PROTON DECAY OF THE ISOBARIC ANALOG OF THE GROUND STATE OF ^{208}Pb POPULATED BY THE (p,n) REACTION*

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The relative widths for the proton ($\tilde{p}$) decay of the isobaric analog of the ^{208}Pb ground state have been remeasured with significantly improved accuracy using the charge-exchange reaction ^{208}Pb(p,n) rather than ^{207}Pb(p,p) and (p,p') excitation functions to populate the isobaric analog level. For the first time the sequential process $(p,n\tilde{p})$ has been observed both with a heavy $(A\sim200)$ target nucleus and also with a target nucleus which is even-even rather than even-odd. The total cross section for the isobaric-analog-state reaction ^{208}Pb$(p,n)^{208}$Bi has also been measured for the range of proton bombarding energies between 25.2 and 47.3 MeV.

The charge-exchange reaction

$${}_{Z}^{A}X_{N}(p,n)\,{}_{Z+1}^{A}X_{N-1}$$

strongly populates the isobaric analog of the ground state of the target nucleus.[1,2] In intermediate and heavy nuclei, the isobaric analog level, ${}_{Z+1}^{A}X_{N-1}(\mathrm{IAS})_{\mathrm{g.s.}}$, can decay predominantly by proton ($\tilde{p}$) emission to the low-lying levels of ${}^{A-1}_{Z}X_{N-1}$; that is

$${}_{Z+1}^{A}X_{N-1}(\mathrm{IAS})_{\mathrm{g.s.}}\to\tilde{p}+{}_{Z}^{A-1}X_{N-1}.$$

The two-step reaction $(p,n\tilde{p})$ was first reported by Yavin et al.[3] in the reaction ^{91}Zr$(p,n\tilde{p})^{90}$Zr. Subsequent work has been reported on the $(p,n\tilde{p})$ reaction in the odd Sn isotopes.[4] However, no work has so far been reported for the $(p,n\tilde{p})$ reaction on target nuclei as heavy as Pb or for cases where the target nucleus is even Z, even N. For all the even-odd targets which have been studied previously in $(p,n\tilde{p})$ experiments, the $\tilde{p}$ decay proceeds almost entirely to the 0^+ ground state of the even-even residual nucleus.[3,4] However, for even-even targets such as ^{208}Pb, the $\tilde{p}$ decay of the isobaric analog state (IAS) may proceed to the low-spin, low-lying excited levels as well as to the ground state of the even-odd residual nucleus, thus making it possible to measure the relative proton decay widths to excited levels. The (d,n) reaction is another direct reaction which can excite isobaric analog levels that subsequently decay by proton emission. In contrast to the direct (p,n) reaction which excites only one isobaric analog level strongly, the (d,n) reaction can excite many isobaric analog levels.

Cue and Richard[5] have published extensive data on the $(d,n\tilde{p})$ sequential process for targets with $A\sim100$. However, for the neutron-rich nuclei around ^{208}Pb $(N-Z=44=2T_0)$, the direct (d,n) cross section for exciting the isobaric analog levels is decreased by a factor $1/(2T_0+1)$, and Cue and Richard were unable to find $\tilde{p}$'s from the reaction ^{206}Pb$(d,n\tilde{p})$. The $(\mathrm{IAS})_{\mathrm{g.s.}}$ may also be studied by measuring the excitation functions for $p+{}^{A-1}_{Z}X_{N-1}$ at energies in the vicinity of the $(\mathrm{IAS})_{\mathrm{g.s.}}$. Recent measurements of ^{207}Pb(p,p) and ^{207}Pb(p,p') excitation functions have yielded values for the proton partial decay widths of the isobaric analog of the ground state of ^{208}Pb.[6,7] One of the main purposes of the present work is to compare the relative proton partial widths extracted from the ^{208}Pb$(p,n\tilde{p})$ data with those extracted from the $p+{}^{207}$Pb data.[6,7] In the two-step $(p,n\tilde{p})$ process the yield of $\tilde{p}$'s associated with a given level in ${}^{A-1}_{Z}X_{N-1}$ will be the product of two terms: the total cross section $[\sigma_t(p,n)]_{\mathrm{IAS}}$ for the excitation of the $(\mathrm{IAS})_{\mathrm{g.s.}}$ in the (p,n) reaction, and the ratio $\Gamma_{\tilde{p}_i}/\Gamma$, where $\Gamma_{\tilde{p}_i}$ is the proton partial width for decay to the state i, and Γ is the total width of the $(\mathrm{IAS})_{\mathrm{g.s.}}$; specifically,

$$\mathrm{Yield}(\tilde{p}_i)\propto[\sigma_t(p,n)]_{\mathrm{IAS}}\Gamma_{\tilde{p}_i}/\Gamma \tag{1}$$

and

$$\frac{\mathrm{Yield}(\tilde{p}_i)}{\mathrm{Yield}(\tilde{p}_j)}=\frac{\Gamma_{\tilde{p}_i}}{\Gamma_{\tilde{p}_j}}. \tag{2}$$

In the work reported here we have excited the isobaric analog in ^{208}Bi of the ground state of the even-even 0^+ target nucleus ^{208}Pb by the reaction

^{208}Pb(p,n), and measured the relative proton partial widths for the decay of this isobaric analog level to the low-lying neutron hole levels of ^{207}Pb. Since the J^{π} of the IAS is 0^+, $\Gamma_{\tilde{p}_i} = \Gamma_{lj}$, where l and j are the quantum numbers of the neutron hole state i in ^{207}Pb.

The reaction ^{208}Pb($p, n\tilde{p}$)^{207}Pb was studied with proton beams from the University of California, Los Angeles, sector-focused cyclotron. A counter telescope of three solid-state detectors (ΔE, E, veto) was used to identify protons in the energy range from approximately 7 to 17 MeV. The energy available for decay from the isobaric analog level in ^{208}Bi to the ground state of ^{207}Pb is 11.44 MeV. The counter telescope subtended a solid angle of 9.2 msr and was placed at a laboratory angle of 140° for most of the measurements. A 10.3-mg/cm^2, enriched (99.3%), ^{208}Pb target was mounted normal to the counter telescope direction for the 140° measurements. In addition to protons, deuterons and tritons were identified by the particle telescope, and peaks in the (p,d) and (p,t) spectra were used to check the energy calibration of the incident proton beam. Figures 1(a) and 1(b) present the proton energy spectra in the vicinity of 11 MeV obtained for proton bombarding energies of 25.2 and 47.3 MeV, respectively. The $\tilde{p}$ groups corresponding to the population of the $\frac{1}{2}^-$ ($3p_{1/2}^{-1}$) ground state in ^{207}Pb and the $\frac{3}{2}^-$ ($3p_{3/2}^{-1}$) level at an excitation energy of 890 keV are clearly evident in the spectra. The ratio of $\tilde{p}$ events from the ^{208}Bi isobaric analog level to the background events from ($p,p'x$) reactions is about one to one. The $\tilde{p}$ group corresponding to the population of the $\frac{5}{2}^-$ ($2f_{5/2}^{-1}$) level at 570 keV is less evident in these spectra. In order to demonstrate that these peaks were associated with the ^{208}Bi isobaric analog level produced in the (p, n) reaction, the proton bombarding energy was increased in approximately 2-MeV steps from 25.2 to 47.3 MeV, and the resulting 12 spectra taken at 140° were added channel by channel to obtain the spectrum shown in Fig. 1(c). The positions of the peaks assigned as $\tilde{p}$ groups remain constant as the bombarding energy is varied by a factor of 2. Therefore, these peaks are clearly associated with the decay of the isobaric analog level. The $\tilde{p}$ group associated with the $\frac{5}{2}^-$ ($2f_{5/2}^{-1}$) 570-keV level in ^{207}Pb is more clearly evident in the summed data due to the higher statistical accuracy. A small number of counts above background are found near 8.9 MeV in Fig. 1(c). This is the position for the $\tilde{p}$ group populating the 2.33-MeV $\frac{7}{2}^-$ ($2f_{7/2}^{-1}$) level in ^{207}Pb. The yield in this region gives an upper limit for the population of the $2f_{7/2}^{-1}$ level. To demonstrate further that the proton peaks were associated with the decay of the ^{208}Bi isobaric analog level, angular distributions were measured for laboratory angles between 90 and 140°. Since the isobaric analog of the ground state of ^{208}Pb is a 0^+ state, the $\tilde{p}$ angular distributions must be isotropic. Figure 2 shows that the angular distributions are isotropic between 90 and 140° at two bombarding energies. At angles less than 90°, the rate of $\tilde{p}$ events is considerably less than the rate of background protons from the

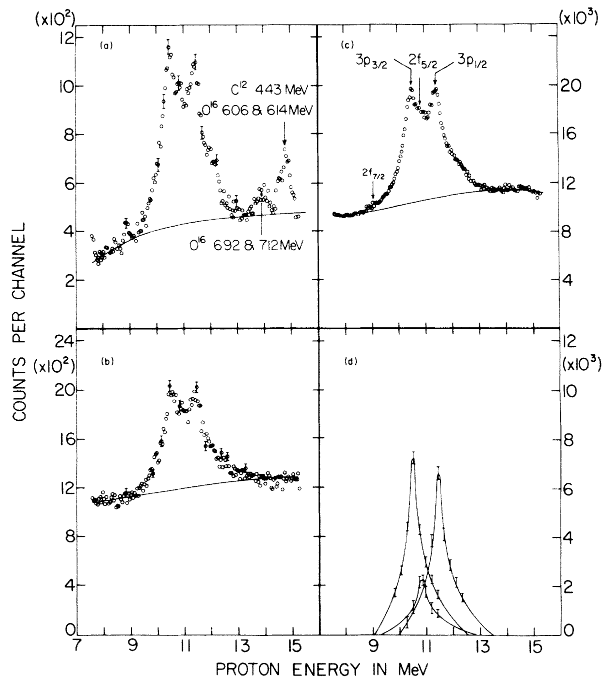

FIG. 1. (a) The energy spectrum of protons near 11 MeV obtained at a laboratory scattering angle of 140° when a ^{208}Pb target is bombarded by 25.2-MeV protons. The peaks denoted by arrows arise from inelastic scattering events from carbon and oxygen. The small peak at about 8.9 MeV is possibly due to the (IAS)$_{0+}$ decay to the $2f_{7/2}^{-1}$ (2339-keV) level in ^{207}Pb. (b) The energy spectrum of protons near 11 MeV obtained at 140° when the proton bombarding energy is 47.3 MeV. Note the absence of discernable peaks due to scattering from impurities. Spectra obtained at ten other energies between 28.0 and 45.7 MeV also are free from contaminant peaks. (c) The summed-energy spectrum of protons near 11 MeV obtained at 140°. The sum included measurements at 12 energies between 25.2 and 47.3 MeV. The expected positions of the $3p_{1/2}^{-1}$(g.s.), $2f_{5/2}^{-1}$ (570-keV), $3p_{3/2}^{-1}$ (897-keV), and $2f_{7/2}^{-1}$ (2339-keV) levels are denoted by arrows. (d) Individual peaks obtained by unfolding the summed-energy spectrum of (c).

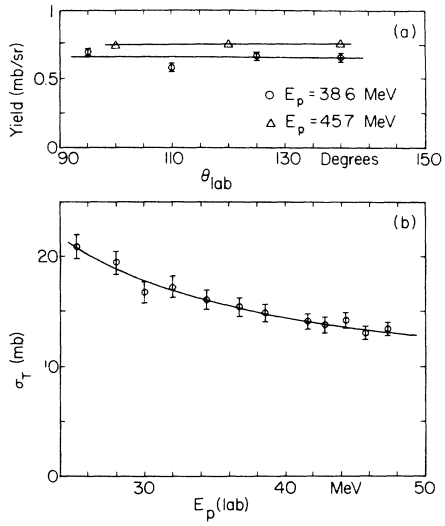

FIG. 2. (a) The yield for proton decay to the ground, 570-keV, and 897-keV states of ^{207}Pb versus the laboratory scattering angle at 38.6 and 45.7 MeV. (b) The total cross section $[\sigma_t(p,n)]_{\rm IAS}$ between 25.2 and 47.3 MeV.

forward-peaked reactions ^{208}Pb$(p,p'x)$. Accurate data at forward angles would demand very long running times in order to obtain the statistical accuracy necessary to unfold the $\tilde{p}$ peaks from a large background. From an analysis of the Fig. 1(c) spectrum and use of formula (2) we obtained relative proton partial widths for the decay of the IAS to the $3p_{1/2}^{-1}$, $2f_{5/2}^{-1}$, and $3p_{3/2}^{-1}$ levels of ^{207}Pb, and an upper limit for the transition to the $2f_{7/2}^{-1}$ level. The spectrum of peaks resulting from this analysis is presented in Fig. 1(d).

Table I presents the relative proton partial widths obtained in our ^{208}Pb$(p,n\tilde{p})$ experiments and compares them both with theoretical calculations[8] and with the values obtained in ^{207}Pb(p,p) and (p,p') excitation functions.[6,7] In the analysis of the $p+{}^{207}$Pb excitation function data the ratio $\Gamma_{p_i}/\Gamma_{p_0}$ is given by[6]

$$\frac{\Gamma_{p_i}}{\Gamma_{p_0}} = 4k^2 \frac{\Gamma^2}{\Gamma_{p_0}^{\ 2}}\left(\frac{d\sigma}{d\Omega_{pp'}}\right)_{\rm max}, \tag{3}$$

where k is the wave number of the incident proton, $(d\sigma/d\Omega_{pp'})_{\rm max}$ is the peak inelastic cross section on resonance, and Γ_{p_0} and Γ_{p_i} are the respective proton partial decay widths to the ground state and to the ith excited state. Thus the error in determining $\Gamma_{p_i}/\Gamma_{p_0}$ is <u>at least</u> twice the error in Γ_{p_0}. Accurate values for Γ_{p_0} $(\Gamma_{3p_{1/2}})$ are difficult to obtain from ^{207}Pb(p,p) excitation-function experiments, since the ground-state resonance is at most a 10% effect, even at back angles, due to the Coulomb-barrier height.[6,7] This is a general property of $p+{}_Z^AX_{N-1}$ excitation functions at the position of the isobaric analog of ${}_Z^AX_N$, since $E_{p_0}=\Delta E_C - B_n({}_Z^AX_N)$, where ΔE_C is the Coulomb energy difference between ${}_Z^AX_N$ and ${}_{Z+1}^{\ \ A}X_{N-1}$, and $B_n({}_Z^AX_N)$ is the neutron binding energy in ${}_Z^AX_N$. Thus p_0 will <u>always</u> be far below the Coulomb-barrier height. The

Table I. Comparison of theoretical and experimental proton partial widths for the decay of the isobaric analog of the ground state of ^{208}Pb in ^{208}Bi to the ground-state $(3p_{1/2}^{-1})$, 570-keV $(2f_{5/2}^{-1})$, and 890-keV $(3p_{3/2}^{-1})$ low-lying, neutron hole levels of ^{207}Pb.

Ratio	^{208}Pb$(p,n\tilde{p})$	Theory[a]	^{207}Pb(p,p) and (p,p') b	c	Estimated error[d]
$\Gamma_{2f_{5/2}}/\Gamma_{3p_{1/2}}$	0.36 ± 0.04	0.27	0.29	0.28	(±50 %)
$\Gamma_{3p_{3/2}}/\Gamma_{3p_{1/2}}$	1.14 ± 0.07	1.22	0.67	0.82	(±50 %)
$(\Gamma_{2f_{5/2}}+\Gamma_{3p_{3/2}})/\Gamma_{3p_{1/2}}$	1.50 ± 0.08[e]	1.49	0.96	1.10	(±50 %)
$\Gamma_{2f_{5/2}}/\Gamma_{3p_{3/2}}$	0.31 ± 0.04	0.22	0.43	0.34	
$\Gamma_{2f_{7/2}}/\Gamma_{3p_{1/2}}$	≤ 0.08	0.15	···	···	

[a]Ref. 7.
[b]Ref. 7. No errors were assigned to the experimental determinations of the Γ_{lj}.
[c]Ref. 6.
[d]The estimated error for the relative proton partial widths determined in Ref. 6 was taken as twice the experimental error for $\Gamma_{3p_{1/2}}$ (61 ± 15 keV), or about 50 % (see text), with the exception of $\Gamma_{2f_{5/2}}/\Gamma_{3p_{3/2}}$ which is known to much better accuracy since the dependence on $\Gamma_{3p_{1/2}}$ cancels out (see text).
[e]The error on this ratio is small, since the summed $\tilde{p}$ yields to the 570- and 890-keV levels can be determined more accurately than their separate yields.

$p+{}^{207}$Pb excitation can determine quite accurate values for the ratio of two inelastic proton widths Γ_{p_i} and Γ_{p_j}, since the dependence on Γ_{p_0} cancels; and

$$\Gamma_{p_i}/\Gamma_{p_j}=(d\sigma_i/d\Omega_{pp'})_{\max}(d\sigma_j/d\Omega_{pp'})_{\max}{}^{-1}.$$

Formula (2) shows that the relative proton partial widths determined by $(p,n\tilde{p})$ experiments have an accuracy dependent only upon the errors assigned to the yield measurements for the various $\tilde{p}$ groups. Thus as is shown in Table I, the $(p,n\tilde{p})$ experiment is able to measure the ratios $\Gamma_{p_i}/\Gamma_{p_0}$ more accurately than $p+{}^{207}$Pb excitation functions, and this is directly attributable to the large error (~25%) in the determination of Γ_{p_0} in the excitation function experiment.

Since the yield of $\tilde{p}$'s from the 0^+ IAS is isotropic, the total cross section for the reaction ${}^{208}\mathrm{Pb}(p,n){}^{208}\mathrm{Bi(IAS)}_{0^+}$ is given by

$$[\sigma_t(p,n)]_{\mathrm{IAS}}=[d\sigma(\tilde{p})/d\Omega]4\pi\Gamma/\textstyle\sum_{lj}\Gamma_{lj}, \qquad (4)$$

where $d\sigma(\tilde{p})/d\Omega$ is the differential cross section for all the $\tilde{p}$ transitions from the isobaric analog level. To obtain absolute values for $[\sigma_t(p,n)]_{\mathrm{IAS}}$, Γ was taken to be 220 keV,[6] while the theoretical value of 60.5 keV[8] was assumed for $\Gamma_{3p_{1/2}}$. (Andersen, Bondorf, and Madsen[8] estimate an error of approximately 15% in the theoretical determination of $\Gamma_{3p_{1/2}}$.) Figure 2(b) presents $[\sigma_t(p,n)]_{\mathrm{IAS}}$ as a function of bombarding energy between 25.2 and 47.3 MeV. The magnitude of the error bars (±5%) in Fig. 2(b) represents only the experimental error in the background subtraction for the determinations of $d\sigma(\tilde{p})/d\Omega$. There is an additional scale factor error due to uncertainties in the values of Γ and $\Gamma_{3p_{1/2}}$. This relatively simple method of measuring $[\sigma_t(p,n)]_{\mathrm{IAS}}$ is also being applied to other nuclei. The sizable $\tilde{p}$ cross section (~1 mb/sr) makes $\tilde{p}$-n coincidence studies feasible with the object of obtaining the differential cross section for the (p,n) reaction.[2] The total cross-section data reported here and the projected (p,n) angular distributions will be useful in clarifying the isospin dependence of the optical-model potential for nucleons.

In summary, the $(p,n\tilde{p})$ reaction on a heavy, even-even target, in this case ^{208}Pb, is a powerful, independent method of obtaining relative proton widths for the decay of ground-state isobaric analog levels when the $\tilde{p}$ groups of interest can be resolved experimentally. In addition, the energy dependence of $[\sigma_t(p,n)]_{\mathrm{IAS}}$ has been determined as part of a larger program to study the isospin dependence of the nuclear potential. One of the authors (C.A.W.) would like to thank Dr. P. Richard for a helpful discussion concerning this work.

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