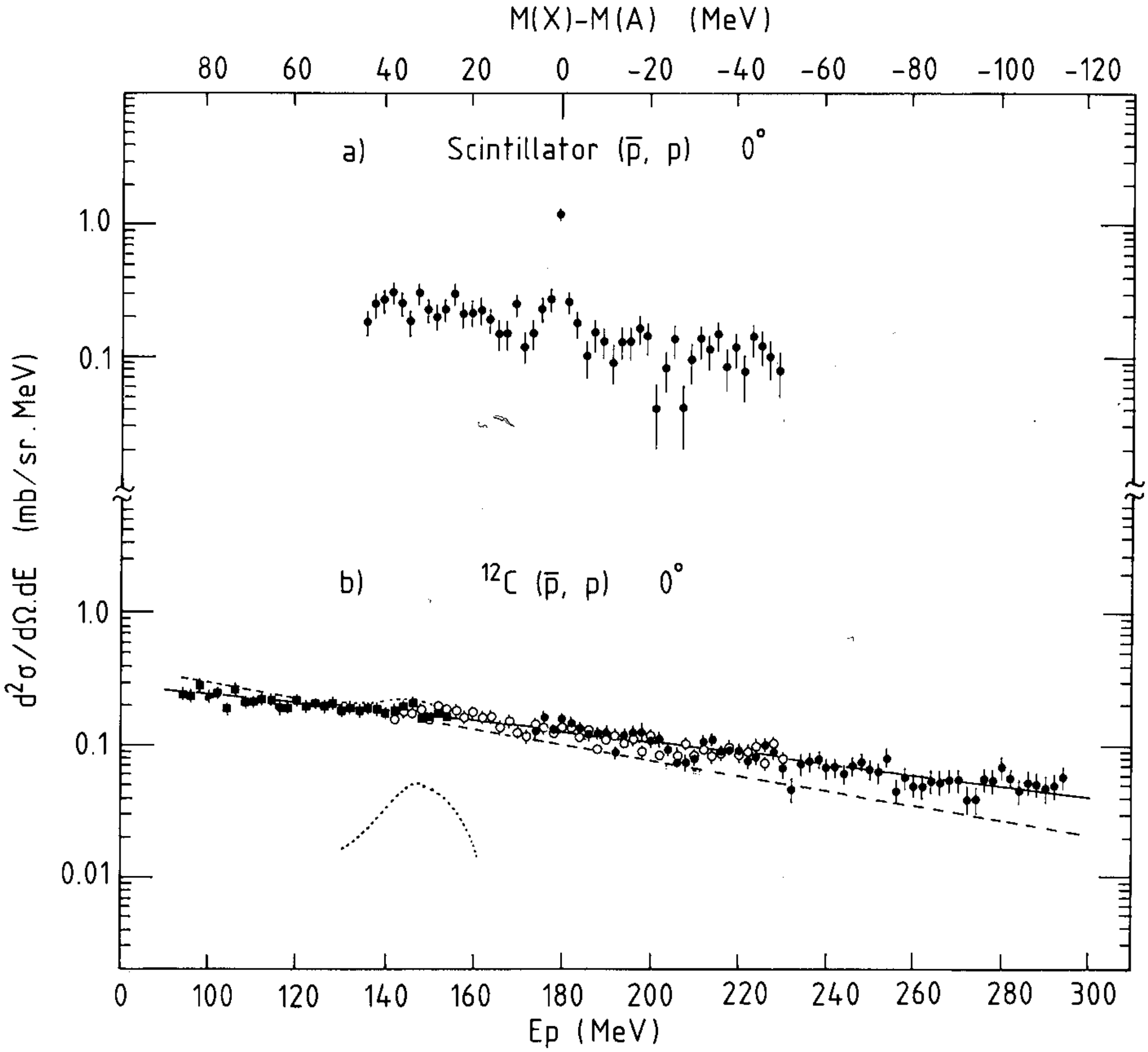
Table 1
Parameters resulting from the best fits to the proton spectra with the expression
$d^2\sigma/d\Omega dE = C\sqrt{E}\exp(-E/T)$

Target	θ_{lab} (degrees)	T (MeV)	C (μb/sr · MeV$^{3/2}$)
^{12}C	0	86 ± 1.5	80
^{12}C	40	77 ± 6	75
^{63}Cu	0	69 ± 10	405
^{209}Bi	0	69 ± 7	770

Figure captions

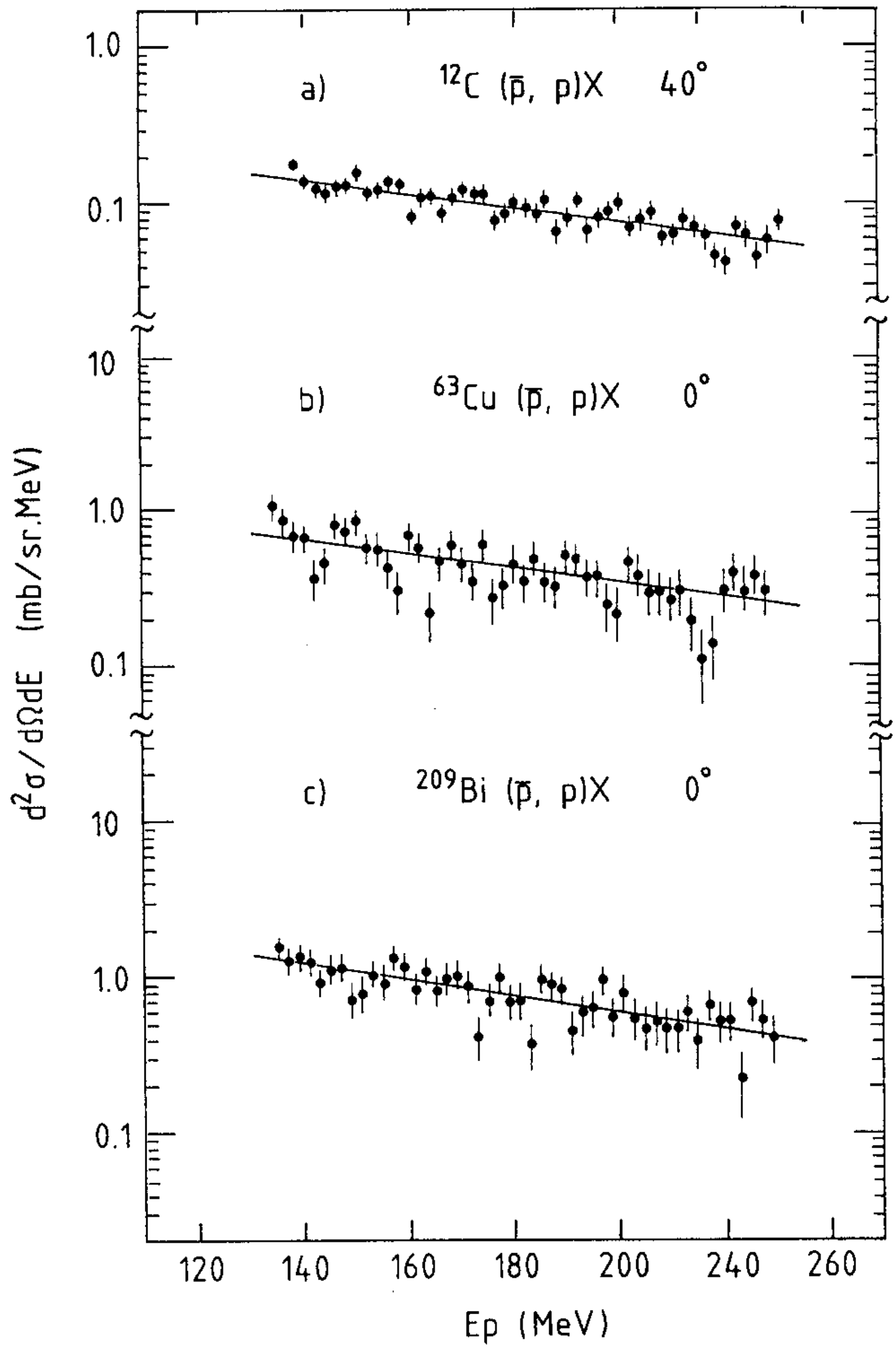
Fig. 1 : Proton spectra for the A($\bar{p}$, p)X reaction at $T_{\bar{p}}$ = 180 MeV and 0° for scintillator (a) and carbon (b) targets. The double differential cross-section is plotted versus the proton kinetic energy and the mass difference [M(X) − M(A)]. The sharp peak near 180 MeV in (a) corresponds to elastic scattering from hydrogen. Also shown are an INC calculation (dashed line) and a Maxwellian distribution best fit (solid line). A calculation for the quasi-free cross-section is indicated by the dotted curves.

Fig. 2 : The ($\bar{p}$, p) spectra from ^{12}C at 40°, and from ^{63}Cu and ^{209}Bi at 0°. The solid curves are best fits assuming a Maxwellian distribution.



M(X)-M(A) (MeV)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
a) Scintillator ($\bar{p}$, p) 0°
1.0
0.1
$d^2\sigma/d\Omega.dE$ (mb/sr. MeV)
b) ^{12}C ($\bar{p}$, p) 0°
1.0
0.1
0.01
0
100
120
140
160
180
200
220
240
260
280
300
Ep (MeV)

Fig. 1



a) ^{12}C ($\bar{p}$, p)X 40°
b) ^{63}Cu ($\bar{p}$, p)X 0°
c) ^{209}Bi ($\bar{p}$, p)X 0°
$d^2\sigma/d\Omega dE$ (mb/sr.MeV)
1.0
0.1
10
120
140
160
180
200
240
260
Ep (MeV)

Fig. 2