$E1$ excitations in ^{208}Pb induced by fast neutrons

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The role of $E1$ excitations in neutron inelastic scattering from ^{208}Pb has been explored. In essence, we find that the excitation of 1^- levels does not reflect their $E1$ strength, even when the transitions are to particularly collective levels. By "collective" 1^- levels, we mean those which have substantial $E1$ photon widths. We have made definite spin assignments to two $J = 1$ levels, at 5805.0 and 5946.4 keV and observed scattering intensities to six of them. This includes all known dipole levels below 6-MeV excitation. The neutron excitation strengths of these levels are compared with those from photon scattering, and with statistical model expectations. Transition energies were measured with uncertainties less than 0.5 keV, to resolve some ambiguities associated with previous level energy determinations.

[NUCLEAR REACTIONS ^{208}Pb$(n,n'\gamma)$, E_n=5.2, 6.2, 7.0, and 8.5 MeV. Measured E_γ, I_γ at 90° and 152° (lab), deduced levels, σ_n^*. Statistical model analysis.]

INTRODUCTION

The role or influence of collective $E1$ modes on intermediate energy neutron scattering has received no attention, while in recent years other collective excitations have been and are being extensively studied in neutron inelastic scattering. The collective excitations referred to are those usually interpreted as excitations of the nuclear surface, associated with nuclear deformations and deformabilities. Very strong $E2$ excitations dominate inelastic neutron scattering to vibrational[1,2] and rotational[2] excited levels in the rare earth region and also in the actinides.[3] Ten years ago Cranberg *et al.*[4] had shown that both 3^- and 2^+ excited levels of ^{206}Pb and ^{208}Pb were strongly excited in neutron inelastic scattering at an incident energy as low as 6 MeV. So even in closed shell nuclei, when the incident energy is not too low, collective excitations stand out as especially strong ones.

On the other hand we know from many detailed studies near closed shells[4,5,6] that the statistical model of Wolfenstein and of Hauser and Feshbach (WHF),[7] which is nuclear dynamics and structure independent, does an excellent job of representing neutron scattering cross sections for scattering to levels which show little or no collectivity. The nuclear structure independent statistical model (WHF) is a very good reference model for examining the magnitude of neutron inelastic scattering cross sections. The appearance of "enhanced" values, i.e., scattering cross sections much larger than WHF predictions, is a nice signature of even fairly modest collective strengths.

The ^{208}Pb$(n,n'\gamma)$ reactions afford us an excellent opportunity to see any influence of $E1$ excitations on neutron scattering. Because ^{208}Pb is an almost ideal nucleus for testing RPA and other calculations of $E1$ and $M1$ strength distributions, the 1^- and 1^+ levels of ^{208}Pb have been mapped out in great detail. Especially recently the high resolution, high intensity photon scattering studies[8,9,10] have given a good picture of $E1$ strength distributions below the (γ,n) threshold at 7.4 MeV. Particle transfer reaction[11] and isobaric analog state[12] studies have also probed this excitation energy region in ^{208}Pb, to identify those 1^- levels dominated by a single particle-hole (p-h) configuration.

Because neutron inelastic scattering is not expected to be as selective as the excitation methods cited above, we hoped to identify and assign additional $J=1$ levels missed in earlier experiments. The measurements reported here are then concerned primarily with identification of $J=1$ levels below 6 MeV in ^{208}Pb, using fast neutrons as a probe. We are led to the conclusion that all the dipole levels of ^{208}Pb below 6 MeV are observed here. An interesting finding of the study is that all dipole levels observed are excited with about the same intensity, independent of the particle-hole character of the state, or of its photon strength. This includes all of the previously known $J=1$ levels.

Also a part of this study was the observation of $J=2$ levels, and measurements of the branching ratios of their decays. A unique feature of ^{208}Pb is that there are no levels with $J=2$ below 4 MeV to which low spin higher excited levels could decay. Thus these higher excited levels decay directly to ground. Identification of these low spin levels between 4 and 6 MeV is important not only for testing model calculations, but also for measuring and understanding the branching ratios from much higher levels.[13]

The $(n,n'\gamma)$ reactions at low incident energies, $E_n < 4$ MeV, have been especially effective spectroscopic probes of low excited levels, i.e., the first ~30 levels of a nucleus. One obtains from such measurements, with confidence, level placements, branching ratios, and many spin assignments.[5,14,15] Usually all of the low-lying levels with $J<8$ are visibly excited in low energy neutron scattering.[16] One of the issues of this experiment was the degree of success we would have in extending these spectroscopic methods to 7 MeV and above. Some previous work had been done on $(n,n'\gamma)$ reaction studies at these energies, including previous experiments[17] on ^{208}Pb. But these studies were plagued by the higher backgrounds associated with the higher incident neutron energies, and generally lower detection sensitivities for high energy γ rays. We wanted to determine in this study the effectiveness with which detailed spectroscopic information could be extracted at incident neutron energies near 7 MeV, with extra attention paid to reducing backgrounds and the use of a rather large efficiency γ-ray detector.

THE EXPERIMENT AND DATA REDUCTION

The technique employed to make these measurements has often been used at lower incident neutron energies.[5,14,15] In our experiment neutrons were produced using a pulsed deuteron beam from the University of Kentucky 6.5-MeV Van de Graaff accelerator reacting in a D_2 gas target to produce neutrons via the $D(d,n)\,^3$He reaction. The 99.8% enriched ^{208}Pb sample, or a radiolead sample, was hung at 0° relative to the beam axis, and an ~82-cm^3 Ge(Li) detector observed γ rays at scattering angles of 90° and 152°. This detector has an efficiency 12% of that of a 7.5-cm NaI scintillator at a γ-ray energy of 1.3 MeV.

As always with this technique,[14] ~90% of the background in the γ-ray spectrum is eliminated by operating in the time-of-flight (TOF) mode; the energy spectrum is gated with the γ peak of the TOF spectrum. The background generally increases at higher incident neutron energies due to neutron capture in moderating and shielding materials near the detector. [It can be reduced by not placing shielding very close to the Ge(Li)]. However, observation of some Fe(n,γ) background was useful in this experiment for providing peaks of well known[18] energies in the γ-ray spectrum for energy calibration.

Spectra were taken at five incident neutron energies, 5.2, 5.5, 6.2, 7.0, and 8.5 MeV, for ^{206}Pb (radiolead) and ^{208}Pb samples. At 5.2 and 7.0 MeV γ rays were observed at both 90° and 152°. The 90° spectrum for ^{208}Pb at 7.0 MeV is shown in Fig. 1. Eight definite ground state transitions were noted, in addition to the very intense 3^- transition not shown in Fig. 1. Two criteria for the establishment of a peak as due to ^{208}Pb are the following: (1) The full-energy (F), single (S)- and double (D)-escape peaks must all be observed for transitions above 4.5 MeV; only the F peak was required below that energy. (2) The peak must not be in a ^{206}Pb spectrum. The peak fitting program SAMPO[19] was used to extract centroids and intensities.

Great care was taken to measure energies accurately. Energy determination was made as follows. Peak centroids determined by SAMPO fixed channel positions for each γ ray. An energy scale was then established using the 2614.53- (Ref. 20) and 4085.37-keV peaks from ^{208}Pb and the 4218.43 F, 5920.50 F, S, and D, 6018.56 F, 7631.21 D, and 7645.61 D keV peaks from Fe(n,γ).[18] The energy of the 4085.37-keV γ ray had been accurately measured first using the ^{208}Pb$(n,n'\gamma)$ reaction at 5.5 MeV incident neutron energy with a ^{56}Co source present during the data collection. As one can see in Fig. 1, the 4085.37 keV is a strong

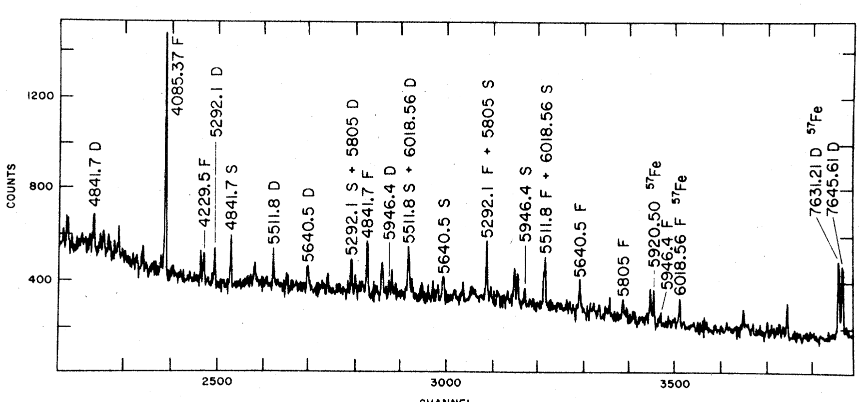

FIG. 1. The γ-ray spectrum observed at 90° for 7 MeV neutrons incident upon ^{208}Pb. Peaks labeled ^{57}Fe are from the ^{56}Fe(n,γ) process. Other labeled peaks are from ^{208}Pb. F, S, and D refer to the full-, single-, and double escape peaks, respectively. All energies are in keV.

TABLE I. Spin-1 and 2 levels observed in this study. The level energies and energy uncertainties (column 1) are our measurements, except for the 2614.53 (3^-), which is taken from Ref. 20. The 152°/90° yield ratios (column 2) measure the level spin (column 3) for all but the 5640.5-keV level. The ratio should be about 0.85 for $J=1$, 1.2 for $J=2$, and 1.5 for $J=3$. Column 4 gives the previous spin and parity assignment for each level (Ref. 24).

Level energy (keV)	152°/90° yield (to ground)	Spin assignment	Previous assignment (Ref. 24)
5946.4 ±1.4	0.82±0.14 [a]	1	$(1)^-$
5805.0 ±1.5	0.81±0.12 [a]	1	...
5640.5 ±1.0	1.08±0.07 [a]	(1, 2) [d]	(1, 2)
5548.0 ±0.6	...	...	2^+
5511.8 ±0.8	0.65±0.11 [a]	1	1^-
5292.1 ±0.8	0.85±0.08 [a]	1	1^-
4841.7 ±0.5	0.83±0.05 [a,b]	1	1
4229.5 ±0.2	1.23±0.07 [b,c]	2	$(4)^-$
4085.37±0.3	1.33±0.07 [b]	2	2^+
2614.53	1.61±0.05 [b]	3	3^-

[a] Measured at 7 MeV incident neutron energy.
[b] Measured at 5.2 MeV incident neutron energy.
[c] This level branches 24% to ground, 76% to the 2614.49(3^-).
[d] Possible doublet.

transition. The 2614.53-keV peak and the well known (Ref. 20) ^{56}Co radiations near 3.2 MeV were used to calibrate that spectrum. Uncertainties in our energy measurements are given in Table I.

LEVELS IDENTIFIED

Nine $J=1$ and 2 levels below 6 MeV excitation energy were found, and are listed in Table I. Figure 1 shows ground state transitions from some of these levels; ground state transitions are easily identified by their relatively high energies. For those levels decaying directly to the 0^+ ground state, and that includes all $J=1$ levels,[21] assigning the spin of the excited level is a simple matter. Since the decay must be by a single multipole, the anisotropy of the decay immediately signals the spin, J, uniquely for any $J \leq 4$. Thus measurements at 90° and 152°, which give the degree of anisotropy of the angular distribution, enable the spin determination directly. For example, only dipole transitions from $J=1$ levels can give 152°/90° yield ratios <1. The ratio would be about 1.2–1.3 for $J=2$ levels, and about 1.5 for $J=3$ levels. Good yield measurements can easily discriminate amongst these possibilities.

Spins were assigned to 7 of the 9 levels. Probably only the 5805.0-keV level is newly observed here. As stated in the Introduction, we believe all of the $J=1$ levels below 6 MeV were observed in this study. We shall discuss these levels, and then make some comparative comments about their excitation "strengths." Above 6 MeV excitation energy no levels were observed. In particular, there was no hint of the known dipole transitions around 7 MeV.[9-12]

The spin-1 levels

4841.7-, 5292.1- and 5511.8-keV levels

These levels were previously known[8,10,12] to be $J=1$, and contain almost all of the photon strength in ^{208}Pb below 6 MeV. The 5292.1- and 5511.8-keV levels have negative parity, as does probably the 4841.7-keV level. Swann[22] has claimed that there are actually two levels at 4843 keV. Both the 4841.7- and 5511.8-keV levels are composites of many particle-hole states, while the 5292.1-keV level is mostly $(s_{1/2}p_{1/2}^{-1})_\nu$. One can see from Fig. 1 that they are all excited with about the same intensity; detailed comparisons will be discussed later.

Incidentally, one also sees in Fig. 1 that the 6018.56-keV (S) capture line[18] at 5507.56 keV interferes with the 5511.8-keV (F) peak. This is probably the reason why the latter energy is often erroneously given as 5508 keV. Furthermore, it has been suggested[23] that there is a doublet of levels at ~5513 keV, and this study reveals a level at 5516.6 keV decaying to the 3^- level (2614.53 keV). Particle inelastic scattering or transfer reaction studies without γ-ray detection would not be able to resolve the 5511.8- and 5516.6-keV levels.

5805.0- and 5946.4-keV levels

Our 152°/90° intensity ratios determine these two levels to be $J=1$. The 5946.4-keV level, previously and tentatively assigned[11,24] as $(1)^-$, had been found[11] to contain most of the $(d_{3/2}p_{1/2}^{-1})_\nu$ configuration strength. It has very little photon strength.[9,10,11]

The $J=1$ level at 5805.0 keV may be the level previously suggested[24] to be 2^+ at 5801 ± 10 keV.

5640.5-keV level

We cannot assign a spin to this level, since our 152°/90° intensity ratio in Table I shows that it cannot be assigned as $J=1$ or 2. The peak at this energy may represent two transitions.

The spin-2 levels

In our study we also observe many other ^{208}Pb levels above 4 MeV, and we shall mention a few of them in the last section for comparison of their cross sections with those of the dipole levels. However, this report is a detailed study of only $J=1$ and 2 levels, so we only discuss two important $J=2$ levels in this section.

4085.37-keV level

This is the very collective first quadrupole excitation in ^{208}Pb. As seen in Fig. 1 it is excited strongly with fast neutrons. There is no sign in the measurements of any branch from the 4085.37-keV level except to ground, even though our sensitivity to such a transition would have been very good. The intensity of a cascade to the 3^- level must be <5% that of the ground state transition.

4229.5-keV level

This is the only level which we observe to decay to both the ground and the 3^- state, a marked departure from the usual decay patterns of low spin excited levels. This level has been assigned in different particle transfer studies[11] as 2^- or 4^-, and until recently had been observed to decay only to the 3^- level. A previous $(n,n'\gamma)$ experiment,[17] however, observed two γ rays which were attributed to decay of that level. Since decay to ground was projected there, the spin assignment $J=2$ was preferred, although no previous experiment has determined the spin. Because a 2^- decay to the ground state is exceptional, we suspected a closely spaced doublet. To test this possibility, we made careful measurements of the two decay energies from this level. The cascade transition energy was readily determined to be 1614.9 ± 0.2 keV. Its energy is close to those of several lines from the ^{56}Co source. The ground state transition was harder to fix, but we did have the 4218.43 (F) line from Fe(n,γ) as well as the previously determined 4085.37-keV line. With these, we determined 4229.7 ± 0.4 keV for the ground state decay. Thus, within an uncertainty of about 0.5 keV, both lines seem to come from the same level. We also tested the apparent branching ratio for decay of the 4229.5-keV level, by making extended measurements of the intensities at several incident neutron energies, ranging between 5.0 and 8.5 MeV. Within an uncertainty of better than 10% the ratio is constant and is, when averaged over all measurements, (24 ± 3)% to ground, and (76 ± 3)% to the 3^- level.

The anisotropy of the 4229.5-keV decay as reflected in the 152°/90° yield ratio (Table I) definitely determines its spin as 2. When this is combined with the particle transfer studies,[11] the level is 2^-. This assignment is also consistent with the nonobservation of the level in the (α,α') experiment of Del Vecchio *et al.*,[25] who excite only the natural parity levels.

It seems at first remarkable that the $M2$ decay to ground can compete successfully with the $M1$ to the first excited level, since single-particle speeds would indicate a ratio of 125 for the two decays, rather than the observed ratio of 2. Thus the $M1$ must be inhibited by a factor of about 50. A very extensive shell model calculation has been carried out for ^{208}Pb by True, Ma, and Pinkston,[26] who used a phenomenological interaction fitted to the properties of other nuclei in this mass region. Their calculation represents very well the excitation energies and proton and neutron partial widths of the odd-parity levels. We find that their lowest energy 2^- wave function has only one major particle-hole component which can decay to the 3^- via an $M1$ transition. That component can decay only to two substantial components of the complex 3^- configuration via a spin-flip $M1$ transition. Estimates of the factors entering the transition amplitudes from the dominant $(g_{9/2}f_{5/2}^{-1})_\nu$ configuration of the 2^- level to the $(g_{9/2}f_{7/2}^{-1})_\nu$ and $(g_{7/2}f_{5/2}^{-1})_\nu$ configuration of the 3^- level show that they are of comparable magnitude, and interfere destructively. In fact, our estimates with these configurations would imply an intensity inhibition of about 150 for the $M1$. This numerical estimate of the degree of cancellation is not complete. One small amplitude has been ignored in the calculation. It appears, nonetheless, that the $M1$ decay inhibition of the 2^- level is a fairly sensitive test of model wave functions. The lowest 2^- level of the True, Ma, and Pinkston model, calculated to lie at 4.422 MeV,[26] corresponds quite well to this observed level at 4.2295 MeV.

RELATIVE EXCITATION STRENGTHS

As is amply clear from Fig. 1, levels identified as $J=1$ are all excited with about the same intensity. Furthermore, their excitations are rather weak when compared with those of other nearby levels; several more strongly excited levels decay by cascade transitions which are not shown in Fig. 1. The 4229.5-keV γ ray in Fig. 1 from the 2^- level represents only $\frac{1}{4}$ of that level's total excitation strength. Qualitatively Fig. 1 tells us quite a lot about the role of $E1$ transitions in inelastic neutron scattering, and reveals a picture which was by no means expected *a priori*. The six dipole levels shown here are of very different character. The 4841.7-, 5292.1-, and 5511.8-keV levels have collective character, in that they contain almost all the $E1$ photon strength for ^{208}Pb below 6 MeV.[9,10] The photon width is a measure of the coherence of the p-h motions which compose a given multipole mode, and in that sense is a measure of the "collectivity" of the level. The photon width of the 5511.8-keV level is four times that of the 4841.7-keV one, and the widths of the 5640.5- and 5805.0-keV levels are so small they are not seen in photon scattering.[9,10]

The observation that the neutron excitation mechanism appears to be independent of $E1$ strength suggests that these levels are being excited through compound system (CS) formation, and not as collective excitations. To quantify this finding we have calculated the expected inelastic neutron scattering cross sections for CS formation and decay, which are just the WHF cross sections[7,27,28] and compared these calculations to our measured inelastic scattering cross sections. In Fig. 2 we display these cross sections as a ratio of the measured value to the calculated value. This is shown with a level scheme. Deviations of measured cross sections from CS formation are represented as black bars—to the left if the measured value is less than the WHF value, to the right if it is more than the calculated value. Large deviations to the right indicate the collective enhancements. Accompanying the $J=1$ and $J=2$ levels, we have included a few other levels in that figure.

Note that the ratio in Fig. 2 of measured neutron inelastic scattering cross section to WHF calculated value is 1 to within $\lesssim 30\%$ for all $J=1$ levels except the 5946.4-keV one, where the ratio deviates 50%. The constancy of this ratio is consistent with the suggestion that these levels participate in neutron inelastic scattering through CS formation and its statistically governed decay.

Plotted on the right vertical axis of Fig. 2 are the reduced photon transition probabilities, as ratios to the probability of a single particle tran-

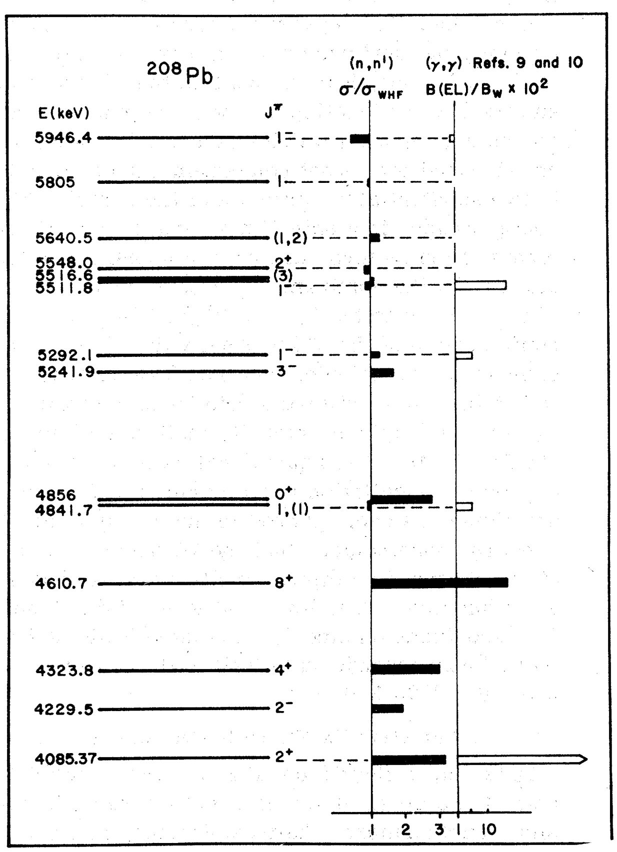

FIG. 2. Partial level scheme above 4 MeV for ^{208}Pb and schematic representation of each level's neutron excitation "strength." Also shown for some of the levels is the ratio of their reduced transition probability, $B(EL)$, to the single particle strength, B_W. The ratios σ/σ_{WHF} and $B(EL)/B_W$ are discussed in the last section of this report.

sition.[29] The open bars showing deviations from this axis indicate the collectivity of the level. The comparisons in Fig. 2 of the photon strengths with the inelastic neutron scattering enhancements amplifies the point that the neutron cross sections do not reflect the collectivity of the $J=1$ levels as defined by their photon widths.

In contrast, excitations of some of the levels of other J are quite enhanced, suggesting that these modes are excited directly. For instance, consider the two 2^+ levels shown in Fig. 2. One of them, the known quadrupole excitation at 4085.37 keV, is excited strongly with neutrons—three times the WHF value—while the cross section for the 5548.0-keV level is no larger than the WHF estimates. So in this case, for 2^+ levels, the neutron scattering does reflect the collectivity of the level. We see the collective 2^+ level is strongly excited in both photon and neutron scattering, while the 5548.0-keV 2^+ level is weakly excited with neutrons, and also has no measured photon width to the ground state.

We have demonstrated that in ^{208}Pb at least electric dipole strengths are not evident in fast neutron scattering, while other multipoles which represent collective modes are strongly excited. A clue to understanding this behavior may be gained by considering the basic microscopic nature of the excitation. The dipole excitation, of course, corresponds to a charge-state separation which occurs in spite of the strong isoscalar ($T=0$) nucleon-nucleon force. De Villiers *et al.* had examined the possibility of charge-state separation effects in Hartree-Fock calculations[30] of the quadrupole moment of deformed ^{154}Sm, and Girod and Gogny extended that test in Hartree-Fock-Bogoliubov calculations of energies and quadrupole moments[31] of ^{152,154}Sm. Both sets of calculations showed no charge-state effects; the $T=0$ force kept the neutrons and protons tightly coupled to each other.

It would appear that as the large susceptibility[32] to changes of the $E2$ deformation of ^{152}Sm, or its softness, may account for the very strong neutron scattering to quadrupole excitations in that nucleus,[2] the rigidity of ^{208}Pb against dipole excitations may result in the absence of any observable influence of $E1$ strengths on neutron scattering to 1^- levels.

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