Comments and Addenda

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Widths of Analog States in Bi and Po from (p, n) Spectra*

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Isobaric analog states have been observed in the neutron spectra of (p, n) reactions on targets of ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi. After removal of instrumental resolution effects, the natural widths are, respectively, 196 ± 26, 203 ± 32, 202 ± 34, and 151 ± 34 keV. Except in the ^{206}Pb case, these widths are substantially smaller than those observed in $\bar{p}$ spectra from $(p, n\bar{p})$ experiments on the same target nuclei but are in agreement with (p, p') resonance results in the two cases that have been measured.

I. INTRODUCTION

Recent $(p, n\bar{p})$ experiments on the lead isotopes[1] and on ^{209}Bi[2] indicate a discrepancy between the total widths of the isobaric analog states (IAS) measured in these experiments and the widths obtained from (p, p') resonance experiments.[3,4] The greatest discrepancy was for the IAS in ^{207}Bi, where the ^{207}Pb$(p, n\bar{p})$ reaction gave a width greater than 500 keV, whereas the width of the same state measured by ^{206}Pb(p, p') was merely 170 keV.[3] The only other case directly comparable was that of the IAS in ^{208}Bi, where the ^{208}Pb$(p, n\bar{p})$ reaction gave a width of 317 ± 24 keV, compared to 220 ± 20 keV obtained from the ^{207}Pb(p, p') reaction.[4] The IAS in ^{209}Po was similar to the ^{208}Bi case. Surprisingly, the total width for the IAS in ^{206}Bi measured by the ^{206}Pb$(p, n\bar{p})$ reaction was quite small (230 $\pm$ 38 keV) and thus more in line with the resonance systematics, although a direct comparison could not be made because the required target (^{205}Pb) is unstable.

Since the decay channels available in the $(p, n\bar{p})$ and (p, p') experiments are the same and the formation channels are different, one might expect the latter to be the source of the discrepancy in the observed width of the IAS. Perhaps the (p, n) reaction populates the states underlying the IAS in a significantly different manner than the resonance reaction. If so, one might expect to see evidence of this in the neutron spectrum of the (p, n) reaction. Previous (p, n) data on ^{208}Pb[5] did not have sufficient energy resolution to determine the total width of the analog state.

To help cast further light on this question, the (p, n) reaction was measured on the isotopes ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi with good enough resolution to directly determine the intrinsic widths of the corresponding analog states.

II. EXPERIMENT

The experiment used the neutron time-of-flight facility of the Michigan State University Cyclotron Laboratory. This system[6] makes use of the natural bunching of the cyclotron beam pulses. The neutron detector is the liquid scintillator NE-213, deoxygenated and encapsulated in a 2-in.-diameter $\times 3/4$-in.-thick glass cell mounted on an RCA-8575 photomultiplier. Start and stop timing signals are derived from a constant-fraction discriminator on the photomultiplier and from the cyclotron rf voltage through a divide-by-2 scaler, respectively. Two-dimensional pulse-shape analysis is used to distinguish neutrons from γ rays.

In order to achieve both high-neutron energy

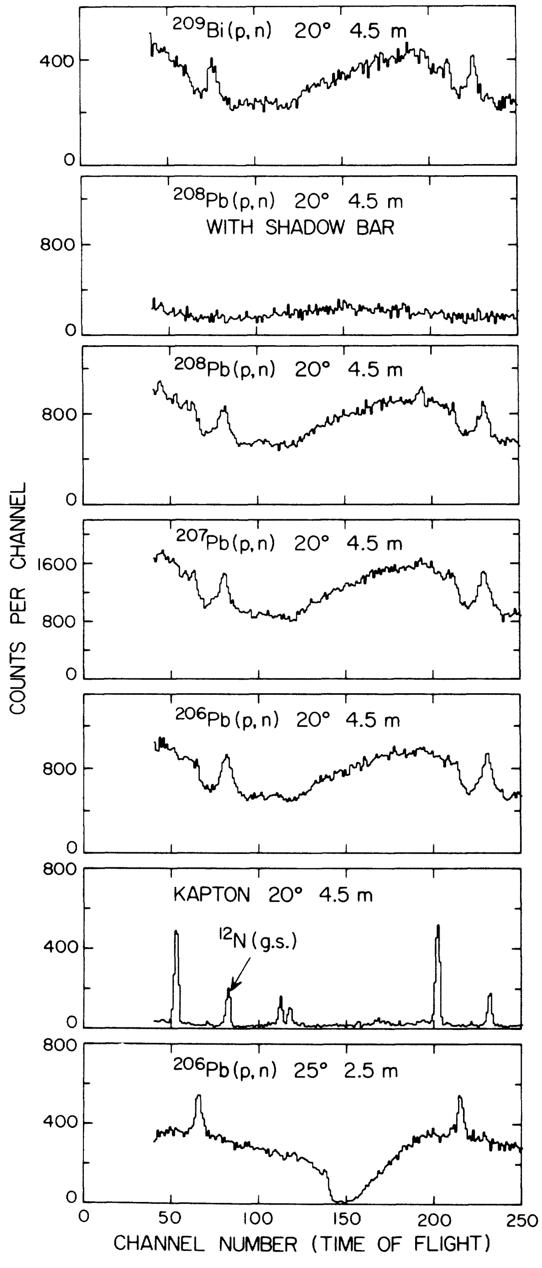

FIG. 1. Comparison of neutron time-of-flight spectra obtained with various targets. The $^{12}C(p, n)^{12}N$(g.s.) transition ($Q = -18.13$ MeV) observed with a Kapton target was used to check the energy resolution of the apparatus. The spectrum measured with a shadow bar between the ^{208}Pb target and the detector has been normalized to the same integrated beam current as the spectrum below it and shows that the neutron background from sources other than the target is weak and has no structure. The stop pulse for the time-to-amplitude converter occurs at a repetition rate which is one half of the beam-pulse rate, so a given neutron energy appears at two places in the spectrum separated by the beam repetition period, 67.534 nsec. The IAS neutron groups appear near channel 80 and channel 230 at 4.5 m.

resolution, which is favored by low-neutron energy, and a low background of compound-nucleus-produced evaporation neutrons, which is favored by high-neutron energy, it was necessary to strike a compromise. Based upon unpublished data,[7] a neutron energy of 6 MeV was chosen for formation of the IAS. As the Q values are close to -19 MeV, the experiment was performed with 25-MeV protons.

Time-of-flight spectra were taken with neutron flight paths of 2.5 and 4.5 m. Lead and bismuth runs were interspersed with calibration runs of $^{12}C(p, n)^{12}N$ using a Kapton target.[8] Isotopic lead and bismuth targets of various thicknesses from 1 to 6 mg/cm^2 were used. The time width (FWHM) of the target γ-ray peak, a measure of beam-pulse length and electronic effects, was always between 0.4 and 0.6 nsec. The neutron peaks were broader because of additional contributions due to target thickness, scintillator thickness, and the natural width of the IAS. With a 20-keV-thick Kapton target, the ^{12}N ground-state group had a width corresponding to 90 keV. This is a measure of the total instrumental width, since the natural width of the ^{12}N ground state is negligible. In all the runs at 4.5 m the instrumental width was small enough that the natural width was the dominant contribution to the observed total width of the peak. At 2.5 m,

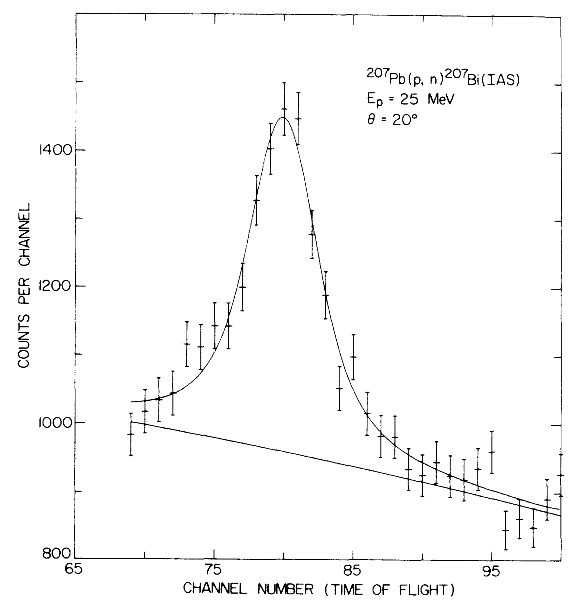

FIG. 2. Example of a fit to a section of a neutron time-of-flight spectrum. The parameters E_0 and Γ have the values 5.823 and 0.181 MeV, respectively. The fit yields $\chi^2/\nu = 1.13$ with $\nu = 27$. The channel width is 0.4534 nsec, which corresponds to approximately 40 keV at the flight-path length of 4.50 m. Note that the zero on the ordinate scale is suppressed.

the instrumental width increased to 150 keV still less than but comparable to the natural width of the IAS.

III. RESULTS

Various (p, n) spectra from the four isotopes and a Kapton target are shown in Fig. 1. One further spectrum with a 24-in.-long brass shadow bar inserted directly between the target and the detector to check the effect of the background is also included. The shadow bar attenuates the neutrons from the target by more than a factor of 1000. The background neutrons contribute a fairly flat spectrum at about $\frac{1}{3}$ the height of the total spectrum. Another noticeable feature of all the 4.5-m spectra is the overlap of slow neutrons from one beam pulse with faster neutrons from the next pulse. This gives rise to structure in the background, which makes background subtraction more difficult. As observed in Fig. 1, for ^{206}Pb(p, n) with a flight path of 2.5 m, the background under the IAS is much flatter, and one is dealing with neutrons primarily from one beam burst. Although the total energy resolution is poorer in this case, the systematic error in the background subtraction is decreased. Results from both 2.5 and 4.5 m were averaged in obtaining the final widths for ^{206}Pb.

The total widths were deduced by making a least-squares fit to a segment of each neutron spectrum including the peak from the analog transition. The functional form employed for the yield as a function of neutron energy, $y(E)$, was a Breit-Wigner line shape superimposed on a linear background:

$$y(E)=\frac{H}{(E-E_0)^2+\frac{1}{4}\Gamma^2}+A+BE\ .$$

In the fits to data this form was modified by folding it with a Gaussian function and a rectangular function to correct approximately for instrumental effects on the line shape. The width of the Gaussian function was set to reproduce the target γ-ray peaks in the time spectra. The width of the rectangular function was set equal to the sum of the widths of the two (rectangular) neutron energy distributions calculated for the thicknesses of the target and of the scintillator, respectively.

To obtain each fit, five parameters were varied: the width, centroid, and normalization of the Breit-Wigner function (Γ, E_0, and H) and the intercept (A) and slope (B) of the background. The nonlinear fitting program FITTEM[9] provides the values of E_0 and Γ and the standard error of each quantity, which corresponds to the change in each parameter required to increase the total χ^2 by one.[10] The optimum values of the other parameters (H, A, B) were calculated directly by the linear least-squares technique. An example of a fit is shown in Fig. 2.

In all cases, the values of χ^2 indicate consistency between the data and the calculated spectrum since χ^2/ν ranges between 0.6 and 1.7, with ν being the number of degrees of freedom.

The results are summarized in Table I, where the values of Γ extracted for different experiments are given for each isotope. The errors on the values come from the statistical error discussed above plus uncertainties in the target thickness, γ-ray line width, and the scintillator thickness. For each 4.5-m run, an error of 30 keV for uncertainty in the background subtraction was also added in quadrature to the other errors.

Coulomb energy differences were also measured for the four isotopes, using the ^{12}C(p, n) reaction as a calibration ($Q=-18.126\pm0.005$ MeV)[11] in each case. In addition to this Q-value error, the only remaining errors associated with this technique arise from uncertainties in extracting the centroids of the IAS and ^{12}N ground-state peaks and from target-thickness contributions. The results are shown in Table II together with the values from the earlier $(p, n\bar{p})$ experiment.[1] The agreement is excellent in all cases, thus confirming the neutron-peak assignments.

TABLE I. IAS total widths.

Isotopes (Parent)	Γ_{tot} (keV) (p,n) (present)	Γ_{tot} (keV) $(p,n\bar{p})$ (Ref. 1)	Γ_{tot} (keV) (p,p')
^{206}Pb	196 ± 26	230 ± 38	No measurement
^{207}Pb	203 ± 32	540	170 [a]
^{208}Pb	202 ± 34	317 ± 24	220 ± 20 [b]
^{209}Bi	151 ± 34	380 ± 80 [c] 327 ± 31	No measurement

[a] From Ref. 3.
[b] From Ref. 4.
[c] From Ref. 2.

TABLE II. Coulomb energy measurements.

Isotopes	ΔE_c (MeV) ± error (keV) from (p,n) experiment (present)	ΔE_c (MeV) ± error (keV) from $(p,n\bar{p})$ experiment [a]
^{209}Po–^{209}Bi	19.011 ± 21	18.991 ± 12
^{208}Bi–^{208}Pb	18.831 ± 20	18.816 ± 13
^{207}Bi–^{207}Pb	18.888 ± 34	18.875 ± 28
^{206}Bi–^{206}Pb	18.911 ± 34	18.899 ± 24

[a] From Ref. 1.

IV. CONCLUSIONS

The (p, n) reaction gives widths of about 150 to 200 keV in the four cases studied. Within the estimated errors of 26 to 34 keV all four widths are the same. The measurements are consistent with the resonance experiments[3,4] in the two cases (^{207}Pb and ^{208}Pb) where resonance data exist. In both of these cases the $(p, n\bar{p})$ widths are larger.

At the present time we can offer no satisfactory explanation for the larger $(p, n\bar{p})$ widths. Further experiments, utilizing n-p coincidences, are planned.

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Anomalous Excited $K = 0$ Rotational Bands in Heavy Nuclei

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We propose that in the region of two quasiparticle excitations, there exist $K=0$ rotational bands such that: (a) $K\pi=0+$, occurs with only odd-J values; and (b) $K\pi=0-$, occurs with only even-J values. Properties of such anomalous bands are investigated.

The usual symmetry arguments of the rotational model lead to the observed and well-studied $K=0$ rotational bands in heavy deformed nuclei which have the properties that: (a) only even-J band members exist for $K\pi=0+$ intrinsic states and (b) only odd-J band members exist for $K\pi=0-$ intrinsic states. Case (a) is best represented by the ground-state band and collective β vibrations while case (b) is best represented by the $K\pi=0-$ member of the collective octupole vibration. In this note we shall discuss the properties of related "anomalous" $K=0$ bands which have the characteristics that (a) only odd-J band members exist for $K\pi=0+$ intrinsic states and (b) only even-J band members exist for $K\pi=0-$ intrinsic states. For a schematic interaction the anomalous bands are found to be noncollective in the vibrational sense with band-head energies of the order of the two-quasiparticle excitation energy.

We know of only one case where such an anoma-