Evidence for a Neutron Halo in Heavy Nuclei from Antiproton Absorption*

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From a study of stopping antiprotons in a variety of elements located in a hydrogen bubble chamber, we find evidence for the existence of a neutron fringe in heavy nuclei.

Since the observation in 1954 by Johnson and Teller[1] that the periphery of heavy β-stable nuclei should be rich in neutrons, considerable interest has attached to the experimental verification of this idea. The most recent experimental results,[2] utilizing high-energy scattering, indicate near equality for the neutron and proton radii in the heavy nuclei. The strongest evidence supporting the existence of a neutron halo has been presented by Davis *et al.*[3] from a study of K^- absorptions in nuclear emulsion. This experiment compared rates of neutron and proton absorptions of stopping K^- mesons in the heavy and light nuclei of nuclear emulsion. They observed that K^- capture by a neutron in (Ag, Br) was $5.0^{+1.2}_{-0.8}$ times as likely as was K^- absorption by a neutron in (C, N, O). A subsequent analysis of these data by Burhop[4] has reduced this number to 4.25 ± 1.0. Since the nuclear absorption of slow, heavy, strongly interacting particles is expected to occur from atomic states of large angular momentum ($l \sim 6\hbar$ in Ag), this implies that the capture occurs in the nuclear surface where the nucleon density is $\lesssim 20\%$ of its central density.[5] The obvious conclusion, therefore, is that a considerable neutron halo exists in heavy nuclei; however, a precise analysis of the extent of this halo is difficult[4] because of the Σ conversion process and the presence of the $Y_0^*(1405)$, which can drastically alter the relative K^-p and K^-n absorption amplitudes. In the present paper we will report on an experiment utilizing $\bar{p}$ absorptions which confirms the existence of a neutron halo in heavy nuclei.

The data were obtained from an exposure of the Brookhaven National Laboratory 30-in. hydrogen bubble chamber to a beam of slow antiprotons. The chamber contained four rectangular plates of carbon, titanium, tantalum, and lead which were mounted so that the optic axis of two of the stereo cameras was approximately parallel to the faces of the plates. The thicknesses of the plates were C, 0.85; Ti, 0.56; Ta, 0.22; and Pb, 0.35 cm. These were selected so that about 25% of the low-momentum $\bar{p}$ beam would stop in the plates. The physics of the experiment derives from the fact that $\bar{p}p$ and $\bar{p}n$ annihilations produce events with a net charge of 0 and -1, respectively. It is presumed that the nuclear capture process, as in the K^- case, occurs in the nuclear periphery.[6]

A summary of our data is presented in Table I in which we give the numbers of events with the observed net charges in the mesonic prongs. Strict scanning criteria were imposed to exclude from our sample all events for which the exact origin of each mesonic prong could not be determined. This is clearly desirable since the annihilation star was not visible when it occurred in one of the plates. The data in Table I have not been corrected for hydrogen events which occurred in the obscured regions about the plates and which were indistinguishable from events occurring in the plates. This hydrogen contamination amounts to 12.3% for C, 9.1% for Ti, 13.3% for Ta, and 11.7% for Pb. Thus, for example, for each 1000 events which appear to stop in

TABLE I. Net observed charge distribution of $\bar{p}$ annihilations after geometric correction.

Bosonic charge	C	Ti	T	Pb
+3	10	6	5	1
+2	141	54	75	45
+1	1166	391	400	265
0	3491	927	940	767
−1	2246	784	856	659
−2	512	209	236	215
−3	43	23	33	30
−4	2	2	0	0

TABLE II. Observed $\bar{p}$ annihilation data and corrections.

Element	Total events including hydrogen	Hydrogen events	Total number of observed π^+	Total number of observed π^-	$N(\pi^+)$ after absorption, charge-exchange, geometry corrections	$N(\pi^-)$ after absorption, charge-exchange, geometry corrections	$N(\pi^+)$ after H exclusion	$N(\pi^-)$ after H exclusion
C	7611	936	8547	10 467	9599	11 901	8148	10 450
Ti	2396	218	2419	3181	2711	3592	2373	3254
Ta	2545	338	2455	3317	2744	3750	2220	3226
Pb	1982	232	1805	2626	2019	2966	1654	2606

tantalum, 133 are in actuality hydrogen captures occurring in darkened regions about the plates.

Although few antiproton annihilation experiments in media other than hydrogen or deuterium have been reported, it is clear from the early experiment of Agnew *et al.*[7] that secondary interactions of the annihilation products are an important facet of any annihilation experiment in nuclear matter. The data in Table I also support this conclusion. Rather than attempt to predict the charge distributions in Table I from a theoretical model, we resort to a purely empirical interpretation which is outlined in Tables II–IV. This analysis relies on the fact that each neutron annihilation will produce a mesonic system with a net charge of -1. Thus, to determine the number of neutron annihilations in any particular plate, we must find the total excess of negative charge in the mesonic prongs.

Corrections must be applied for pion absorption in the target material (excluding the parent nucleus), for π^- charge exchange in the hydrogen immediately surrounding the plates which is occluded from view, and for our geometric limitations. The pion loss associated with target absorption, estimated from the calculations of Sternheim and Auerbach[8] and from the data of Miller,[9] suggests that ~45% of the pion absorption cross section represents the disappearance of the charged pion. The percentages of pions lost due to these effects are 1.06%, 0.84%, 0.64%, and 0.64%, respectively, for C, Ti, Ta, and Pb. The negative-pion loss resulting from charge exchange in the invisible hydrogen region is estimated using an average $\pi^-p \to \pi^0 n$ cross section[10] of 30 mb. This amounts to losses of 1.15%, 0.77%, 1.10%, and 0.98% for C, Ti, Ta, and Pb, respectively. For our experimental arrangement, we estimate a geometric correction of about 10%. Since all of these corrections apply to each target material, our final results are virtually independent of the precise values of the parameters used to effect these corrections. In Table II we summarize our observations and the results after these corrections.

Next, the hydrogen interactions which are indistinguishable from those occurring in the plates must be removed. The number of these hydrogen events is equal to the spatial rate of $\bar{p}$ stoppings multiplied by the length of hydrogen which is not visible about each plate. Since the corrections in the preceding paragraph have already been made, each $\bar{p}p$ interaction should produce[11] on the average 1.55 π^+ and 1.55 π^-. The results of this subtraction are shown in the final columns of Table II.

Table III illustrates our calculation of the charged-pion reabsorption probability in the par-

TABLE III. Deduction of charged-pion reabsorption probabilities in parent nuclei.

Element	Events in element	$N(\pi^-)+N(\pi^+)$	Charged-pion multiplicity	Charged-pion reabsorption probability
C	6675	18 598	2.79	0.110 ± 0.01
Ti	2178	5627	2.58	0.174 ± 0.01
Ta	2207	5446	2.47	0.211 ± 0.012
Pb	1750	4265	2.44	0.221 ± 0.014

TABLE IV. "Halo factor" analysis.

Element	$N(\pi^-) - N(\pi^+)$	$N(\bar{p}n)$	$N(\bar{p}p)$	$\frac{N(\bar{p}n)}{N(\bar{p}p)}$	$\left.\frac{N(\bar{p}n)}{N(\bar{p}p)}\right\|_c$	$\frac{N}{Z}$	Halo factor
C	2302	2586	4089	0.632	1.00	1.00	1.00
Ti	881	1067	1111	0.960	1.52	1.18	1.29 ± 0.21
Ta	1006	1276	931	1.371	2.17	1.48	1.46 ± 0.24
Pb	947	1216	534	2.270	3.59	1.54	2.34 ± 0.50

ent nucleus. The charged-pion multiplicity[11] for $\bar{p}$ interactions in deuterium is 3.13. If it is assumed that this same multiplicity obtains for all complex nuclei at the instant of the annihilation, prior to any secondary interactions in the parent nucleus, the last column shows our results for the charged-pion reabsorption probabilities in our elements. These range from 11% for carbon to 22% for lead and are quite consistent with the $18 \pm 2\%$ that has been reported by Ekspong[12] from a nuclear emulsion experiment. In emulsion,[13] ~63% of the $\bar{p}$'s suffer heavy-nucleus (AgBr) capture while the remaining 37% are captured by C, N, O. Assuming 11% for the light-nucleus captures and 19% for AgBr, our absorption data indicate an emulsion rate of ~16%.

Since each $\bar{p}n$ interaction will yield a single excess negative pion, the quantity of major interest is the π^- excess $N(\pi^-) - N(\pi^+)$ prior to secondary interactions in the parent nucleus. To determine this, we again assume that the true multiplicity at the annihilation has its deuterium value of 3.13. The number of $\bar{p}n$ annihilations is then the π^- excess times the ratio of 3.13 to the observed multiplicity. The numbers of neutron and proton captures so deduced form the entries in columns 1 and 2 of Table IV. Columns 4, 5, and 7 of Table IV list the ratio $\bar{p}n/\bar{p}p$ for each element, $\bar{p}n/\bar{p}p$ normalized to the carbon result, and the "halo factor" which we define as the normalized $\bar{p}n/\bar{p}p$ ratio divided by N/Z for each element.

The most striking feature of Table IV is that the neutron-to-proton annihilation ratio for the various elements, normalized to the carbon data, always exceeds the ratio of neutrons to protons in the capturing nucleus. Thus, an antiproton is 3.5 times as likely to be absorbed by neutrons in lead as it is in carbon. One would expect this ratio to be 1.54 merely because of the neutron excess of heavy nuclei. Over and above this expected neutron enhancement, neutron captures are 2.34 times as likely as proton captures in Pb. The corresponding enhancements in Ti and Ta are 1.29 and 1.46, respectively. It is seen that tantalum appears to be more similar to titanium than to lead even though it is much nearer to lead in the periodic table. While this must remain a mystery, it is interesting to observe that nearby elements exhibit anomalous behavior in the K^--mesonic x-ray studies of Weigand and Kunselman.[14] In these x-ray experiments, the x-ray intensities observed near the termination of the atomic cascade are far less for elements similar to Ta than for those observed for most other heavy elements. It is also possible that the large quadrupole moment of Ta could affect either the atomic cascade or the subsequent nuclear annihilation process. Wilkinson[15] has pointed out that nuclei of large eccentricity, e.g., Ta, can, through the $\bar{p}$-nucleus potential, mix the orbital states of the $\bar{p}$, which can subsequently induce capture in the nuclear interior.

Our conclusion is that for nuclei with a neutron excess, the neutron-to-proton ratio in the nuclear periphery is enhanced to a value greater than expected from N/Z. On the basis of the available evidence, it would appear that the conclusion voiced by several authors[16,17] is valid: namely, that while the mean square radii of neutrons and protons in heavier nuclei are quite similar, there nevertheless exists in their tenuous outer reaches an ethereal neutron halo. It should, perhaps, be emphasized that these results are contingent on the relative $\bar{p}n$ and $\bar{p}p$ annihilation amplitudes being constant for all of our elements. If this should not be the case, it would be incumbent to reanalyze our data.

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Comparison of Nuclear and Coulomb Measurements of Nuclear Shapes*

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A calculation is described which contains hitherto neglected terms in the extraction of nuclear shapes from scattering data. These corrections are used in the comparison of deformations determined by measurements of distributions of nuclear potential with those of charge distributions, and serve to reduce the apparent discrepancies between those two types of measurements.

It has been well established that permanently deformed nuclei often have shapes that are more complicated than simple spheroidal deformations. These shapes were first accurately measured in the nuclear potential by scattering of α particles with energies well above the Coulomb barrier and for the rare-earth nuclei.[1] A systematic trend of hexadecapole deformation was discovered. Since then these basic results have been confirmed by a number of other experiments using other projectiles and energies,[2-8] have been extended to other regions of the periodic table,[9,10] and have been described by several theoretical treatments.[11,12] The experiments can be classified into two major categories, those that measure the shape of the nuclear potential[1-3,8,9] and those that measure the charge deformation.[4-8,10]

A simple and usual way of characterizing these deformations is to describe an appropriate nuclear radius in a multipole expansion

$$R = R_0(1 + \beta_2 Y_{20} + \beta_4 Y_{40} + \beta_6 Y_{60} + \cdots), \tag{1}$$

where the Y_{L0} are spherical harmonics and the β_L are the experimentally determined deformation parameters. The experiments all measure transition probabilities between states of the rotational band built on the ground state, since these probabilities are sensitively predicted by the nuclear shape in the rotational model. Complicated avenues of excitation are included by means of the coupled-channels calculations for nuclear excitation[13] and the Winter–de Boer code[14] for Coulomb excitation. Deviations from and additions to the simple rotational model can also be included, if found to be necessary.

A puzzling discrepancy has become apparent between the nuclear and Coulomb experimental results, in that the Coulomb work systematically