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# $^{206}$Pb LEVEL STRUCTURE FROM $^{206}$Pb(n,n'$\gamma$) MEASUREMENTS

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ABSTRACT

A study of gamma-ray data produced by neutron inelastic scattering from a lead sample enriched in the isotope $^{206}$Pb has resulted in placements, or tentative placements, of 146 gamma rays as transitions among 112 known or postulated levels of the $^{206}$Pb level structure.

## I. INTRODUCTION

In the course of a series of experiments[1] to determine secondary gamma-ray production cross sections for shielding analyses, measurements were obtained for a lead sample enriched in the isotope $^{206}$Pb. Initially it was anticipated that many of the observed gamma rays could be assigned as transitions among levels in $^{206}$Pb based upon previous experimental data. It turns out that most of the presently known gamma-ray assignments are from measurements of the decay of $^{206}$Bi, and these make up a somewhat selective set of transitions among 21 of the 37 "known" levels having excitation energies ($E_x$) < 3.6 MeV. For $E_x$ > 3.6 MeV, the only reported gamma-ray transitions are due either to ($\gamma$,$\gamma$) measurements[2] or from the $^{204}$Hg($\alpha$,2n$\gamma$) reaction[3] populating the $J^\pi = 12^+$ level at 4027-keV excitation energy. For evaluation purposes it is important to determine transition energies and branching ratios (i.e., decay probabilities) especially for levels produced by neutron excitation. In this report 146 gamma rays (out of a total of 318 gamma rays observed) have been placed or tentatively placed as transitions among 112 excited states in $^{206}$Pb, including perhaps 50 newly located states.

Some guidance for the present analysis was obtained from the nuclear shell model. In this model, $^{208}$Pb is an excellent "core" nucleus, and the level structure of $^{206}$Pb is simply described by the properties of two "holes" in the neutron shells labelled (to indicate NLJ) as the $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, $1i_{13/2}$, $1h_{9/2}$, and $2f_{7/2}$ orbits.

One can deduce much of the expected level structure of $^{206}$Pb by simple shell model considerations involving the $^{208}$Pb "core" and the observed level structure of $^{207}$Pb. A synopsis of these considerations is given in Figure 1 for $E_x < 3.6$ MeV. The (sparse) level structure of $^{208}$Pb is given at the left, and next to it are the six states in $^{207}$Pb corresponding to one-hole (1-h) states in each of the six orbitals of interest. The third column indicates the more complex level structure to be expected in $^{206}$Pb estimated from the basic angular momentum couplings of two holes (2-h states). For example, the $(p_{1/2})^2_{J=0}$ state [strictly the $(p_{1/2}^{-1})^2$ state; the -1 superscript will be dispensed with in most of the remaining discussion, used only when needed for clarification.] represents the ground-state of $^{206}$Pb. Next, at a relative excitation energy of ~570 keV (corresponding to the excitation energy of the first excited state in $^{207}$Pb), there should be the degenerate pair $(f_{5/2}\ p_{1/2})_{J=2}$ and $(f_{5/2}\ p_{1/2})_{J=3}$ configurations. Empirically, the first $2^+$ and $3^+$ states in $^{206}$Pb are not degenerate, and they have an average energy ~1.2 MeV, i.e., about 0.6 MeV greater than that expected from the most basic consideration. In fact, it appears that the ground state of $^{206}$Pb is lower in energy by about 0.6 MeV than expected.[4] In Figure 1, therefore, all of the basic (2-h) configurations are shown increased by 0.6 MeV.

Extending this basic picture involves coupling (2-h) configurations to the excited states of the core $^{208}$Pb. One might expect that the excited states of $^{208}$Pb could be described as particle-hole states, by raising a neutron from one of the six described neutron orbits into the $2g_{9/2}$ level. The $5^-$ and $4^-$ states at $E_x$ = 3198 and 3470 keV likely[5] have the shell model description $(g_{9/2}\ p_{1/2}^{-1})_{J=4,5}$. The $3^-$ state at $E_x$ = 2614.5 keV is not so simply represented; it is better described as a collective state.[6]

The "basic coupling" schemes (column 3 of Fig. 1) involve combining the $^{208}$Pb excited states with a (2-h) configuration already discussed.

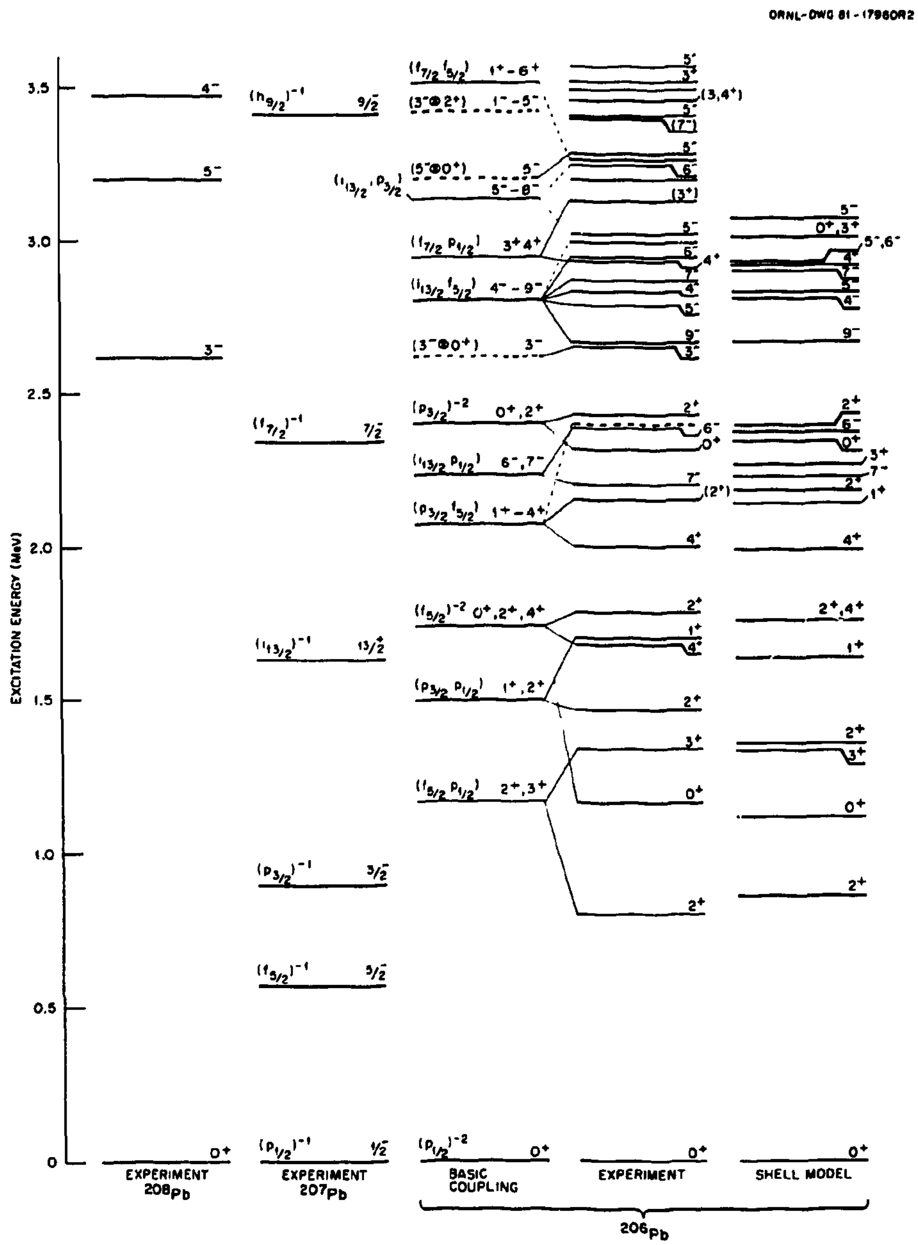


Fig. 1. Level structure information on the stable isotopes $^{206,207,208}$Pb and two shell-model estimations of the $^{206}$Pb level structure. The center column suggests very simple coupling of single-particle (actually single-hole) states. The right-most column presents results of a more realistic calculation.

Empirically the (2-h) states can be taken directly from the $^{206}$Pb (known) level structure, although presumably one could use calculated shell-model configurations. Coupling the $^{208}$Pb $J^\pi = 3^-$ state with the $^{206}$Pb $J^\pi = 0^+$ ground state gives an expected $J^\pi = 3^-$ state in $^{206}$Pb at $E_x \simeq 2615$ keV. Empirically the lowest-lying $J^\pi = 3^-$ state in $^{206}$Pb is observed at 2648 keV. In Fig. 1, the "basic coupling" configuration is labelled as $(3^- \otimes 0^+)_{J=3}$. If the $J^\pi = 5^-$ and $4^-$ states in $^{208}$Pb at $E_x = 3198$ and 3470 keV were pure $(g_{9/2}\ p_{1/2}^{-1})$ configuration and if the $J^\pi = 0^+$ ground state in $^{206}$Pb were pure $(p_{1/2}^{-1})^2$, then no analogue to either of these states would be observed among the excited states of $^{206}$Pb. However, the $J^\pi = 5^-$ state at $E_x = 3279$ in $^{206}$Pb is probably the analogue to the $J^\pi = 5^-$ state at $E_x = 3198$ in $^{208}$Pb, simple evidence that there is some configuration mixing in the wave functions describing these levels. At $E_x \sim 2.6 + 0.8 = 3.4$ MeV, the five levels described by the $(3^- \otimes 2^+)$ configurations having $J^\pi = 1^-$ to $5^-$ are expected.

In this fashion one may estimate at least a lower limit to the number of levels as a function of excitation energy in $^{206}$Pb. The results for $E_x < 4.7$ MeV are shown in Fig. 2 along with the number of levels determined from the most recent evaluations[7] of experimental data. The agreement is good for $E_x < 4$ MeV, with evident divergence at the higher excitation energies. The present data provide evidence leading to definition of additional levels in $^{206}$Pb having $E_x > 4$ MeV; however, there are not enough additional new levels to reproduce the estimated density of levels.

Returning to Fig. 1, the fourth column shows the presently evaluated[7] experimental data. Correspondence with the "basic coupling" states in column 3 is indicated. There have been several complete model calculations[8,9] of the $^{206}$Pb level structure; that of McGrory and Kuo[9] is shown in the right-hand column of Fig. 1. Especially for $E_x < 2.5$ MeV the comparison between experiment and calculation is very good. Only for the $1^+$ and $3^+$ states predicted at $E_x \sim 2.1$ keV does there seem to be a problem. A tentatively[7] suggested state in $^{206}$Pb at 2391 keV may be one of these predicted states. For $3.6 > E_x > 2.5$ MeV identification of some experimental states can be made from among

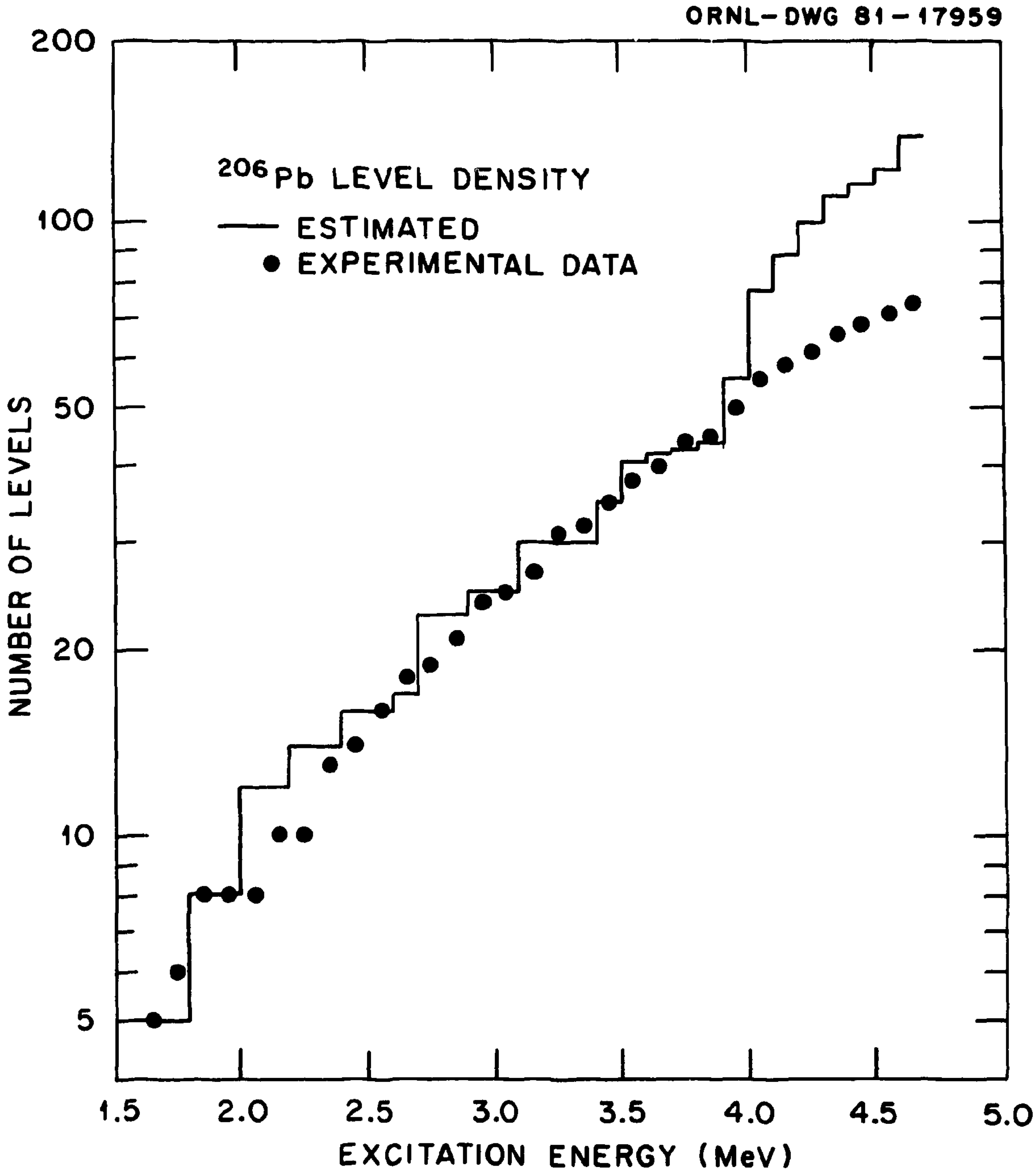


Fig. 2. Number of $^{206}Pb$ energy levels as a function of excitation energy. The experimental data are obtained from current evaluations (ref. 7). The solid line is an estimate of levels expected from the "basic-coupling" configurations, and may be a lower-level estimate since only neutron configurations are included.

the predicted (2-h) shell-model states and the excited states of $^{208}Pb$ coupled to (2-h) states. For $E_x > 3.6$ MeV the correspondence can be made for only a few of the predicted levels.

## II. EXPERIMENTAL DATA

Spectra were obtained of gamma rays produced by neutron inelastic scattering from a 65-g sample of radiogenic lead. Measurements were made using two different detection systems and neutron sources. The most complete spectrum was obtained from a nearly monoenergetic and pulsed 4.8-MeV neutron beam produced using the $D(d,n)^3He$ reaction. The resulting gamma radiation was detected using a 48-$cm^3$ Ge(Li) detector. The system has been described in a report[1] on data obtained for a $^{208}Pb$ sample. The spectrum obtained is given in detail in the appendix. Other similar spectra were obtained for $E_n$ up to 8.0 MeV; however, as discussed later, these data did not provide as much additional spectroscopic information as had been hoped for.

The other important data were obtained using a 90-$cm^3$ Ge(Li) detector and a "white-source" of neutrons produced at the Oak Ridge Electron Linear Accelerator (ORELA). The experiment was set up at the 22-meter station on flight path 8. This system is a modification of one previously described.[10] The major difference is that more shielding has been added surrounding the detector. Data with this system were most useful for determining some neutron-energy thresholds of gamma-ray production, particularly for gamma rays having large yields.

## III. DATA REDUCTION

The raw data in the 4.8-MeV neutron spectrum were analyzed to give the energy ($E_\gamma$) and yield ($I_\gamma$) for each of ∿260 peaks identified in the spectrum. These are listed in the first and last columns of Table 1. Note that the yields are relative to the yield for the dominant 803-keV gamma ray. Much effort went into trying to ascertain an absolute normalization so as to report the yield data as absolute differential

Table 1. Gamma Ray Produced by 4.8-MeV[a] Neutron Interactions with $^{206}Pb$

| $E_{\gamma}$ (keV)[b,c] | Assigned transition[c] | Intensity |
|---|---|---|
| (314) | | 17.0 ± 2.5 |
| 317 | 1784-1467 | 17.0 ± 2.5 |
| 343.5 | 1684-1340 | 73.4 ± 3.0 |
| (364) | | 2.0 ± 1.5 |
| 398 | 2782-2384 | 33.8 ± 2.3 |
| 434.9[d] | | 6.5 ± 1.6 |
| 450 | | 4.5 ± 1.7 |
| 472 | | 3.6 ± 1.6 |
| 479.5[e] | (2865-2384) | 22.6 ± 3.1 |
| 497.1 | 3279-2782 | 20.9 ± 3.1 |
| (515.7) | {(2200-1684) / (3776-3260)} | 16.0 ± 3.5 |
| 537.5 | 1341-803 | 320 ± 4 |
| 607.0 | | 4.4 ± 2.0 |
| 610.3 | | 4.5 ± 2.0 |
| 617.6 | | 4.0 ± 2.5 |
| 620.5 | 3403-2782 | 2.7 ± 1.3 |
| 632.3[d] | 3017-2384 | 17.7 ± 1.7 |
| 637.1 | | 5.9 ± 2.3 |
| 657.2 | 1997-1340 | 66.5 ± 1.6 |
| 663.7 | 1467-803 | 73.0 ± 1.7 |
| 719.1 | | 10.5 ± 0.9 |
| 729.2 | | 2.0 ± 0.8 |
| 739.4 | 2939-2200 | 9.8 ± 1.3 |
| 747.3 | | 5.8 ± 1.9 |
| 755.0[d] | | 3.3 ± 1.9 |
| 803.1 | 803-g.s. | 1000 |
| 814.7 | | 1.2 ± 0.9 |
| 840.9[d] | 3225-2384 | 7.2 ± 2.3 |
| 856 | 2197-1341 | 29.9 ± 1.8 |
| 863 | | 3.0 ± 1.5 |
| 868 | | 4.5 ± 2.5 |
| 881.0 | 1684-803 | 173.0 ± 2.5 |
| (894.7) | 3279-2384 | 18.4 ± 2.5 |
| 898 | | 22.0 ± 2.5[f] |
| 920.7[d] | | 4.0 ± 1.0 |
| 926.1 | | 2.0 ± 1.5 |
| 930.4 | | 2.0 ± 1.5 |
| 935.4 | | 1.7 ± 1.2 |

Table 1. Continued

| $E_\gamma$ (keV)[b,c] | Assigned transition[c] | Intensity |
|---|---|---|
| 957.5 | (3606-2648) | 6.3 ± 1.3 |
| 962[g] | | 7.1 ± 1.4 |
| 968.9 | | 3.0 ± 1.3 |
| 980.9 | 1784-803 | 52.3 ± 2.0 |
| 995.1 | (4116-3121) | 2.1 ± 0.7 |
| 1014[h] | | 1.4 ± 0.7 |
| 1018.6 | 3403-2384 | 2.7 ± 0.6 |
| 1024.1 | | 1.3 ± 0.9 |
| 1031.0 | | 3.8 ± 1.0 |
| 1047.6 | 3244-2197 | 2.2 ± 1.1 |
| 1075.9 | (4005-2929) | 3.8 ± 2.0 |
| 1093.3 | | 12.7 ± 2.1 |
| 1098.3 | 2782-1684 | 23.3 ± 2.1 |
| 1113.4 | | 1.7 ± 0.5 |
| 1124.4 | | 1.8 ± 1.0 |
| 1139.3 | | 4.4 ± 2.1 |
| 1142.4 | 2826-1684 | 5.6 ± 2.3 |
| 1180.7 | | 7.7 ± 1.2 |
| 1193.8 | 1997-803 | 6.5 ± 1.5 |
| 1235.0 | | 2.4 ± 0.7 |
| 1239.0[i] | (4459-3195) | 2.4 ± 0.7 |
| 1246.5 | 3244-1997 | 5.4 ± 0.8 |
| 1268 | | 5.1 ± 1.3 |
| 1283 | | 5.4 ± 1.3 |
| 1291 | | 3.2 ± 1.3 |
| 1305 | | 2.4 ± 1.8 |
| 1325 | | 4.9 ± 2.4 |
| 1332.3 | | 4.9 ± 2.4 |
| 1344.8 | 2148-803 | 29.7 ± 2.1 |
| 1361.4 | | 7.4 ± 3.3 |
| 1368.0[d] | | 2.6 ± 1.2 |
| 1385.5 | | 6.0 ± 2.0 |
| 1393.7 | 2197-803 | 23.4 ± 1.5 |
| 1432.6[d] | 2235-803 | 28.1 ± 1.5 |
| 1452.3 | | 5.2 ± 2.5 |
| 1457 | | 5.3 ± 2.5 |
| 1460[d] | | 5.4 ± 3.0 |
| 1466.7 | 1467-g.s. | 21.3 ± 1.3 |
| 1472.4 | | 6.0 ± 3.0 |
| (1480)[j] | | 2.1 ± 1.2 |

Table 1. Continued

| $E_\gamma$ (keV)[b,c] | Assigned transition[a] | Intensity |
|---|---|---|
| 1487[j] | | 2.2 ± 1.3 |
| 1495[k] | | 2.3 ± 1.0 |
| 1520.0 | (3944-2423) | 2.7 ± 1.0 |
| 1525.5 | | 2.4 ± 1.0 |
| 1532.7 | | 1.3 ± 0.7 |
| 1537.7 | | 1.1 ± 0.7 |
| 1546.4[l] | | 1.4 ± 0.6 |
| 1560.3 | 3244-1684 | 12.0 ± 1.6 |
| 1565.0 | 3563-1997 | 3.6 ± 1.2 |
| 1575.9 | 3260-1684 | 7.7 ± 1.6 |
| 1580.1 | | 3.3 ± 1.6 |
| 1585.1 | | 7.8 ± 2.4 |
| 1588.2 | 2929-1341 | 19.4 ± 2.3 |
| 1595.3 | | 5.8 ± 2.3 |
| 1620.0 | 2423-803 | 18.7 ± 1.9 |
| 1648 | | 3.3 ± 0.9 |
| 1653[j] | | 2.6 ± 1.3 |
| 1655.5[j] | | 2.6 ± 1.3 |
| 1690[d] | | 6.6 ± 1.2 |
| 1700.1 | 3484-1784 | 15.4 ± 5.5 |
| 1703.5 | 1703-g.s. | 46.2 ± 5.5 |
| 1717.3[j] | | 8.2 ± 2.4 |
| 1718.7[j] | 3403-1684 | 8.3 ± 2.4 |
| 1749[d] | | 4.2 ± 1.0 |
| 1757.0 | | 2.1 ± 0.8 |
| 1764.8 | | 2.5 ± 1.2 |
| 1769.7 | | 13.9 ± 1.6[f] |
| 1778.4 | (3776-1997) | 1.6 ± 0.8 |
| 1782[j] | | 1.3 ± 0.8 |
| 1784.7 | 1785-g.s. | 2.7 ± 0.8 |
| 1786.5 | | 3.3 ± 1.0 |
| 1795.3 | | 9.8 ± 1.7 |
| 1800.9 | | 5.3 ± 1.7 |
| 1821.7[d] | (3606-1784) | 9.8 ± 0.9 |
| 1835.9[j] | | 4.9 ± 2.2 |
| 1844.4 | 2648-803 | 58.1 ± 1.6 |
| 1854.1 | (4238-2384) | 2.0 ± 1.5 |
| 1861.5 | | 4.1 ± 0.8 |
| 1869.7 | | 2.7 ± 1.2 |
| 1873.4[j] | | 3.7 ± 1.4 |

Table 1. Continued

| $E_\gamma$ (keV)[b,c] | Assigned transition[c] | Intensity |
|---|---|---|
| 1878.7 | 3563-1684 | 8.5 ± 1.0 |
| 1899.6 | (3683-1784) | 3.6 ± 1.4 |
| 1903.6[j] | 3244-1341 | 8.2 ± 1.4 |
| 1933.1 | | 2.0 ± 1.3 |
| 1938.5 | | 2.8 ± 1.3 |
| 1955.2[j] | | 2.9 ± 1.3 |
| 1961.0[j] | | 2.9 ± 1.3 |
| 1971.3[d] | | 7.6 ± 0.8 |
| 1981 | | 0.8 ± 0.4 |
| 1988.4[j] | | 0.8 ± 0.4 |
| 1995.8[j] | | 1.0 ± 0.9 |
| 1995.5[j] | (3780-1784) | 2.7 ± 1.3 |
| 2002.5 | | 4.1 ± 1.0 |
| 2008.0 | (4005-1998) | 4.3 ± 1.1 |
| 2041 | (3744-1703) | 3.0 ± 0.8 |
| 2049.5 | | 1.7 ± 0.6 |
| 2055[d] | | 2.7 ± 0.7 |
| 2092.1[d] | 3776-1684 | 11.1 ± 3.2[f] |
| 2127 | | 2.0 ± 0.6 |
| 2149[d] | | 1.1 ± 0.5 |
| 2159.6[d,j] | | 2.9 ± 0.6 |
| 2165[i] | | 1.3 ± 0.6 |
| 2181.6 | | 3.6 ± 1.5 |
| 2185.7[d] | | 3.6 ± 1.5 |
| 2208.2 | | 1.8 ± 1.2 |
| 2219.4 | | 3.8 ± 1.0 |
| 2235[d] | (4469-2235) | 3.4 ± 1.4 |
| 2256[j] | | 3.2 ± 1.0 |
| 2268.7 | | 3.5 ± 2.0 |
| 2300[j] | | 3.4 ± 1.4 |
| 2305 | (3989-1684) | 5.1 ± 1.4 |
| 2314 | (3780-1467) | 5.0 ± 1.3 |
| 2317.8 | 3121-803 | 10.1 ± 1.3 |
| 2324[j] | | 3.6 ± 1.4 |
| 2333[j] | | 4.2 ± 1.4 |
| 2347[d] | | 3.0 ± 1.5 |
| 2355 | | 4.5 ± 1.5 |

Table 1. Continued

| $E_\gamma$ (keV)[b,c] | Assigned transition[c] | Intensity |
|---|---|---|
| 2370 | | 3.0 ± 1.2 |
| 2380[d] | | 2.3 ± 1.0 |
| 2385 | (4697-2313) | 1.4 ± 0.9 |
| 2390[d] | | 2.8 ± 1.3 |
| 2394 | | 2.6 ± 1.3 |
| 2411[d] | | 3.2 ± 0.9 |
| 2415 | | 3.2 ± 0.9 |
| 2424[j] | | 1.4 ± 0.6 |
| 2433[j] | | 1.0 ± 0.5 |
| 2438[j] | | 1.4 ± 0.7 |
| 2460[k] | (4657-2197) | 3.1 ± 1.5 |
| 2488 | | 3.9 ± 1.3 |
| 2495[d,j] | (4730-2235) | 1.0 ± 0.7 |
| 2503[d] | (4187-1684) | 2.9 ± 0.7 |
| 2518[d] | | 3.4 ± 0.7 |
| 2539[d,j] | | 3.6 ± 1.2 |
| 2546[d,j] | | 3.7 ± 1.2 |
| 2565[d] | | 3.7 ± 1.3 |
| 2583[d] | (4730-2148) | 5.1 ± 2.0 |
| 2605 | (3944-1341) | 2.1 ± 1.3 |
| 2619[j] | | 7.5 ± 5.0 |
| 2627[l] | (4331-1703) (4410-1784) | 1.9 ± 1.4 |
| 2632 | | 5.7 ± 1.2 |
| 2641.4 | | 7.5 ± 2.0 |
| 2650.4 | 3454-803 | 26.7 ± 2.5 |
| 2660 | | 2.7 ± 1.2 |
| 2664 | | 2.8 ± 1.2 |
| 2672 | | 2.9 ± 1.5 |
| 2676[j] | | 6.0 ± 1.5 |
| 2681[j] | 3484-803 | 13.4 ± 2.0 |
| 2685[j] | | 4.0 ± 2.0 |
| 2701 | (4385-1684) | 1.5 ± 1.0 |
| 2713[j] | 3516-803 | 6.8 ± 1.3 |
| 2717[j] | (4420-1703) | 4.5 ± 1.5 |
| 2738 | | 2.6 ± 0.6 |
| 2761 | | 1.6 ± 0.9 |
| 2764.6 | | 8.3 ± 1.5 |
| 2775.0[d] | (4116-1341) | 6.1 ± 1.4 |
| 2803[j] | | 3.8 ± 0.8 |
| 2808[j] | | 1.9 ± 0.8 |

Table 1. Continued

| $E_\gamma$ (keV)[b,c] | Assigned transition[e] | Intensity |
|---|---|---|
| 2825[d] | | 2.5 ± 1.4 |
| 2834[d] | | 5.0 ± 1.4 |
| 2844[d] | | 3.2 ± 1.5 |
| 2860[d] | | 0.8 ± 0.6 |
| 2870[d] | | 1.4 ± 0.8 |
| 2880 | (3683-803) | 1.6 ± 0.8 |
| 2907 | | 2.7 ± 0.9 |
| 2930 | | 0.7 ± 0.4 |
| 2941[j] | (3744-803) | 1.0 ± 0.4 |
| 2944[j] | | 1.8 ± 1.0 |
| 2977 | (3780-803) | 0.6 ± 0.4 |
| 2987 | | 3.3 ± 0.6 |
| 3009[d] | | 3.7 ± 0.6 |
| 3064 | | 1.3 ± 0.8 |
| 3079 | (4420-1341) | 3.2 ± 0.6 |
| | (4782-1703) | |
| 3114[d] | | 1.4 ± 1.0[m] |
| 3141[d] | (3944-803) | 2.1 ± 0.5 |
| | (4606-1467) | |
| 3168 | (3971-803) | 2.9 ± 0.4 |
| 3186 | 3989-803 | 3.0 ± 0.7 |
| 3195 | 3195-g.s. | 6.9 ± 0.7 |
| 3207[j] | 4010-803 | 3.3 ± 1.0 |
| 3211[j] | | 1.7 ± 1.0 |
| 3232 | 4035-803 | 1.6 ± 0.8 |
| 3242 | 4045-803 | 2.3 ± 1.1 |
| 3252 | | 0.9 ± 0.4 |
| 3263 | 4066-803 | 2.2 ± 0.6 |
| 3273 | 4076-803 | 2.2 ± 0.6 |
| 3299[j] | | 2.9 ± 1.4 |
| 3307[j] | (4648-1341) | 3.0 ± 1.5 |
| 3384[d,j] | | 1.7 ± 0.7 |
| 3419 | | 1.7 ± 0.5 |
| 3448[j,k] | | 1.7 ± 0.8 |
| 3497 | | 1.4 ± 0.4 |
| 3522 | | 2.3 ± 0.5 |
| 3544 | (4347-803) | 4.0 ± 0.5 |
| 3578 | | 3.4 ± 0.5 |

Table 1. Continued

| $E_\gamma$ (keV)[b,c] | Assigned transition[a] | Intensity |
|---|---|---|
| 3595[j] | | 1.5 ± 0.6 |
| 3607[j] | 4410-803 | 8.3 ± 1.5 |
| 3624 | (4427-803) | 3.9 ± 1.5 |
| 3631 | 4434-803 | 2.2 ± 1.1 |
| 3644 | | 0.9 ± 0.5 |
| 3656 | 4459-803 | 0.6 ± 0.3 |
| 3709 | 4512-803 | 1.0 ± 0.5 |
| 3722 | 4545-803 | 2.4 ± 0.4 |
| 3744.3 | 3744-g.s. | 6.3 ± 0.6 |
| 3854[d] | 4657-803 | 2.3 ± 0.4 |
| 3872[d] | 4675-803 | 1.0 ± 0.2 |
| 3894 | 4697-803 | 1.4 ± 0.3 |
| 3927[d,j] | 4730-803 | 2.3 ± 0.8 |
| 3953[j] | 4756-803 | 1.7 ± 0.5 |
| 3963[j] | 3963-g.s. | 0.7 ± 0.4 |
| 3971[j] | 3971-g.s. | 1.6 ± 0.5 |
| 3992[j] | 4795-803 | 1.3 ± 0.9 |
| 3997[j] | 3997-g.s. | 1.3 ± 0.9 |
| 4051 | 4051-g.s. | 0.8 ± 0.4 |
| 4116.7 | 4117-g.s. | 8.6 ± 0.7 |
| 4212 | 4212-g.s. | 1.1 ± 0.3 |
| 4330.7 | 4331-g.s. | 2.9 ± 0.4 |
| 4340 | 4340-g.s. | 1.3 ± 0.5 |
| 4420 | 4420-g.s. | 0.8 ± 0.3 |
| 4434 | 4434-g.s. | 1.0 ± 0.5 |
| 4469.2 | 4469-g.s. | 1.3 ± 0.3 |
| 4482.9 | 4483-g.s. | 2.4 ± 0.5 |
| 4606 | 4606-g.s. | 0.8 ± 0.3 |
| 4648 | 4648-g.s. | 0.8 ± 0.4 |
| 4717 | 4717-g.s. | 0.4 ± 0.2 |
| 4763 | 4763-g.s. | 0.6 ± 0.3 |
| 4782 | 4782-g.s. | 0.6 ± 0.3 |

[a]Ideally, the incident neutron fluence from the d(d,$^3$He)n system that was used would be a uniform distribution of neutrons having energies between 4.7 and 5.0 MeV. All non-linear effects (e.g., multiple scattering, finite size, etc.) reduce the average neutron energy. However, there will still be enough higher-energy neutrons to excite levels in the sample up to 4.8 MeV.

[b] $\Delta E_\gamma \simeq 0.6 + 3 \times 10^{-4}\ E_\gamma$ for entries given to one decimal place; $\Delta E_\gamma \simeq 1.3 + 5 \times 10^{-4}\ E_\gamma$ for other entries.

[c] Data given in parentheses are not as certain as data not in parentheses.

[d] Peak in spectral data is broad and may represent response of more than one gamma ray; the yield given is for the total peak.

[e] Peak may contain a contribution from the $^{7}Li(n,n'\gamma)$ reaction.

[f] After subtraction of estimated $^{207}Pb$ contribution.

[g] Peak may contain a contribution from the $^{63}Cu(n,n'\gamma)$ reaction.

[h] Peak may contain a contribution from the $^{27}Al(n,n'\gamma)$ reaction.

[i] Peak may contain a contribution from neutron interactions with $^{56}Fe$.

[j] Data estimated for yield of one gamma ray in a large or broad peak and is not the yield for the total recorded response.

[k] Peak could be due to background of undetermined origin.

[l] Peak could be due at least partly to a contribution from $^{207}Pb(n,n'\gamma)$, which contribution is included in the reported yield.

[m] May be entirely due to an escape response of a higher-energy gamma ray.

cross sections. The major problem is the lack of knowledge of the isotopic composition of the sample. "Radiogenic" lead is thought to have an approximate isotopic composition of 88% $^{206}Pb$, 9% $^{207}Pb$, and 3% $^{208}Pb$ (c.f. ref. 11); however, the present sample may be richer in $^{207}Pb$ by as much as a factor of two. A sample of normal Pb was studied using the ORELA system, and if the isotopic composition of the normal Pb sample is the "normal" composition, then the $^{207}Pb$ content of the radiogenic sample is $\sim$18%. However, there are wide variations in isotopic composition of various lead deposits. The uncertainties related to the isotopic concentrations provide the largest uncertainty for absolute yield data. As a consequence, absolute yields were not determined.

Gamma-ray data for other $E_\gamma$ obtained at other $E_n$ are given in Table 2. Deduced transition assignments are given for 146 gamma rays in these tables.

## IV. GAMMA-RAY PLACEMENTS

Deduced gamma-ray placements as transitions among excited states in $^{206}Pb$ are presented in Figs. 3 to 5 and given in Table 1. In these figures the excitation energies and many $J^\pi$ assignments were obtained from the literature[7] augmented by the present data. The small numbers at the interstitial points of Figs. 3 and 4 represent branching ratios (in %) determined from the present data.

### A. Structure for $E_x < 2.5$ MeV

As may be observed in Fig. 1, there is a gap in the level structure of $^{206}Pb$ for $E_x \sim 2.5$ MeV, not only for the experimental data, but also for all model calculations. Most of the gamma-ray transitions shown in Fig. 3 were assigned on the basis of prior experimental knowledge verified by threshold measurements from the ORELA experimental system. The analysis up to this gap in $E_x$ appears definitive and very nearly complete.

#### 1. $E_x$ = 803.1, 1165.0, 1340.6, and 1466.6 keV

No gamma ray of ∿360 keV corresponding to the 1165-803 keV transition was observed. Hence, the 1165-keV level decays (almost) entirely by E0 pair production. The very strong 803- and 537-keV gamma-ray placements are verified.

The 664- and 1467-keV gamma rays are observed having correct thresholds, and so their prior placements in the level structure have been verified.

Table 2. Gamma Rays Observed[a] Following Neutron Inelastic Scattering From $^{206}Pb$

| $E_{\gamma}$ (keV)[b,c] | Assignment[c] | Spectrum Observed in[c,d] 5.4 | 5.9 | 6.4 | #7 | #6 | Remarks |
|---|---|---|---|---|---|---|---|
| 184.0 | (2384-2200) | | | | (X) | (X) | $E_n$ threshold indistinct |
| 1416 | | X | | | | | |
| 1614 | | X | | | | | |
| 1686 | | X | | | | | |
| 1714 | | X | | | X | | |
| 1927 | | | | X | | | |
| 3106 | | | | X | | | |
| 3285 | | | | X | | X | In #6 as part of a broad peak |
| 3484 | | | | X | | X | |
| 3538 | | | | X | | X | |
| 3686 | | | | X | (X) | (X) | In #7 and #6 as part of a broad group |
| 3712 | | | | X | | X | In #6 as part of a broad group |
| 4004 | | | (X) | X | | (X) | In #6 as part of a broad group |
| 4111 | (4914-803) | X | | | X | | Transition to 803-keV level more likely than transition to 1165-keV level |
| 4163 | (4966-803) | X | | X | X | | |
| 4286 | 5089-803 | X | | | X | | |
| 4356 | | | | | X | (X) | Not in 5.4, not obvious in 5.9 |
| 4473 | 5276-803 | X | | | X | | In 5.4 as part of a group partially including an escape peak |
| 4576 | 5379-803 | X | | | X | | |
| 4599 | | X | | | | | Not obvious in #7. May be an escape peak or a background contribution. |
| 4612 | (5415-803) | | X | X | X | (X) | |
| 4631 | | | | X | | (X) | |
| 4799 | 5602-803 | | X | | X | | May include an escape peak |

Table 2. Continued

| $E_\gamma$ (keV)[b,c] | Assignment[c] | Spectrum Observed in[c,d] | | | | | Remarks |
|---|---|---|---|---|---|---|---|
| | | 5.4 | 5.9 | 6.4 | #7 | #6 | |
| 4824 | | | | X | | X | May include an escape peak |
| 4848 | 4848-g.s. | X | | | X | | |
| 4938 | 5741-803 | | X | (X) | | X | |
| 4960 | | | | (X) | | X | |
| 4972 | (4972-g.s.) (5775-803) | (X) | X | X | | (X) | May well be both transitions |
| 4985 | | X | X | | | (X) | Not obvious in #7; may be background contribution |
| 5029 | (5832-803) | | | X | | (X) | |
| (5042) | (5042-g.s.) | X | X | | | | |
| 5180 | 5180-g.s. | | X | | X | | |
| 5195 | 5195-g.s. | (X) | X | | X | | |
| (5236) | (5236-g.s.) | X | X | | | | Not apparent in #7 |
| 5247 | (5247-g.s.) | X | X | | | (X) | |
| 5282 | (5281-g.s.) | X | X | | | | |
| (5300) | | | | | X | | |
| 5315 | 5315-g.s. | X | (X) | | X | | |
| (5326) | | | | | X | | |
| 5350 | (5350-g.s.) | | X | | (X) | | |
| 5385 | | | | | | X | |
| 5390 | 5390-g.s. | | X | (X) | X | | |
| (5409) | | | | X | | (X) | Widepeak in 6.4 MeV spectrum |
| 5513 | (5513-g.s.) | | | X | | X | |
| 5522 | (5522-g.s.) | | | X | | (X) | |
| 5580 | 5580-g.s. | | | X | | (X) | Escape peak observed in 5.9-MeV spectrum |
| 5589 | | | | | | X | |
| 5618 | 5618-g.s. | | | X | | | Escape peak may be in 5.9-MeV spectrum |
| 5840 | 5840-g.s. | | | X | | | |
| 5936 | (5936-g.s.) | | | X | | | Escape peak may be in 5.9-MeV spectrum |

Table 2. Continued

| $E_\gamma$ (keV)[b,c] | Assignment[c] | Spectrum Observed in[c,d] 5.4 | 5.9 | 6.4 | #7 | #6 | Remarks |
|---|---|---|---|---|---|---|---|
| 5994 | 5994-g.s. | | | X | | | |
| 6197 | 6197-g.s. | | | X | | | |
| 6236 | (6236-g.s.) | | | X | | | Could be due possibly to $^{56}Fe$ (n,γ) capture. |
| 6251 | 6251-g.s. | | | X | | | |
| 6260 | 6260-g.s. | | | X | | | |

[a]Excludes the gamma rays given in Table 1.

[b]$\Delta E_\gamma$ as given in Table 1, footnote b.

[c]Values in parentheses are less certain.

[d]Column headings are, respectively, $E_n \approx 5.4$, $E_n \approx 5.9$, and $E_n \approx 6.4$ MeV Van de Graaff measurements, and #7 is $4.9 < E_n < 5.9$, #6 is $5.9 < E_n < 7.3$ MeV bins for ORELA measurements. $E_\gamma(max) = 5.4$, 5.4, 6.28, 5.63, and 5.63 MeV, respectively; and $E_\gamma(min) = 0.5$, 0.4, 0.4, 0.1, and 0.1 MeV, respectively. "X" indicates gamma ray identified in the spectrum designated by the column heading.

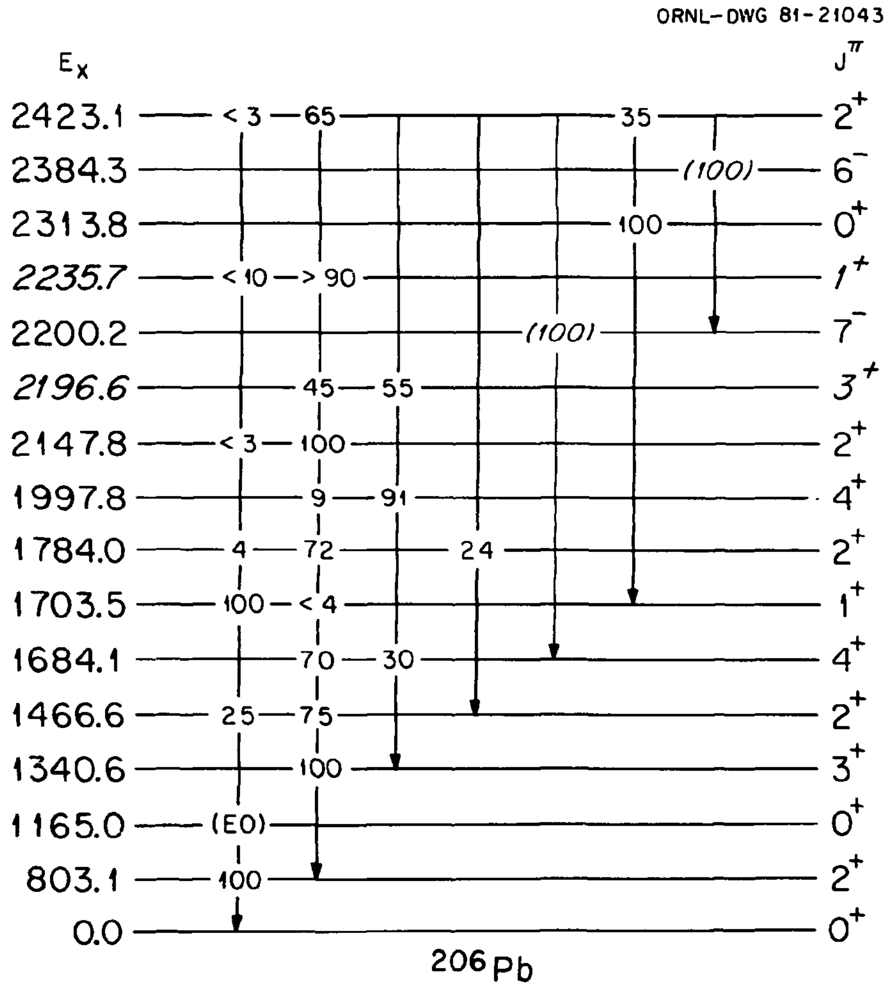


Fig. 3. $^{206}$Pb level structure for $E_x$ < 2.6 MeV deduced from the present experiment. Two new levels, at $E_x$ = 2196.6 and 2235.7 keV are indicated, and one previously (and tentatively) suggested level at $E_x \cong$ 2391 keV is not included. All of the excited states in this energy region have most likely been located.

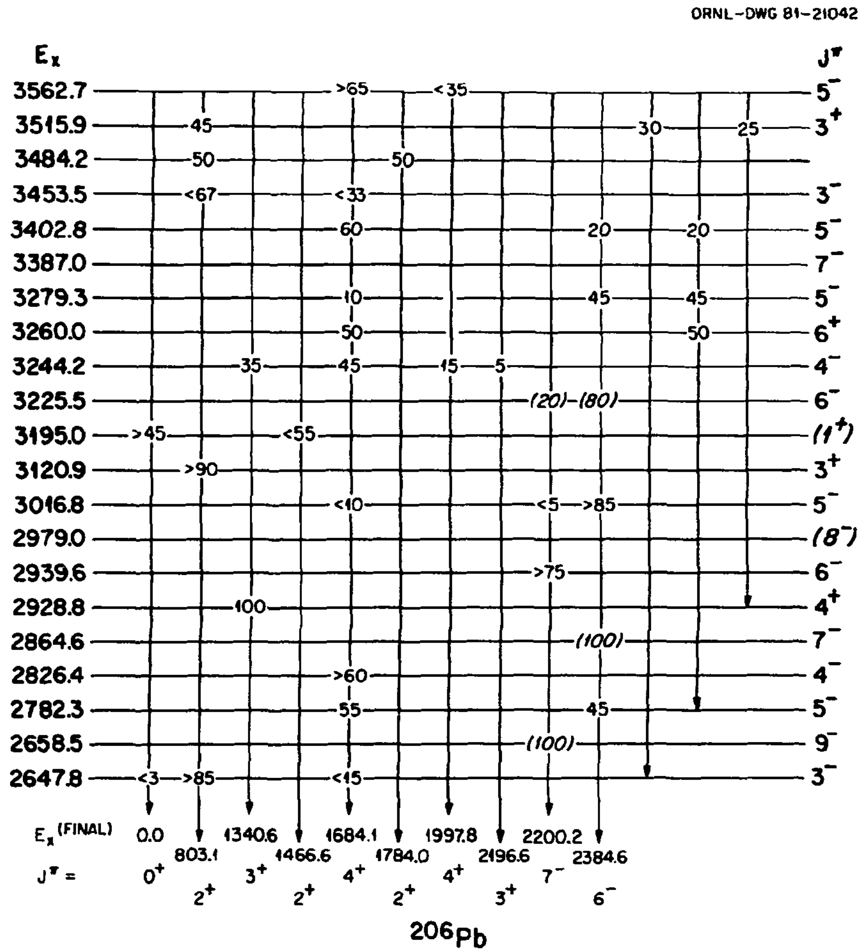


Fig. 4. $^{206}$Pb level structure for $2.6 < E_X < 3.6$ MeV. Most of the anticipated levels for this energy region are indicated. The present gamma ray data are indicated; some previously observed gamma rays (see ref. 12) were too weak to be unambiguously observed in the present experiment and are not included.

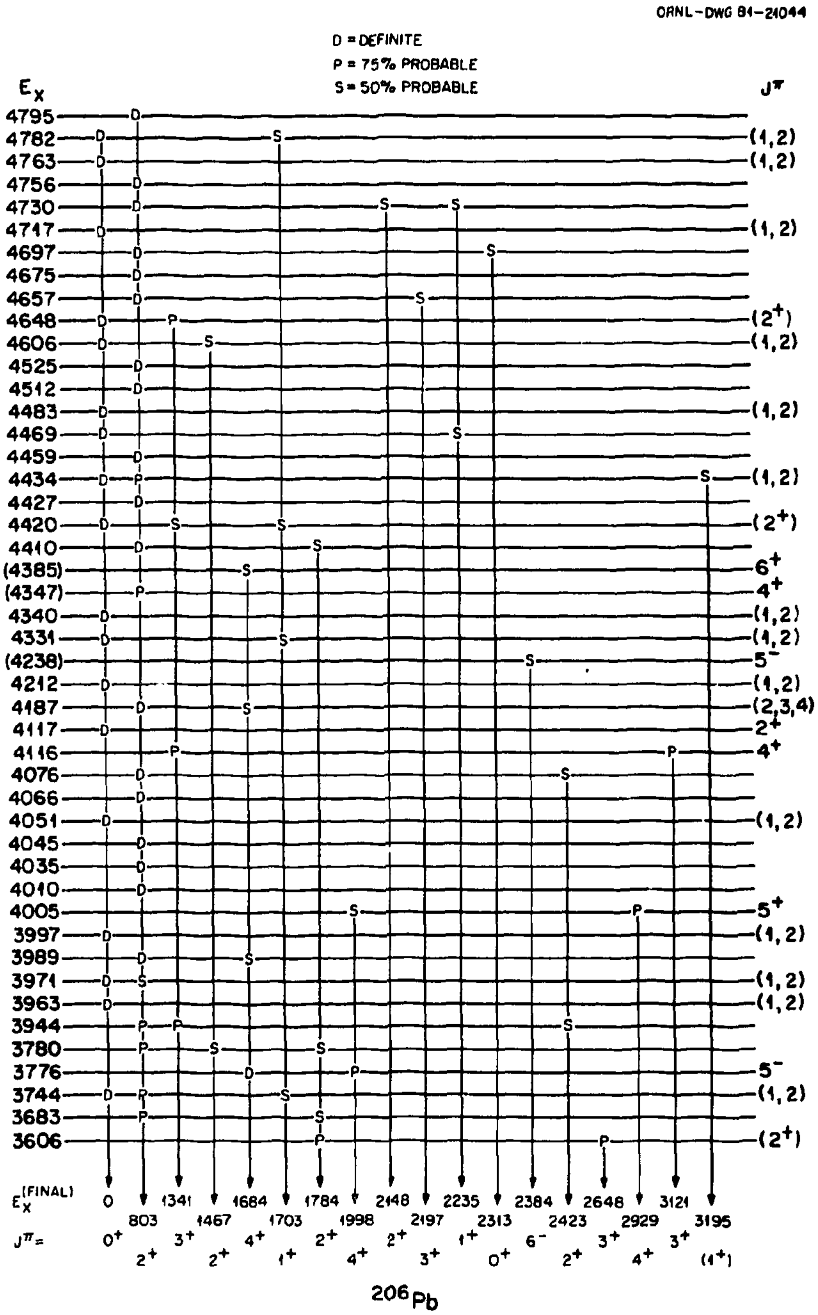


Fig. 5. $^{206}Pb$ level structure for $3.6 < E_X < 4.8$ MeV as determined from the present experimental data. Except for levels at $E_X$ = 3606, 3776, 4005, 4238, 4347, and 4385 keV, the present data were utilized to locate and delineate the exhibited levels. For the six specified levels, the transitions shown represent likely (S) or very likely (P) assignments of gamma rays observed in the present experiment consistent with prior information about these levels.

2. $E_x = 1703.5$ keV

A strong 1703-keV gamma ray is observed for $E_n < 2$ MeV. A possible 900-keV transition is masked by the strong 898-keV gamma ray from $^{207}Pb(n,n'\gamma)$. A measurement was made for a natural Pb sample for $E_n < 3$ MeV. There was no evidence for a 900-keV contribution >4% of the $E_\gamma = 1703$ keV yield. (There is evidence, however, for a $^{206}Pb$ contribution in the 898-keV gamma-ray yield at $E_n = 4.8$ MeV.)

3. $E_x = 1784.0$ keV

The strong 981-keV gamma ray is observed for $E_n < 2$ MeV, and the weaker 1784- and 317-keV gamma rays are observed for $E_n$ < 2.5 MeV. The 317-keV gamma ray is placed as the 1784-1467 keV transition as shown in Fig. 3 because this is the only transition available for $E_n < 2.5$ MeV having the correct energy. This transition, however, is predicted to be very weak by a complete shell-model calculation.[8]

4. $E_x = 1997.8$ keV

The strong 657-keV gamma ray is observed for $E_n < 2.5$ MeV; the 1195-keV gamma-ray is weakly observed for $E_n < 3.5$ MeV. Its placement as the 1998-803 keV transition is tentative and due to this transition designation in $^{206}Bi$ decay.[12] The 314-keV gamma ray is not definitely observed except probably at $E_n = 4.8$ MeV, and its placement as the 1998-1684 keV in $^{206}Bi$ decay[12] is not verified.

5. $E_x = 2147.8$ keV

The strong 1345-keV gamma ray is observed for $E_n < 2.5$ MeV. A weak 2148-keV gamma ray is observed for $E_n = 4.8$ MeV which may include the 2148-keV to ground state transition. No other gamma rays having correct energies for other possible transitions from this level were observed.

6. $E_x$ = 2196.6 and 2235.7 keV: New Levels

These two levels are postulated to be the $J^\pi = 1^+$ and $3^+$ levels missing from the "basic-coupling" $(p_{3/2}\ f_{5/2})$ configuration shown in Fig. 1. The 856-, 1393-, and 1432-keV gamma rays are definitely observed for $E_n < 2.5$ MeV. (The 856-keV peak observed is probably a doublet.) A weak 2235-keV gamma ray is observed for $E_n = 4.8$ MeV which could include the 2235-keV to ground state transition. On the basis of correct assignment of the 856-keV gamma ray as the 2197-1341 keV transition, a $J^\pi$ of $3^+$ is favored for the 2197-keV level, leaving a $J^\pi = 1^+$ assignment for the 2235-keV level. The $3^+$ assignment to the 2197-keV level is strengthened by the placement of a 1048-keV transition between $E_x = 3244$ keV, $J^\pi = 4^-$ and the 2197-keV level. The existence of these two levels is supported by the neutron spectra obtained and reported by Cranberg et al.[13]

Shown in Fig. 1 is a level at $E_x = 2391$ keV proposed from the analysis of $^{206}$Bi decay.[12] The proposed 1588-keV gamma ray assigned as the 2391-802 keV transition is not observed for $E_n < 2.5$ MeV, but appears to have a threshold at $E_n \sim 3$ MeV. There is no other direct evidence for a level at $E_x = 2391$ keV, and with the location of all members of the $(p_{3/2}\ f_{5/2})$ quartet and other nearby "basic-coupling" configurations, the existence of this level is in doubt and it is not included in Fig. 3.

7. $E_x$ = 2200.2 and 2384.3 keV

The $J^\pi = 7^-$ level at $E_x = 2200$ keV decays to the 1684-keV level emitting a 516-keV gamma ray. This level has a 125-μs lifetime, however, and it is not likely that the 516-keV gamma ray observed for $E_n = 4.8$ MeV is due solely to this transition since the electronic system was set to observe "prompt" information within a few microseconds after neutron scattering.

The $J^\pi = 6^-$ level at $E_x = 2384$ keV decays to the 2200-keV level by emission of a 184-keV gamma ray. This gamma ray is possibly evident for $E_n > 3.5$ MeV. This is a situation where the apparent $E_n$ threshold predicts level placement poorly. The $6^-$ state is not expected to be strongly excited directly by neutron scattering. Rather the creation of the state in this experiment is due primarily to decay from higher-lying lower-spin excited states.

8. $E_x$ = 2313.8 and 2423.1 keV

The $J^\pi = 0^+$ state at $E_x$ = 2314 keV is not expected to be strongly populated either by direct neutron excitation or by decay from higher-lying excited states. A weak 610-keV gamma ray is observed for $E_n$ = 4.8 MeV which may include the 2314-1703 transition shown in Fig. 3. This transition is the most likely one, since it involves a preferred change of "basic-coupling" configuration from $(p_{3/2}\ p_{3/2})$ to $(p_{3/2}\ p_{1/2})$. It is also the most likely one predicted by a more detailed shell-model calculation.[8] No other gamma rays are observed that could be transitions from this level unless the weak 848-keV gamma ray in the raw data ascribed to background from $^{56}$Fe(n,n'$\gamma$) includes the 2314-1467 transition in $^{206}$Pb.

A 1620-keV gamma ray observed for $E_n$ < 2.9 MeV is assigned as decay from the 2424-keV level. A very weak 2424-keV gamma ray is observed for $E_n$ = 4.8 MeV. It could be the $E_x$ = 2423-keV level to ground-state transition. Other gamma rays observed at $E_n$ = 4.8 MeV which could correspond to transitions from this level have $E_\gamma$ = 637, 719, and 957 keV. The one closest in energy is the 719-keV gamma ray and its probable branching ratio is shown in Fig. 3.

9. Summary for $E_x$ < 2.5 MeV

A very nearly complete picture of the transitions among the 16 lowest energy levels in $^{206}$Pb has been deduced and is shown in Fig. 3. The uncertainties correspond to possible transitions from the decay of the $E_x$ = 1998-, 2148-, 2235-, and 2423-keV levels.

## B. Structure for 2.6 MeV < $E_x$ < 3.6 MeV

There are 21 excited states in $^{206}$Pb in this interval of excitation which have been previously observed;[7] 11 of these have been studied in the beta decay of $^{206}$Bi.[12] Transitions corresponding to gamma-ray decay of 19 of these levels were observed, or probably observed, but not all of the known gamma-ray transitions[12] were detected.

1. $E_x$ = 2647.8 keV

This level is known to be a collective state[6] and is indicated in the "basic coupling" column of Fig. 1 as the $^{208}$Pb $3^-$ state coupled with the $(p_{1/2}^{-1})^2$ state. A very strong 1844.5-keV gamma-ray is observed with the correct threshold. Previous experiments[12] suggest a second transition of 964 keV from decay of this state. A gamma ray of ∿964 keV was observed; however, there is a known background line due to $^{63}$Cu(n,n'γ) at about this excitation energy which may be contributing to the observed peak. In addition, a peak for $E_\gamma$ ∿964 keV is observed at $E_n$ less than threshold for exciting the 2648-keV level. The experimental system described in ref. 1 was designed to reduce background due to (n,n'γ) reactions, and so some portion of the observed data for $E_\gamma$ = 964 keV is due to the transition in question. The values indicated for the branching ratios in Fig. 4 (i.e., >85% for the 1844-keV transition) reflect the facts presented above and the lack of a more definitive quantification for the 964-keV gamma ray. The possible ground-state transition gamma ray was searched for, and none was observed that had a yield >4% of the yield of the 1844 keV gamma ray.

2. $E_x$ = 2658.5, 2782.3, 2826.4, 2864.6, 2939.6, and 2979 keV

The $J^\pi$ of the first five of these states are known. The wave functions are probably dominated by the $(i_{13/2}\,f_{5/2})_{J^\pi=4^-\text{ to }9^-}$ configurations. Gamma-ray decay of 4 of these states (2782, 2826, 2865, and 2940 keV) has been observed in the $^{206}$Bi decay.[12] The present data were studied to obtain information on the production of these gamma rays in the present experiment. Gamma rays having the largest yields in the $^{206}$Bi decay were observed; most of the gamma rays weakly observed in the $^{206}$Bi decay were not seen in the present data. For the decay of the $J^\pi = 9^-$ $E_x$ = 2659 keV state, identified in the $^{204}$Hg(α,2nγ) reaction,[3] a weak gamma ray of ∿449 keV was observed in the $E_n$ = 4.8 MeV spectrum.

As this gamma ray corresponds to the only reasonable decay transition of this state, it is possible that the given placement is correct despite the fact that the $9^-$ state will be only very weakly directly excited by the (n,n') reaction. The two transitions shown for the 2782-keV state correspond to gamma rays exhibiting correct $E_n$ thresholds. The 398-keV gamma ray is probably a doublet at $E_n$ = 4.8 MeV. The given branching ratios were deduced from lower energy ($E_n$) data and do not include transitions unobserved in this experiment. For $E_x$ = 2826 keV, only one weak gamma ray was definitely observed. Estimates were made of the yields of other possible (or previously reported) gamma rays, resulting in the lower limit for the branching ratio given in Fig. 4. The $^{206}$Bi decay experiments[12] report a gamma-ray transition of 435 keV to a postulated level at 2391 keV, which level probably does not exist. For $E_x$ = 2865 keV, $J^\pi = 7^-$ the only gamma ray observed in this experiment which corresponds to the previously reported[12] 479 keV $J^\pi = 7^-$ to $6^-$ transition is probably due to either the 3260-2782 keV transition or to the $^7$Li(n,n'$\gamma$) reaction, or both. Upper limits for yields of the other two gamma rays at $E_\gamma$ = 1181 and 664 keV were estimated from the data to arrive at the lower limit of the branching ratio given in Fig. 4. This branching ratio is somewhat larger than deduced from $^{206}$Bi decay data.[12] No gamma-ray transitions were observed which could be definitely assigned as decay of the 2979-keV level. This level has been observed very weakly only in the $^{208}$Pb(p,t) reaction.[14] The evidence, such as it is, suggests that this level could be the missing $8^-$ of the "basic coupling" ($i_{13/2}\ f_{5/2}$) sextuplet, and so this suggested $J^\pi$ is indicated in Fig. 4.

3. $E_x$ = 2928.8 and 3120.9 keV

These two positive parity levels are likely related to the "basic-coupling" ($f_{7/2}\ p_{3/2}$) configuration. The 1588-keV gamma ray has the correct threshold for the 2929-1341 keV transition, and it is a comparatively strong transition. The somewhat weaker 2318-keV gamma ray has the correct threshold for the 3121-803 keV transition. A possible 1781-keV transition (3121-1340) was masked by the stronger 1784-keV gamma ray. The lower limit of the branching ratio given in Fig. 4

indicates the best quantitative estimate of the possible yields of other unobserved gamma rays, especially the amount of 1781-keV transition in the data for the 1784-keV gamma ray.

4. $E_x$ = 3016.8 keV

This level could be the $J^\pi = 5^-$ level of the "basic coupling" $(i_{13/1}\ p_{3/2})$ configuration. The previously reported[12] 632-keV gamma ray is observed with the correct threshold in the present experiment. Previously reported gamma rays having $E_\gamma$ = 234 and 1332 keV were not observed in the present experiment with sufficient yield for positive identification.

5. $E_x$ = 3195.0 keV

This level is observed[7] in (p,d) and (p,t) pickup reactions but not in stripping, $(\gamma,\gamma')$ or (p,p') measurements. A weak, but definite, gamma-ray peak is observed in the data with the correct threshold to represent the ground-state transition. A careful search for gamma rays corresponding to transitions to $J^\pi = 2^+$ level was made. No gamma ray having $E_\gamma \sim 2392$ keV could be definitely identified. A gamma ray having $E_\gamma \sim 1728$ keV was observed; however, this gamma ray could also be due at least partly to $^{207}$Pb$(n,n'\gamma)$, and the limits to the branching ratios given in Fig. 4 reflect the unknown contribution from the $^{207}$Pb isotope. The spin of this state is likely to be J = 1. This state could be the $J^\pi = 1^+$ state of the $(f_{7/2}\ f_{5/2})$ basic coupling or else the $J^\pi = 1^-$ state of the $(3^- \otimes 2^+)$ coupling. Based upon the lack of observation in (p,p') and stripping reactions, the $J^\pi = 1^+$ is favored.

6. $E_x$ = 3225.5 and 3387.0 keV

These states could be the $J^\pi = 6^-$ and $7^-$ states of the "basic coupling" $(i_{13/2}\ p_{3/2})$ configuration. The $E_x$ = 3225.5 keV state is reported in $^{206}$Bi beta decay.[12] Two weak gamma rays were observed in the present experiment corresponding to previously reported transitions. The very weak 1025-keV gamma ray has the correct threshold; however, background from the strong $^{72}$Ge$(n,n'\gamma)$ gamma ray at about this $E_\gamma$

hampered efforts to determine the threshold of the 841-keV gamma ray. The branching ratios given in Fig. 4 assume the correct placement of this gamma ray as the 3226-2385 keV transition. No gamma rays were observed which could be definitely placed as transitions from the 3387-keV level, consistent with the high-spin assignment of this state.

7. $E_x$ = 3244.2 keV

This $J^\pi = 4^-$ state has been observed in $^{206}$Bi decay;[12] it may be the $4^-$ state of the $(3^- \otimes 2^+)$ basic coupling. All of the gamma-ray placements given in Fig. 4 appear to have correct thresholds, although the threshold for the weak 1047-keV gamma ray is partially masked by the $^{70}$Ge(n,n'$\gamma$) background peak at $E_\gamma$ = 1040 keV. The same four gamma rays are observed in $^{206}$Bi decay[12] with the 1904-, 1560-, and 1247-keV gamma rays assigned as shown in Fig. 4. The other gamma ray, $E_\gamma$ = 1048 keV, is observed in $^{206}$Bi decay[12] and was determined to have E1 multipolarity, but was not placed in the level structure. The present placement is consistent with the determination of a (new) level at $E_x$ = 2197 keV and having $J^\pi = 3^+$. The branching ratios given in Fig. 4 are averages of those deduced from the present yields and those deduced from the $^{206}$Bi decay yields.

8. $E_x$ = 3260.0 keV

This is the $J^\pi = 6^+$ level observed strongly in $^{208}$Pb(p,t) $^{206}$Pb reaction.[14] In the present experiment a gamma ray having energy $E_\gamma$ = 1576 keV is observed with the correct threshold for the 3260-1684 keV transition. The 478-keV gamma ray mentioned above in the discussion for $E_x$ = 2865 keV has an apparent threshold equivalent to the 3260-2782 keV transition with a yield about the same as for $E_\gamma$ = 1576 keV. No other gamma rays were observed having $E_\gamma$ > 300 keV and yields large enough for positive identification to correspond to another transition from this energy level. These assigned gamma rays are in agreement with $J^\pi = 6^+$, and if this is the correct $J^\pi$, this level may be assigned to the "basic coupling" $(f_{7/2}\ f_{5/2})$ configuration as suggested in Fig. 1.

9. $E_x$ = 3279.3 keV

Gamma rays corresponding to the two previously reported[12] strongest transitions from this level were definitely observed in the present experiment. The threshold for $E_\gamma$ = 497 is correct; the yield for $E_\gamma$ = 895 keV was separated from that for the much stronger 898-keV gamma ray due to $^{207}$Pb(n,n'γ) in the $E_n$ = 4.8 MeV spectrum; a threshold for this gamma ray could not be determined. A gamma ray having $E_\gamma$ = 1595 was observed having the correct threshold for the 3279-1684 keV transition; however, no gamma ray having $E_\gamma \sim$ 262 keV, corresponding to the previously reported 3279-3017 keV transition, was observed. The upper limit for the branching ratio for this transition would be <5% if the yields of the three placed gamma rays are correct. This level is strongly populated in $^{206}$Bi decay[12] (42% of the total beta decay) and strongly populated in (n,n'γ). This evidence supports assigning the "basic coupling" ($5^- \otimes 0^+$) configuration to this state.

10. $E_x$ = 3402.8 and 3562.7 keV

The $E_x$ = 3403 keV is the other strongly populated $J^\pi = 5^-$ level in $^{206}$Bi decay and the 3563-keV level is the highest energy level populated in $^{206}$Bi decay[12] and has $J^\pi = 5^-$ also. Gamma rays were observed in the present experiment corresponding to the stronger previously reported transitions[12] but the yields of these gamma rays were much less than those for the $J^\pi = 5^-$, $E_x$ = 3279 keV. Of the 5 gamma rays observed in the present experiment assigned as transitions from these two levels, only the rather weak $E_\gamma$ = 1565 keV, corresponding to the 3563-1998 keV transition, has a poorly defined threshold. Based primarily on the $^{206}$Bi decay strength, the $E_x$ = 3403 keV level may be related to one member of the "basic coupling" ($3^- \otimes 2^+$) configuration.

11. $E_x$ = 3453.5, 3484.2, and 3515.9 keV

These levels have been observed in (p,p'), (p,d), and (p,t) reactions. Three gamma rays having $E_\gamma$ = 2650, 2681, and 2713 keV are observed in the present data having about the same threshold, and they are assigned as transitions from these excited states to the $J^\pi = 2^+$ 803-keV first-excited state in $^{206}Pb$. Based upon the more accurate excitation energies provided by these three assignments, the present data were carefully studied for other gamma rays having correct energies and thresholds. Three other gamma rays were found satisfying these criteria, and the resulting branching ratios are shown in Fig. 4 for these three levels. On the basis of the accuracy of these assignments and the expectation that M1 transitions should be favored over E2 or higher multipolarity transitions, the 3453- and 3516-keV states should have J = 3. One of these, perhaps the 3516-keV state, may correspond to the $J^\pi = 3^+$ state of the "basic coupling" $(f_{7/2}\ f_{5/2})$ configuration. Probably the 3453-keV state has negative parity[15] and may correspond to the $J^\pi = 3^-$ state of the "basic coupling" $(3^- \otimes 2^+)$ configuration. If so, one would expect to observe a transition to the $J^\pi = 3^-$ $E_x$ = 2648 keV state. The calculated gamma-ray energy for this transition is 805.7 keV, unfortunately nearly degenerate with the dominant 803-keV gamma ray. Hence the branching ratios shown in Fig. 5 are upper limits. The spin of the 3484-keV state is most likely J = 1, 2, or 3, with J = 2 slightly favored on the basis that J = 1 might well have a ground-state transition (not observed in the present, or any other, experiment) and J = 3 would mean observation of three very close-lying states having the same spin.

## 12. Summary for $2.6 < E_x < 3.6$ MeV

New gamma-ray transitions have been determined for five levels in this $E_x$ energy span, and two previously transitions assigned as tentative[7] have been verified. Identification of five of the six "basic coupling" $(i_{13/2}\ f_{5/2})$ states has been supported, as has a candidate for the sixth state of this configuration. Both of the "basic coupling" $(f_{7/2}\ p_{1/2})$ states have been identified. Identification of three of the four "basic coupling" $(i_{13/2}\ p_{3/2})$ states has been suggested; the $J^\pi = 8^-$ state of this configuration has not yet been observed; this state would have been only very weakly excited by (n,n'). It is likely to lie close to $E_x$ = 3.2 MeV. Identification of the "basic coupling" $(5^- \otimes 0^+)$ state seems reasonably positive. Identification of 2 or 3 of the six "basic coupling"

$(f_{7/2}\ f_{5/2})$ states has been suggested. Only for $E_x$ = 3484 is it not yet reasonable to tentatively assign a unique spin. It is likely that several more excited states having excitation energies $E_x$ between 3.3 and 3.6 MeV will be located corresponding to the rest of the $(f_{7/2}\ f_{5/2})$ and $(3^- \otimes 2^+)$ configurations. So the picture of the transitions from these 21 energy levels in $^{206}$Pb as shown in Fig. 4 is not as complete as shown in Fig. 3 for the lower-lying levels, but it is more complete than in present evaluations.[7]

## C. Structure for $3.6 < E_x < 4.8$ MeV

In this section, the placements of gamma rays determined from the $E_n$ = 4.8 MeV measurement will be discussed. The current evaluations[7] give ∿40 excited states for this region of excitation energy in $^{206}$Pb. The estimated number of level should be >100 from the simple estimation given in Fig. 2, bearing in mind that the estimation exhibited in this figure is a lower limit since it was made from "basic coupling" configurations of neutron shell-model orbits only. One may also expect states based upon configurations of proton shell-model orbits[16] as well as states described by collective excitation configurations.[17]

Unfortunately, for this region of excitation, the correspondence of levels seen in different reactions is very uncertain. Only levels at $E_x$ ∿ 3770 ($J^\pi = 5^-$), 4115 ($J^\pi$ = probably $4^+$), 4325 ($J^\pi = 1^+$), and possibly 4390 ($J^\pi = 6^+$) keV are apparently identified in more than one experiment at close to the same excitation energy. There have been reported all told a sufficient number of levels with large enough uncertainties in excitation energy to blanket the region of excitation $E_x$ > 3950 keV. Only for a few of these levels can a definite $J^\pi$ assignment be made based upon experimental evidence.

It must be evident then that with so many observed gamma rays (Table 1), one could find transitions among the elements of just about any set of proposed levels. Unfortunately, for most of the unassigned gamma rays, the incident neutron-energy threshold is not as well defined as for the already assigned gamma rays, partly due to the small gamma-ray yields and partly due to the increased incident neutron-energy bin widths required to compensate for the rapid decrease in incident-neutron intensity with increased energy.[10] In addition, many of the levels observed in (specialized) transfer reactions will not be appreciably excited by neutron inelastic scattering. Consequently, detailed comparisons of the energies of possible transitions with observed gamma-ray energies will yield very little new definitive information. In fact, only for the few levels mentioned a few sentences back was it reasonable to make such detailed comparisons with some confidence.

The gamma-ray data, however, do yield definitive information about the $^{206}Pb$ level structure. All gamma rays having $E_\gamma > 4.0$ MeV observed in the $E_n = 4.8$ MeV spectrum must correspond to ground-state transitions and so define the excitation energies of 14 levels having $E_x$ between 4.0 and 4.8 MeV. There are 17 reported gamma rays having $E_\gamma$ between 3.6 and 4.0 MeV, and these must be either ground-state transitions or transitions to the $E_x$ = 803-keV first-excited state. Threshold measurements are sufficient to identify one type from the other for 16 of these gamma rays, resulting in assigning excitation energies to 11 more levels having $E_x > 4.4$ MeV. In addition, data taken using the ORELA system provide unambiguous thresholds for six more gamma rays, $E_\gamma$ = 3186, 3207, 3232, 3242, 3263, and 3273 keV. These gamma rays are assigned as transitions to the $E_x$ = 803-keV first-excited states. Thus, assignments of gamma-ray transitions have been made for 36 levels in $^{206}Pb$ having $4.8 > E_x > 3.7$ MeV based solely upon the present data. These assignments corroborate previously observed gamma-ray transitions[2] for $E_x$ = 3744, 4117, 4331, and 4606 keV, and the agreements in gamma-ray energies for these four transitions is excellent. Correspondence of any levels reported in prior measurements[2,12-19] with the other 31 newly postulated levels was attempted but without any success. Most likely, more than half of these are new levels.

These results are shown graphically in Fig. 5. In this figure, the "definite" labels ("D") indicate gamma-ray placements dictated by threshold considerations as discussed above. The symbols "P" and "S" stand for gamma-ray placements that cannot be rigorously defended, but which can be assigned based on reasons of energy agreement between the gamma ray and the assigned transition and a consistent $E_n$ threshold and the likelihood of the existence of the proposed transition. The degree of confidence of these placements is such that it is expected that 75% or more of those designated "P" have been correctly assigned, and that 50% or more of those designated "S" have been correctly assigned. $J^\pi$ assignments given in Fig. 5 in parentheses are those consistent with correct assignments of observed gamma rays as transitions and the assumption that these transitions have only E1, M1, and E2 multipolarities.

As mentioned above, there are a few excited states for which gamma-ray transitions can be reliably assigned on the basis of near equality in energy and consistent, if not definite, $E_n$ threshold determinations. These are discussed now.

1. $E_x = 3606$ keV, $J^\pi = 2^+$

This state is observed in the $^{208}Pb(p,t)$ reaction and $J^\pi = 2^+$ assigned on the basis of agreement in triton angular distribution with a DWBA calculated angular distribution.[14] The "basic coupling" configuration for this state could be $(f_{7/2}\ f_{5/2})$ or perhaps $(i_{13/2})^2$. Gamma rays corresponding to the 3606-1784 and 3606-2648 keV transitions (i.e., $E_\gamma = 1822$ and 958 keV) are observed with consistent $E_n$ thresholds. Three other gamma rays, having $E_\gamma = 3607$, 2803, and 1457 keV, which could correspond to additional transitions from decay of the 3606-keV level, have $E_n$ thresholds > 4 MeV.

2. $E_x = 3744.3$ keV, $J^\pi = 1^-$

This state has been observed in $(\gamma,\gamma')$ reactions[2,20] from which the spin and parity were deduced.[20] It is also probably seen in $^{207}Pb(p,d)$ measurements.[18] The present data include a gamma ray having $E_\gamma = 2942$ keV with a threshold consistent with the 3744-803 keV transition. Two other gamma rays having $E_\gamma = 1595$ and 1961 keV in agreement with possible transition energies 3744-2140 and 3744-1784 keV have apparent $E_n$ thresholds > 4 MeV.

3. $E_x$ = 3776 keV, $J^\pi = 5^-$

This strongly excited state is probably the analogue to the $J^\pi = 5^-$, $E_x$ = 3710 keV state in $^{208}$Pb. It is reported in (p,p') measurements[15,19] and in $^{204}$Pb(t,p) measurements.[17] Two gamma rays, having $E_\gamma$ = 2092 and 1778 keV, are observed having $E_n$ thresholds consistent with 3776-1684 and 3776-1998 keV transitions, both to $J^\pi = 4^+$ states. Another possible transition is the 3776-3260-keV transition. The gamma ray in question, having $E_\gamma$ = 516 keV, does not have a definite threshold, and part of the yield for this gamma is likely observed in the 2200-1685 keV transition as shown in Fig. 4. However, the yield of this gamma ray observed in the $E_n$ = 4.8 MeV spectrum is (comparatively) large and it is possible that a portion of the yield corresponds to the 3776-3260 keV transition. The gamma ray having $E_\gamma$ = 1576 keV corresponding to a possible 3776-2200 keV transition has a lower $E_n$ threshold and has been assigned to the 3260-1684 keV transition. The gamma ray having $E_\gamma$ = 497 keV corresponding to a possible 3776-3279 keV transition also has a lower $E_n$ threshold and has been assigned to the 3279-2782 keV transition. A possible 3776-2929 keV transition is masked by the known $^{56}$Fe background 847-keV gamma ray. There are no other gamma rays having energies $E_\gamma$ close to other possible transition energies for decay of this level.

4. $E_x$ = 4115.6 keV, $J^\pi = 4^+$ and 4116.5 keV, $J^\pi = 2^+$

These two levels are degenerate to within the resolving power of the present detection system. A strong ground-state transition is observed identifying the $J^\pi = 2^+$ as the analogue of the strong $J^\pi = 2^+$ $E_x$ = 4084 keV level in $^{208}$Pb. The other $^{206}$Pb excited state is observed in the $^{208}$Pb(p,t) reaction with a $J^\pi = 4^+$ assignment,[14] and in the $^{207}$Pb(p,d) reaction with angular momentum transfer[18] $\ell$ = 5,so that this state likely corresponds to the "basic coupling" $(h_{9/2}\ p_{1/2})_{J=4}$ configuration. Two other gamma rays, having $E_\gamma$ = 2775 and 995 keV, have thresholds consistent with 4116-1341 and 4116-3121 keV transitions. For all other likely transitions, gamma rays having energies sufficiently close to postulated transition energies have inconsistent $E_n$ thresholds. It is not possible to be certain of transition assignments, other than for the 4116.5-0.0 transition. The only two probable assignments are suggested as both corresponding to decay of the $J^\pi = 4^+$ level for two reasons: (a) The $^{208}$Pb analogue of the $J^\pi = 2^+$ level (at $E_x$ = 4084 keV in $^{208}$Pb) decays only by a ground-state transition,[1] and there are no obvious reasons for enhancements of either the 4116-1341 or 4116-3121 keV transitions with respect to other plausible transitions; (b) the decay of the $J^\pi = 4^+$ "basic-coupling" $(h_{9/2}\ p_{1/2})$ configuration might be expected to preferentially populate states corresponding to "basic-coupling" $(f_{5/2}\ p_{1/2})_{J=3}$ and $(f_{7/2}\ p_{1/2})_{J=3,4}$ since these involve only one neutron-hole orbital change. Therefore, both gamma rays are assigned as transitions from the $J^\pi = 4^+$ level of this doublet with the caveat that such assignments have invoked shell-model considerations and so should not be later construed as verification of more accurate shell-model predictions.

5. $E_x$ = 4005 keV, $J^\pi = 5^+$

A state is reported in the $^{207}$Pb(p,d) reaction at $E_x$ = 4008 keV having angular momentum transfer[18] $\ell = 5$ which may be the $J^\pi = 5^+$ state of the "basic-coupling" $(h_{9/2}\ p_{1/2})$ configuration. A study of the present data supports an excited state of this description. A gamma ray having energy $E_\gamma$ = 1076 keV is observed having a threshold consistent with assignment as the 4005-2929 keV transition. Another gamma ray having energy $E_\gamma$ = 2008 keV is observed in the $E_n$ = 4.8 MeV spectrum, but it is not positively identified in any of the spectra obtained using the ORELA. It could be the 4005-1998 keV transition. The possible 4005-2384 keV transition is nearly degenerate with the 2423-803 keV transition. Other likely transitions cannot be matched with observed gamma rays. The resulting picture is consistent with the shell-model interpretation for a $J^\pi = 5^+$ level of the $(h_{9/2}\ p_{1/2})$ configuration, but the caveat expressed in the last paragraph is repeated.

6. $E_x$ = 4238 keV, $J^\pi = 5^-$; 4347 keV, $J^\pi = 4^+$; and 4385 keV, $J^\pi = 6^+$

The $J^\pi = 5^-$ and $6^+$ levels are identified in $^{204}$Pb(t,p) measurements[17] and the $J^\pi = 4^+$ and $6^+$ levels are observed with large yields in inelastic proton scattering measurements.[15] Gamma rays having energies and thresholds consistent with plausible transitions are indicated in Fig. 5.

### D. Structure for $E_x > 4.8$ MeV

As mentioned in the first part of the experimental section, data were obtained for $E_n > 5$ MeV, and gamma rays which were identified with reasonable certainty are given in Table 2. In this highly excited region, the level density has increased substantially, so much so that the level spacing is smaller than the resolving power of the experimental system. About 50 levels have been "adopted" having $E_x$ up to 8226 keV.[7] As for the level-structure discussion in subsection C, correspondence among any of the different experiments is an uncertain business. The best comparisons are probably for energies of ground-state transitions from the present experiment (given in Table 2) and those for reported $(\gamma,\gamma')$ measurements[2] which are indicated in Fig. 6. Possible correlation of excitation energies (to within 5 keV) are indicated along the right-hand edge of Fig. 6. In this figure the symbols "D", "P", and "S" have the same meaning as in Fig. 5.

## V. SUMMARY

Neutron inelastic scattering from the $^{206}$Pb nucleus has provided much new information about the level structure of $^{206}$Pb, in particular locating for the first time many levels, and providing for the first time information on transitions among previously reported levels. Over half of the observed gamma rays could not be and were not identified with particular transitions among $^{206}$Pb levels; there is a richness in detail awaiting further study. The knowledge of the $^{206}$Pb level structure is more complete, however, and may prove a severe test for additional more-sophisticated shell-model calculations.

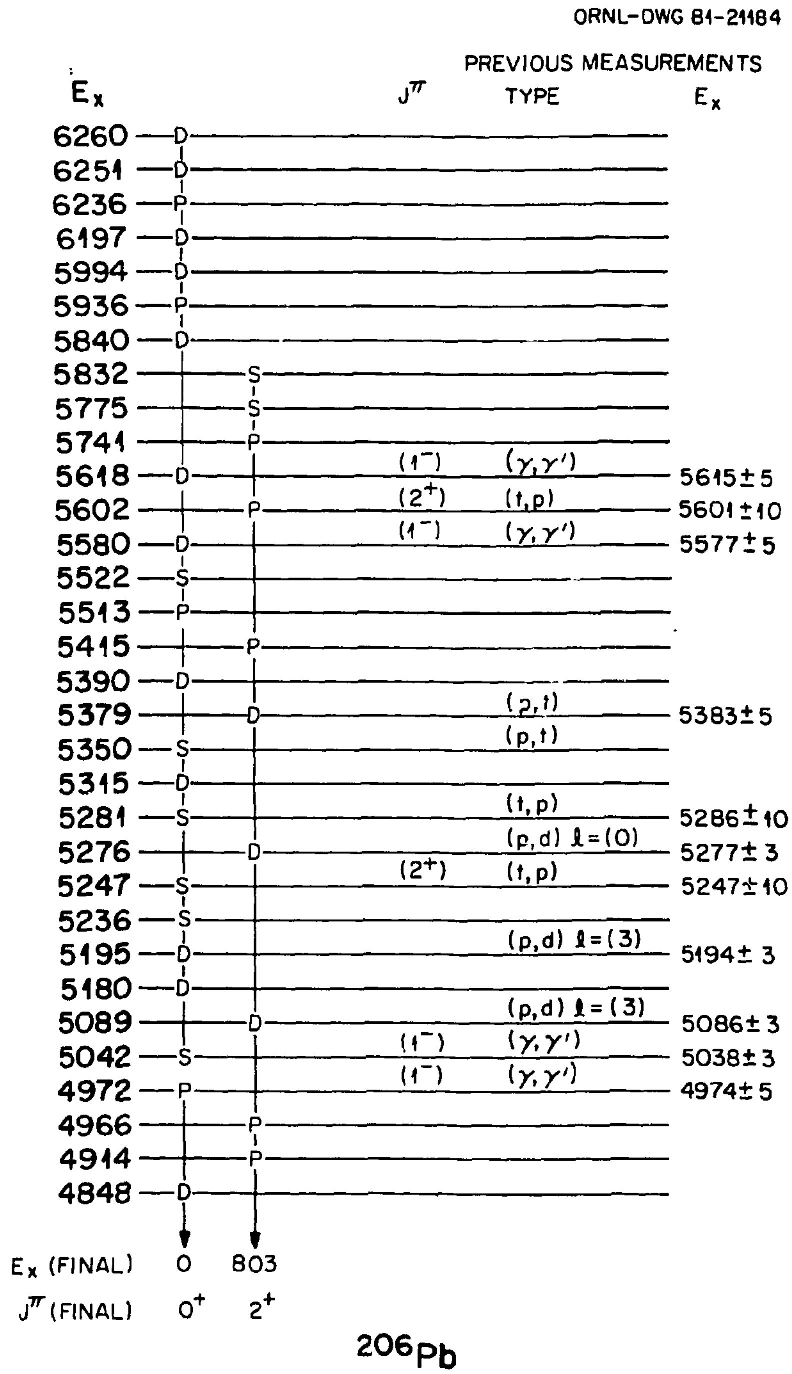


Fig. 6. $^{206}$Pb levels for $E_x$ > 4.8 MeV deduced from the present data.

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## APPENDIX: SPECTRUM OF GAMMA RAYS OBTAINED FOR $E_n$ = 4.8 MeV

Data were obtained using a PDP-7 computer and stored in two manners. The Analog-to-Digital Converter was set at 4096 channels, and data were stored in an event-by-event mode on a magnetic tape in a two-dimensional mode; i.e., gamma-ray pulse height plus information on the time of the event (in the detector) following the beam burst. Data were also saved in a 2048-channel total pulse-height array in the computer. The reel of magnetic tape was filled after $\sim 10^6$ events had been processed. The run was continued, however, to acquire additional data in the 2048-channel spectrum. The data on the magnetic tape were processed off-line in a manner to reduce background contributions by requiring specified time limits with respect to the incident beam to specify a "valid" event. These time constraints were not included in the 2048-channel data stored in computer memory; however, the latter were obtained for about four times the neutron fluence used for the 4096-channel spectrum, and show much better the high-energy gamma-ray data.

The spectral data shown in the following figures are a mix of portions of the 4096-channel spectrum having a dispersion of $\sim$1.25 keV/channel and a smaller background contribution, and portions of the 2048-channel spectrum having a dispersion of $\sim$2.5 keV/channel and more definitive high-energy data.

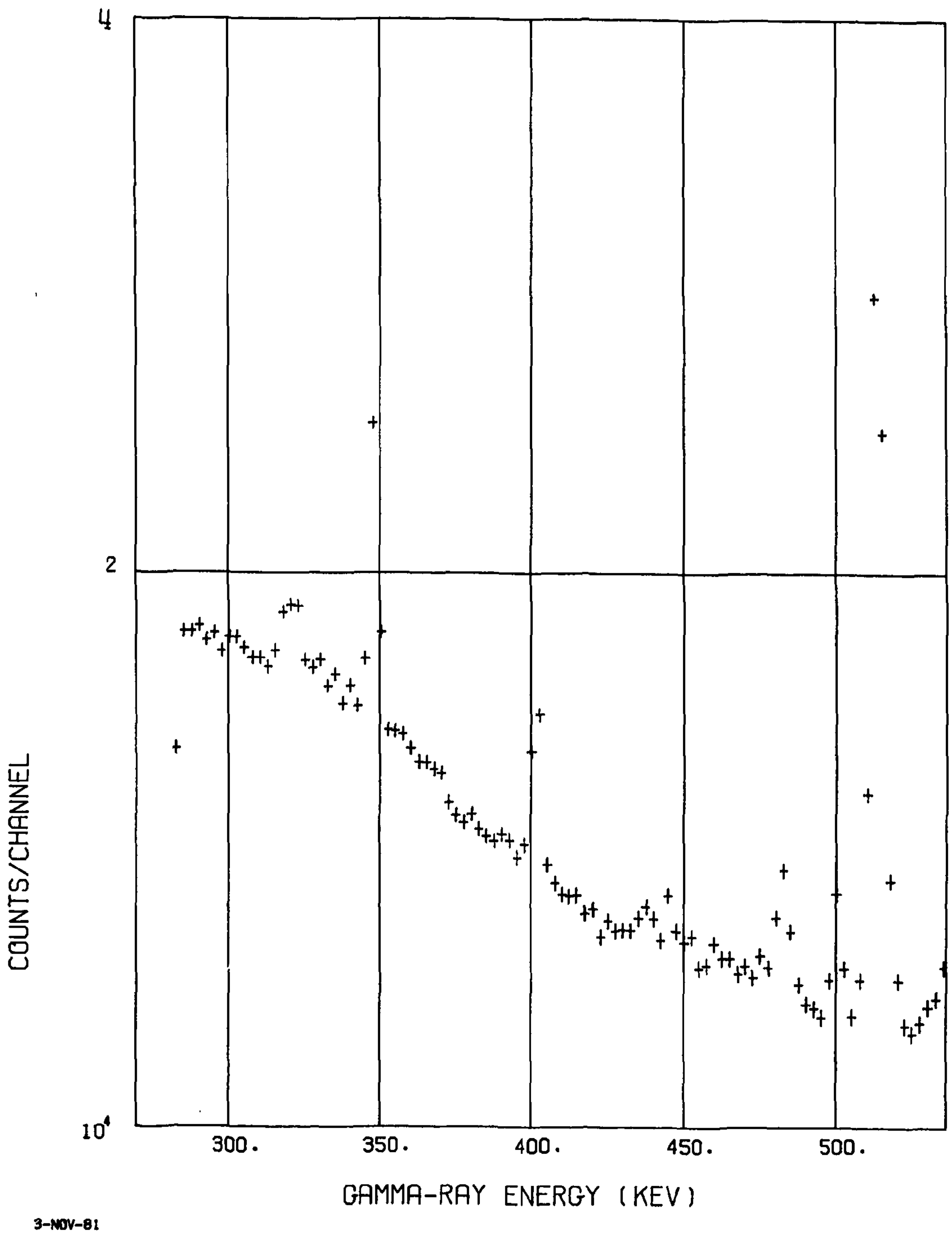


Fig. A-1. Dispersion is 2.5 keV/channel. Wide peak at 316 keV assumed due to two equal-yield photons, one having $E_\gamma$ = 317.4 keV and the other having $E_\gamma$ ~314 keV. The peak at 442 keV appears to be primarily background from an undetermined source.

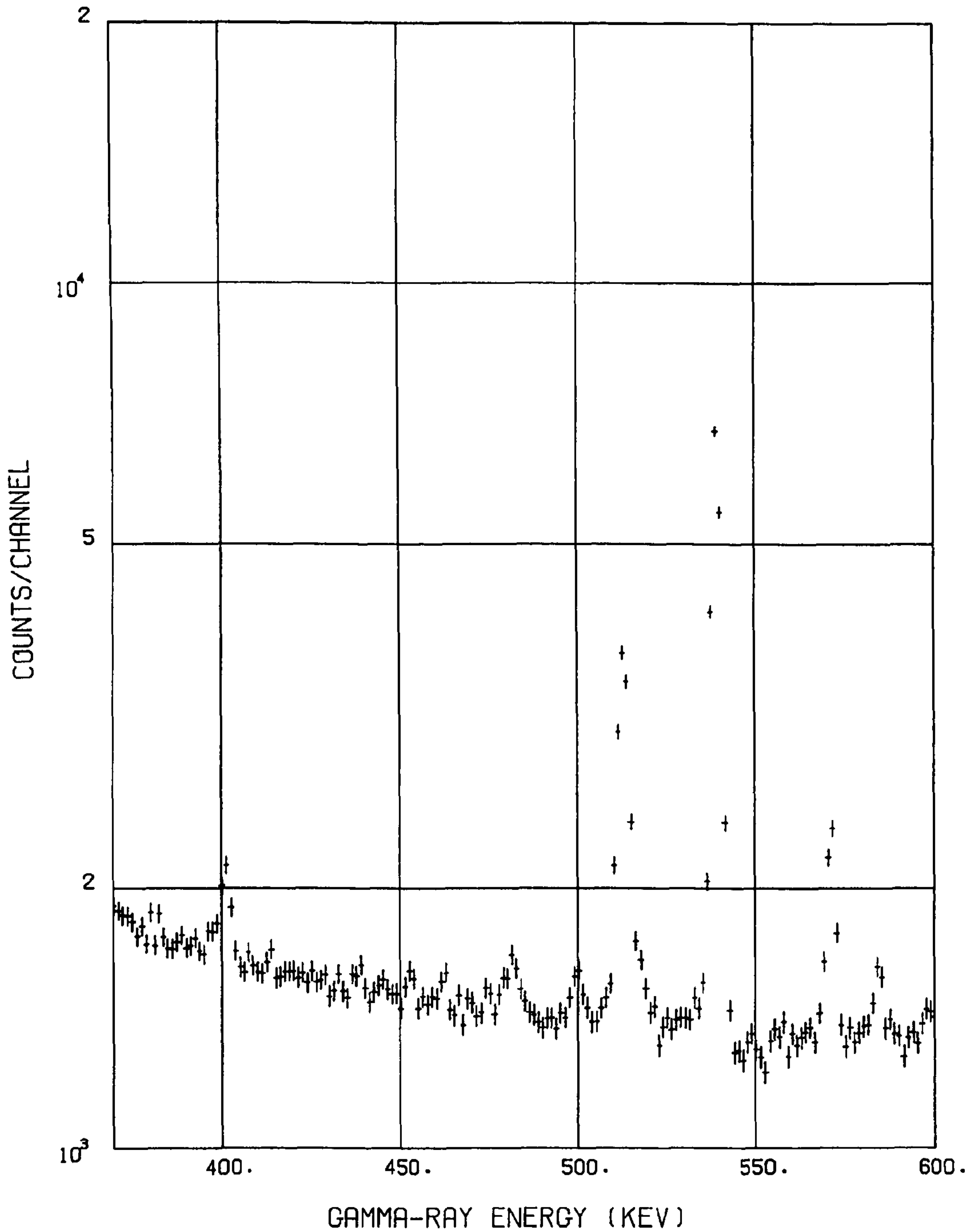


Fig. A-2. Dispersion is 1.25 keV/channel. The unresolved contribution on the high-energy edge of the $E_\gamma$ = 511 keV peak is assumed due to a gamma ray having $E_\gamma$ = 516.2 keV corresponding to the correct energy for the 2200.2 to 1784.0 keV transition. Peak stripping results in the yield given in Table 1 for a gamma ray of this energy. Peaks at $E_\gamma$ = 567 and 583 keV are, respectively, due to neutron inelastic scattering from $^{207}$Pb and $^{208}$Pb.

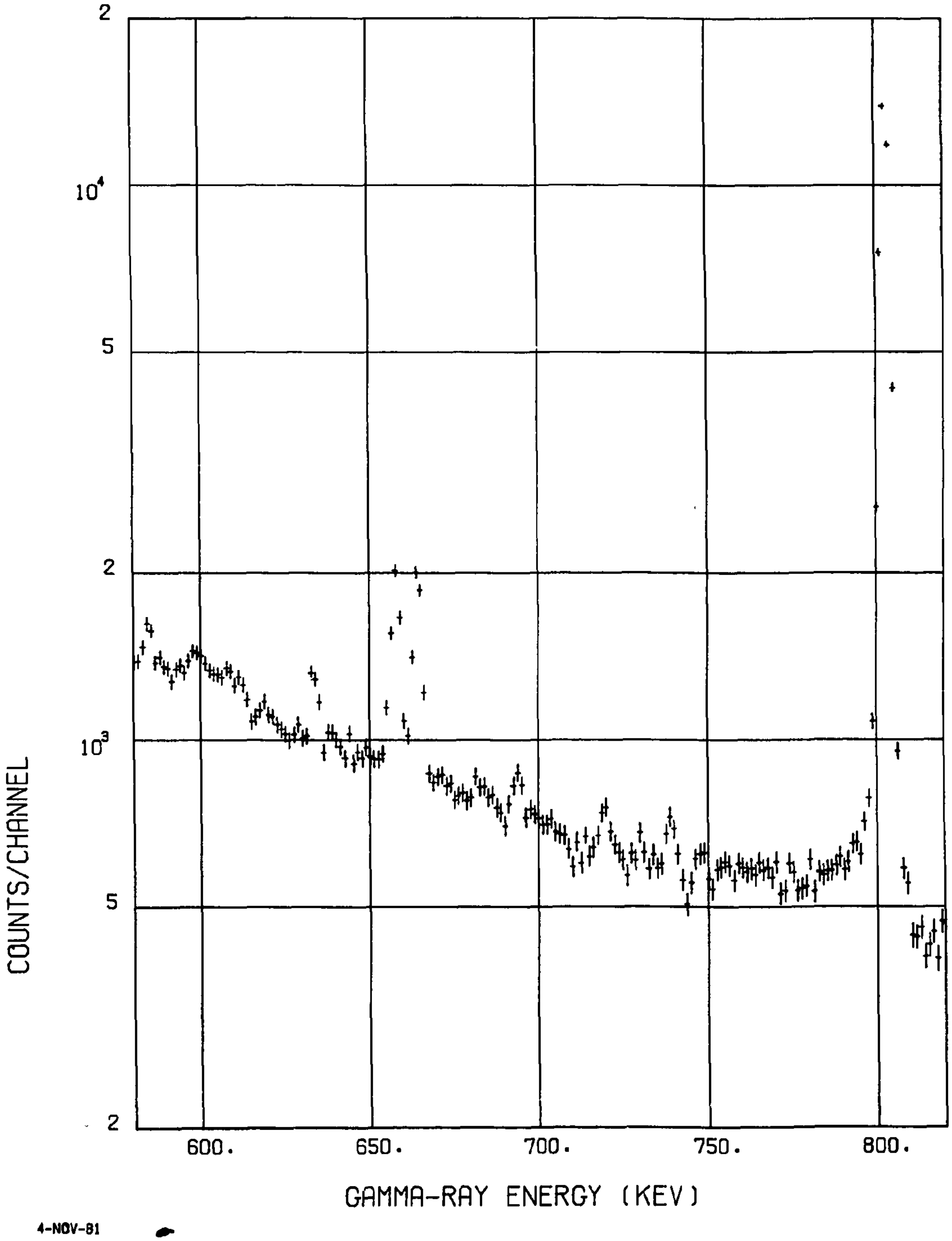


Fig. A-3. Dispersion is 1.25 keV/channel. Broad group at $E_\gamma$ ~596 is due to $^{74}Ge(n,n'\gamma)$ interactions of neutrons with the detector. Weak peak near $E_\gamma$ ~680 keV may include the double-escape peak of the 1703-keV gamma ray. The broad peak near $E_\gamma$ ~693 keV is due to $^{72}Ge(n,n'\gamma)$ interactions.

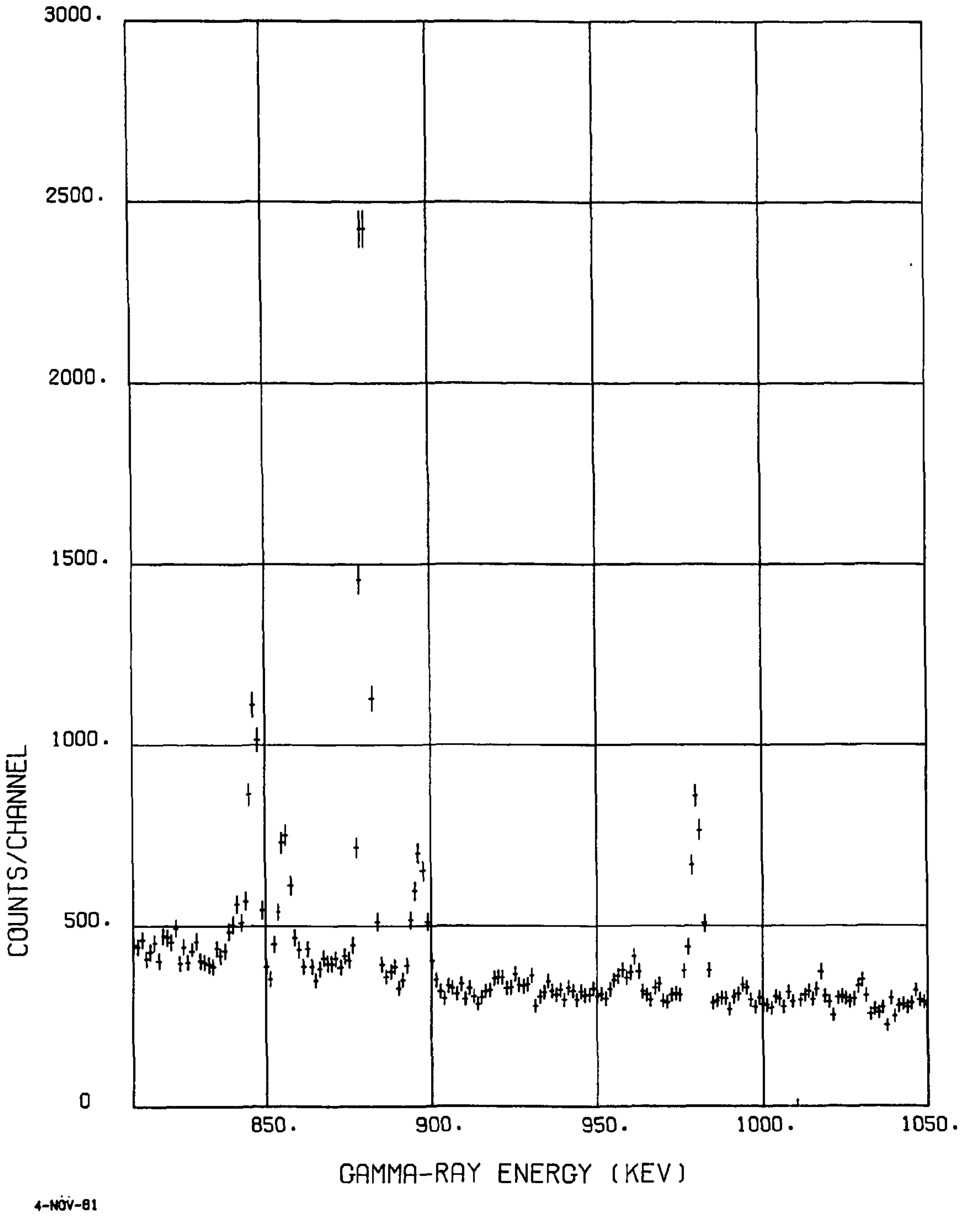


Fig. A-4. Dispersion is 1.25 keV/channel. Peak at $E_\gamma$ = 897 keV is probably a doublet of unresolved gamma rays, one having $E_\gamma$ = 898 keV and due to $^{207}$Pb(n,n'$\gamma$). Peak near $E_\gamma$ = 962 keV may include $^{63}$Cu(n,n'$\gamma$) interaction of neutrons with the copper in the detector.

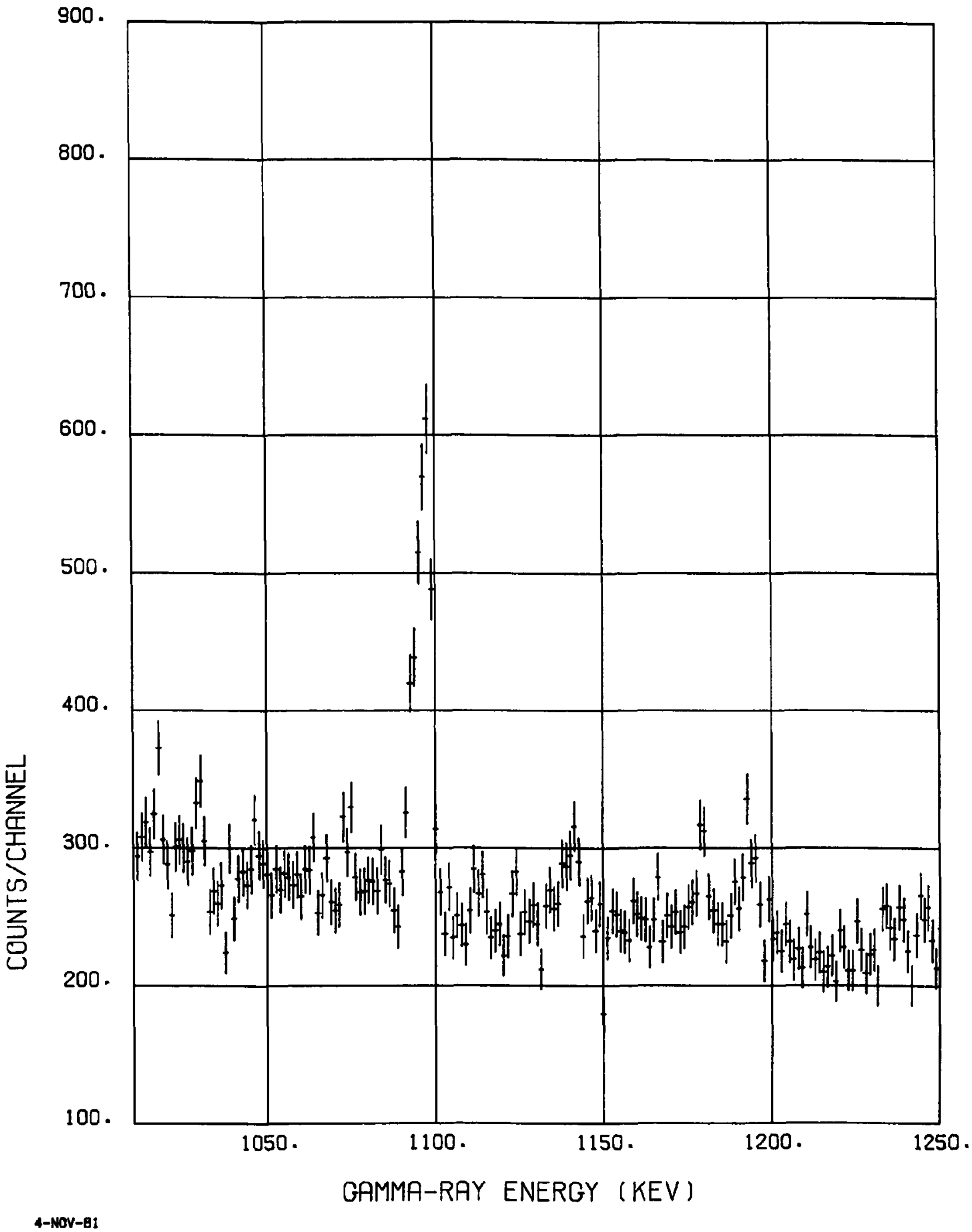


Fig. A-5. Dispersion is 1.25 keV/channel. Peak at $E_\gamma$ = 1097 keV is probably a doublet of unresolved gamma rays, one having $E_\gamma$ = 1095 keV and due to the 2728 to 1633-keV transition in $^{207}$Pb. A portion of the weak peak near $E_\gamma$ = 1115 keV may be due to $^{65}$Cu(n,n'$\gamma$) interactions.

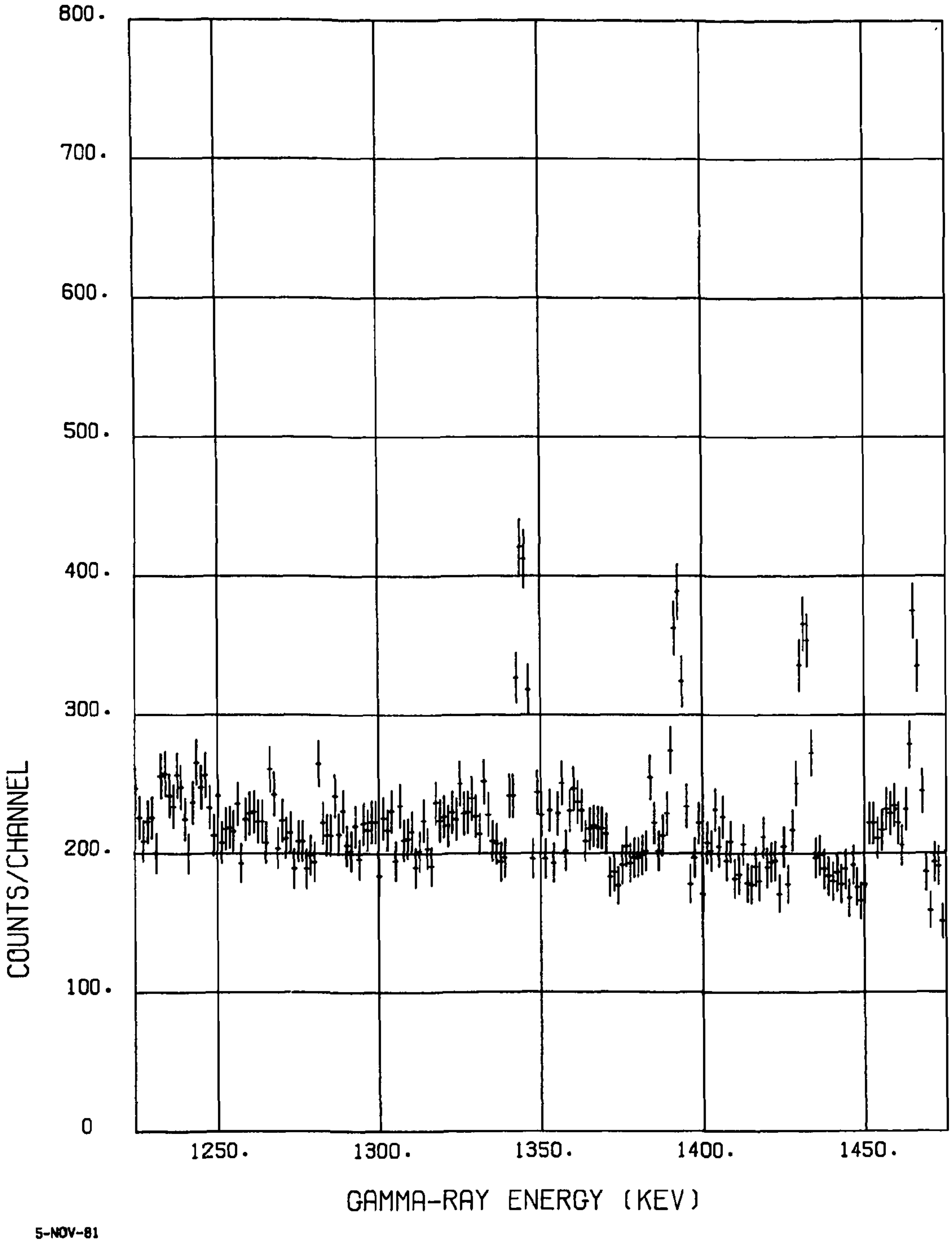


Fig. A-6. Dispersion is 1.25 keV/channel. Peak near $E_\gamma$ = 1238 keV is at least partly due to $^{56}Fe(n,n'\gamma)$. Peak at $E_\gamma$ = 1467 keV appears to be slightly wide, but has been treated as being the response to a single gamma ray.

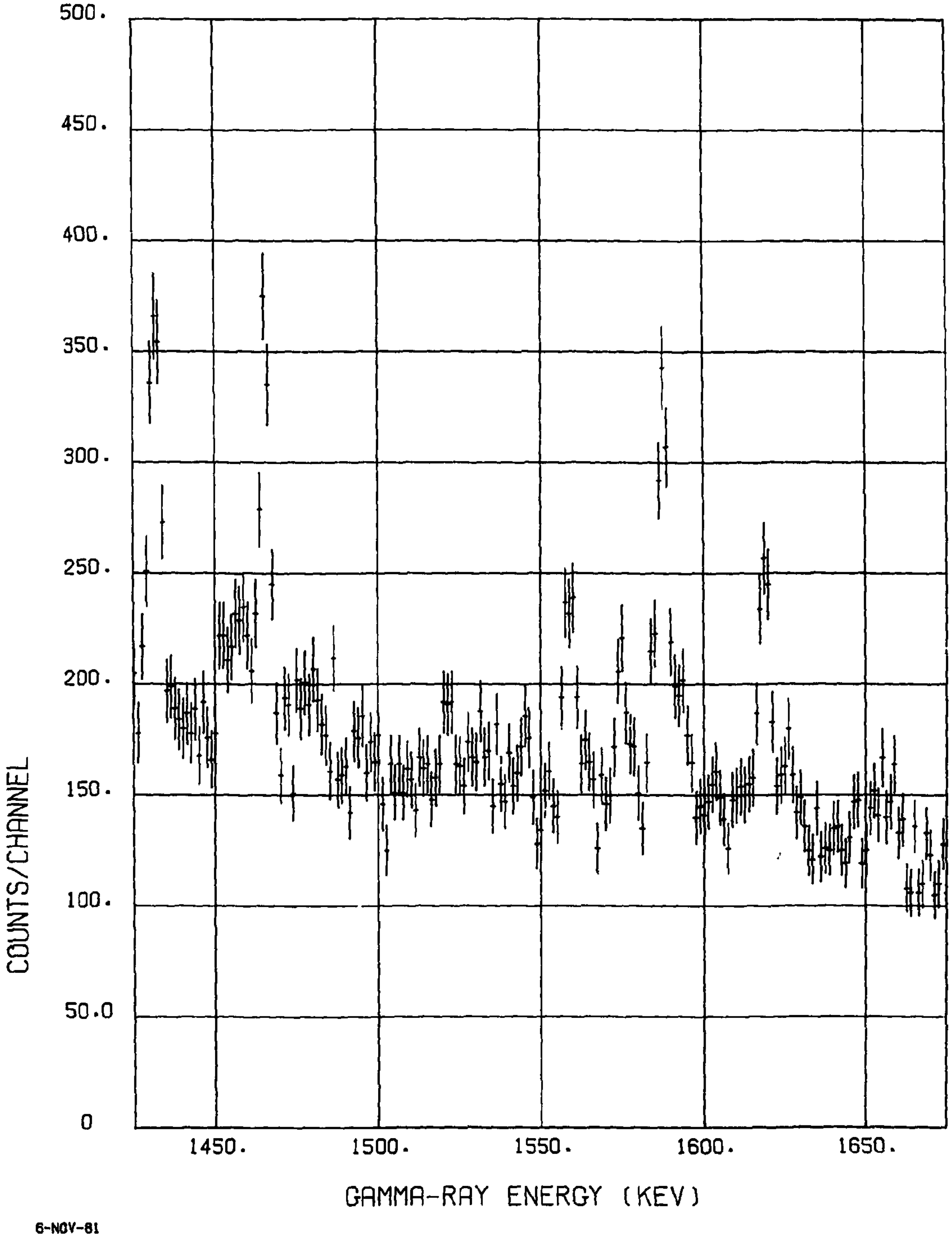


Fig. A-7. Dispersion is 1.25 keV/channel. Peak near $E_\gamma \approx 1592$ keV is the double-escape response of the 2614.5-keV gamma ray due to $^{208}Pb(n,n'\gamma)$.

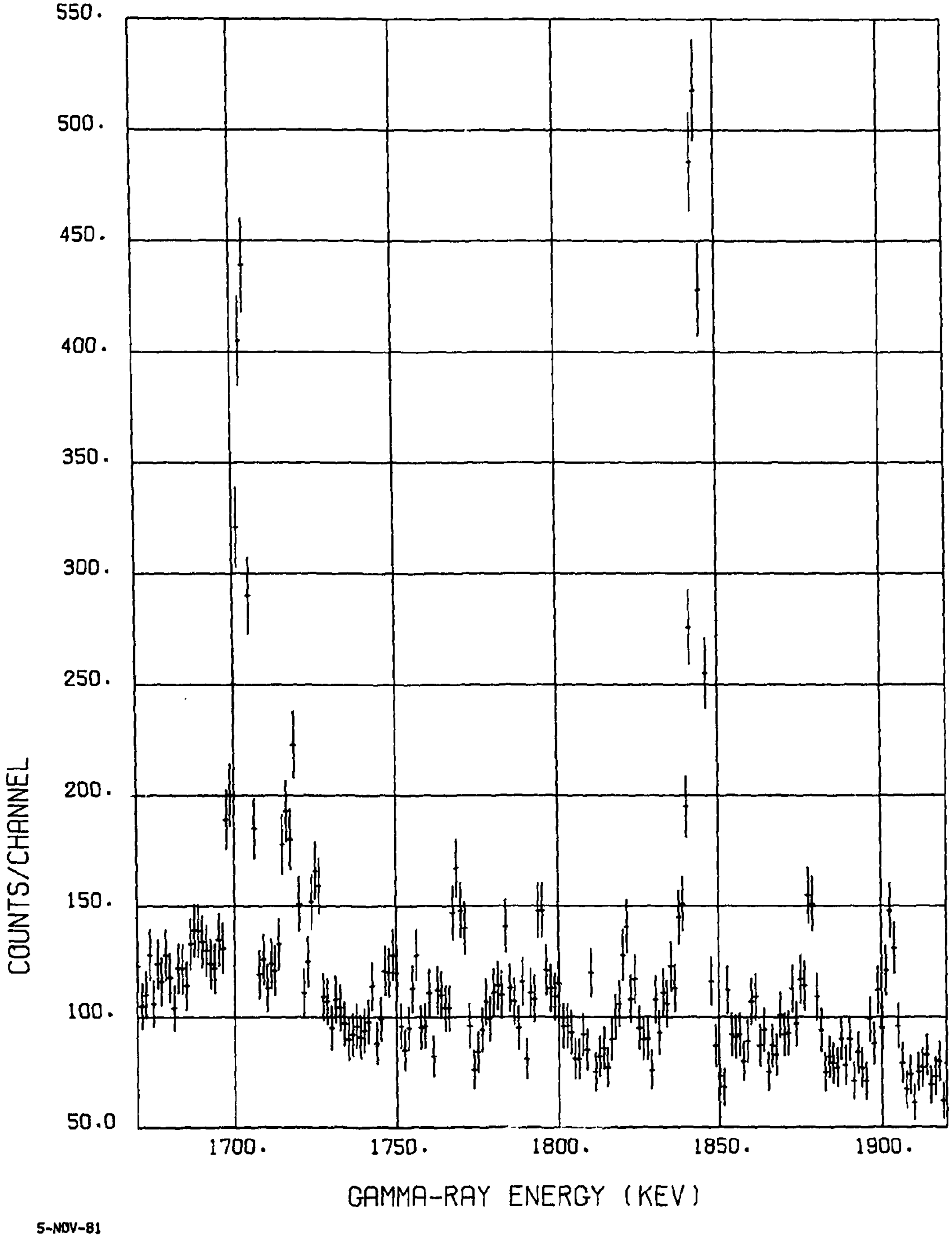


Fig. A-8. Dispersion is 1.25 keV/channel. Peaks near $E_\gamma$ = 1725 and 1770 keV are due primarily if not entirely to $^{207}Pb(n,n'\gamma)$.

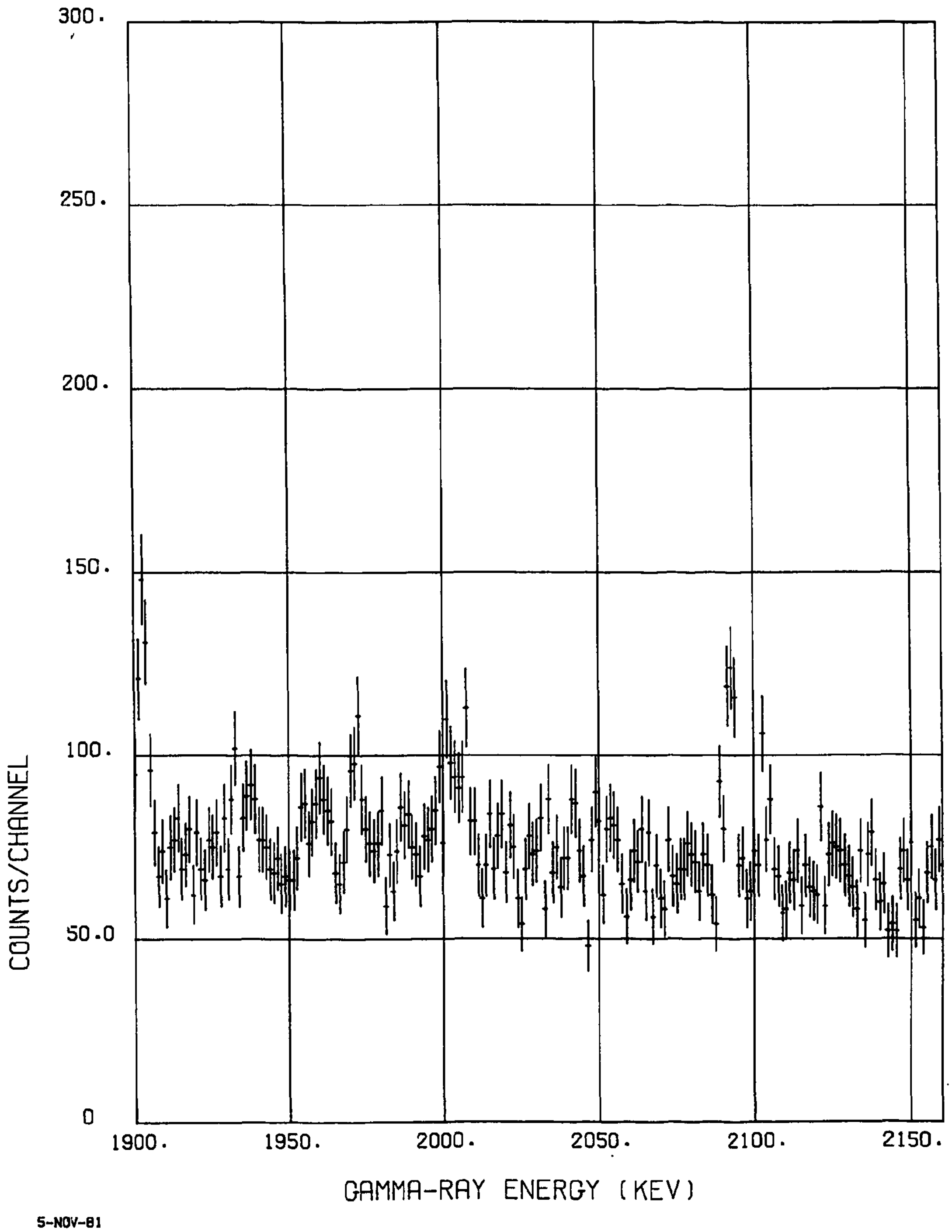


Fig. A-9. Dispersion is 1.25 keV/channel. Peak near $E_\gamma$ = 2092 keV is due primarily if not entirely to $^{207}Pb(n,n'\gamma)$. Escape peaks due to the detector response to higher-energy gamma rays are present in this portion of the spectrum. For these and higher-energy observed peaks the escape response must be accounted for.

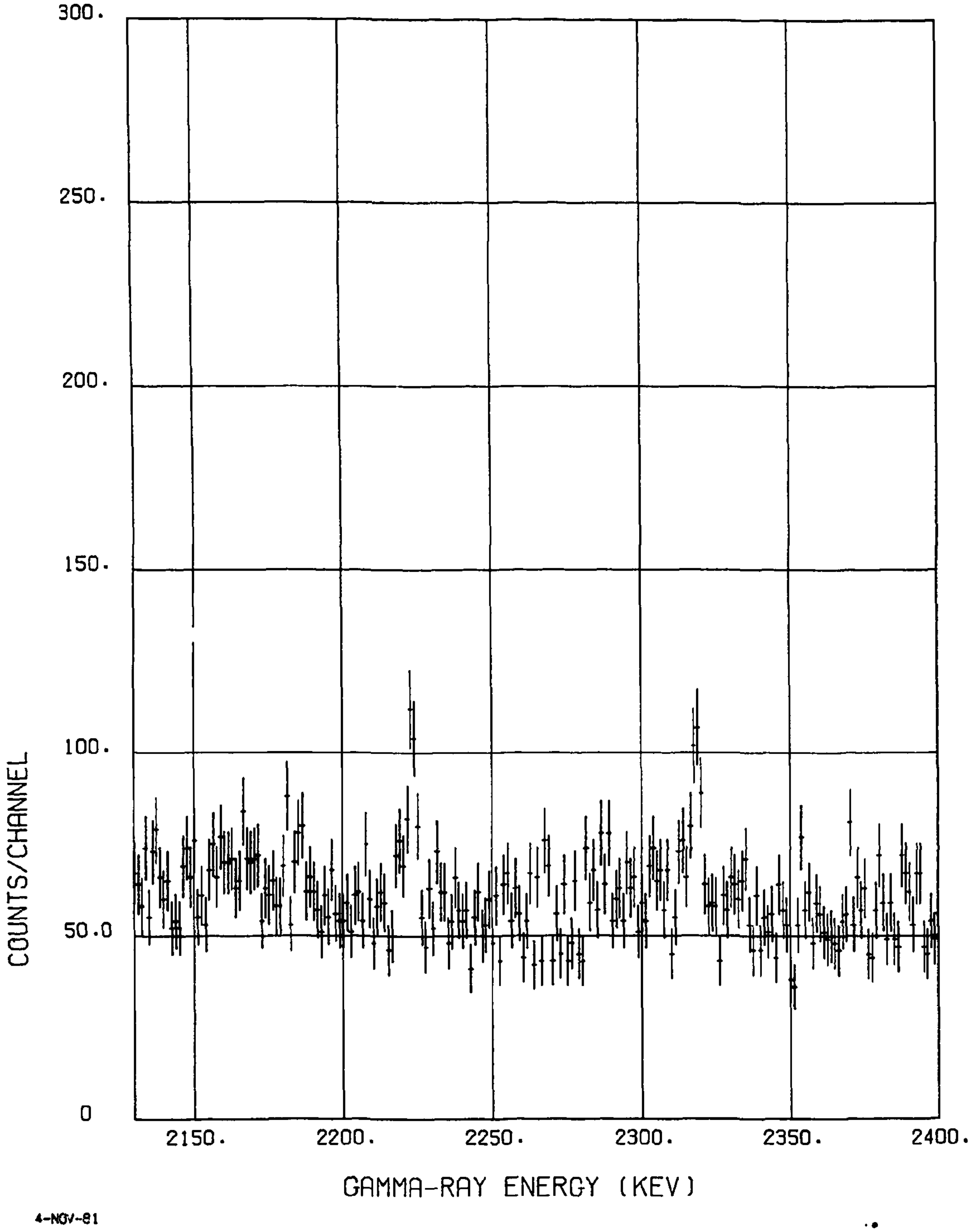


Fig. A-10. Dispersion is 1.25 keV/channel. Peak near $E_{\gamma}$ = 2223 keV is due to $^{1}H(n,\gamma)$ capture in the paraffin shielding material surrounding the detector.

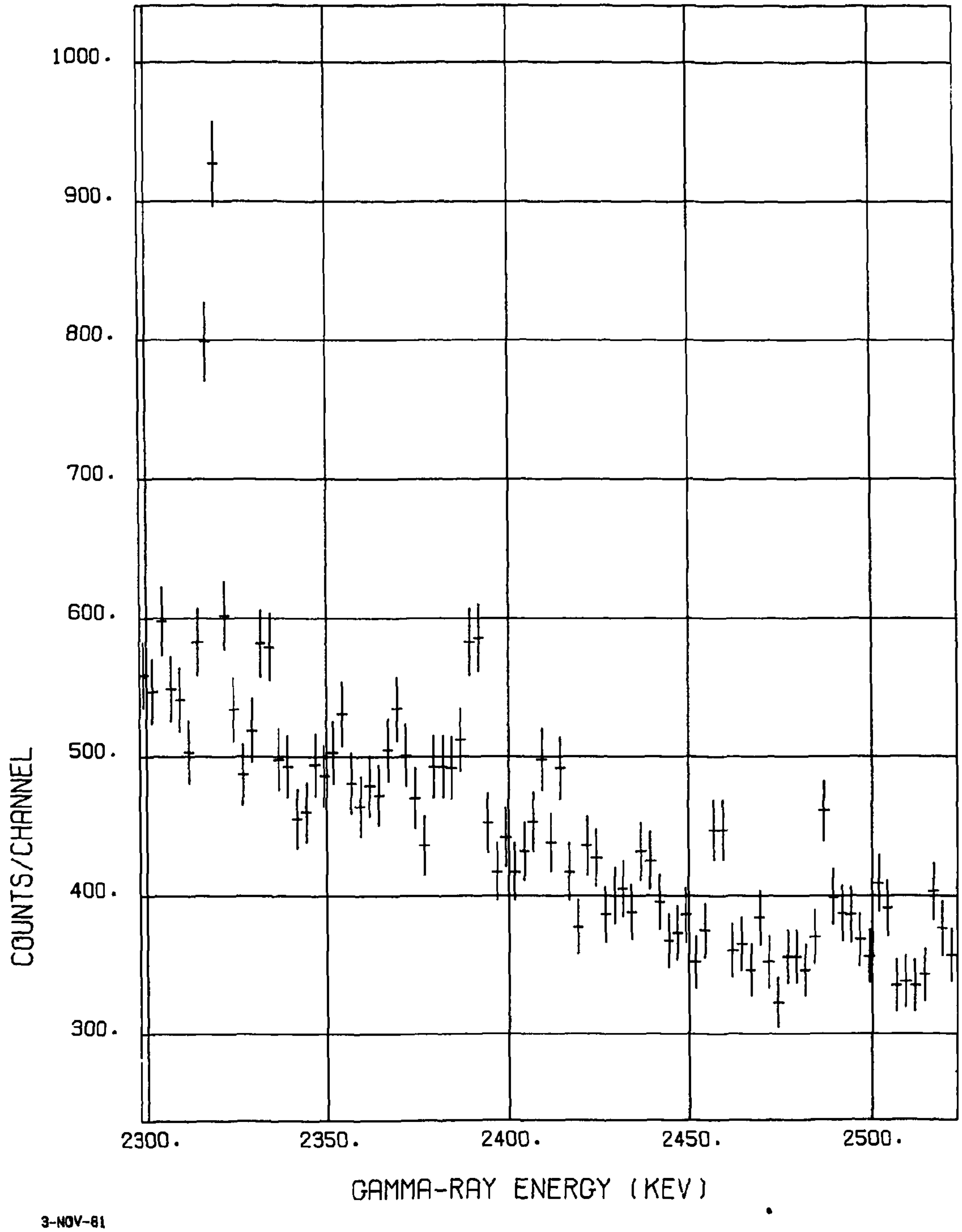


Fig. A-11. Dispersion is 2.5 keV/channel. The lower-energy portion of this spectrum overlaps Fig. A-10. Corrections to yields in Table 1 have been made to account for escape peak contributions, e.g., for peaks near $E_\gamma$ = 2460, 2500, and 2522 keV.

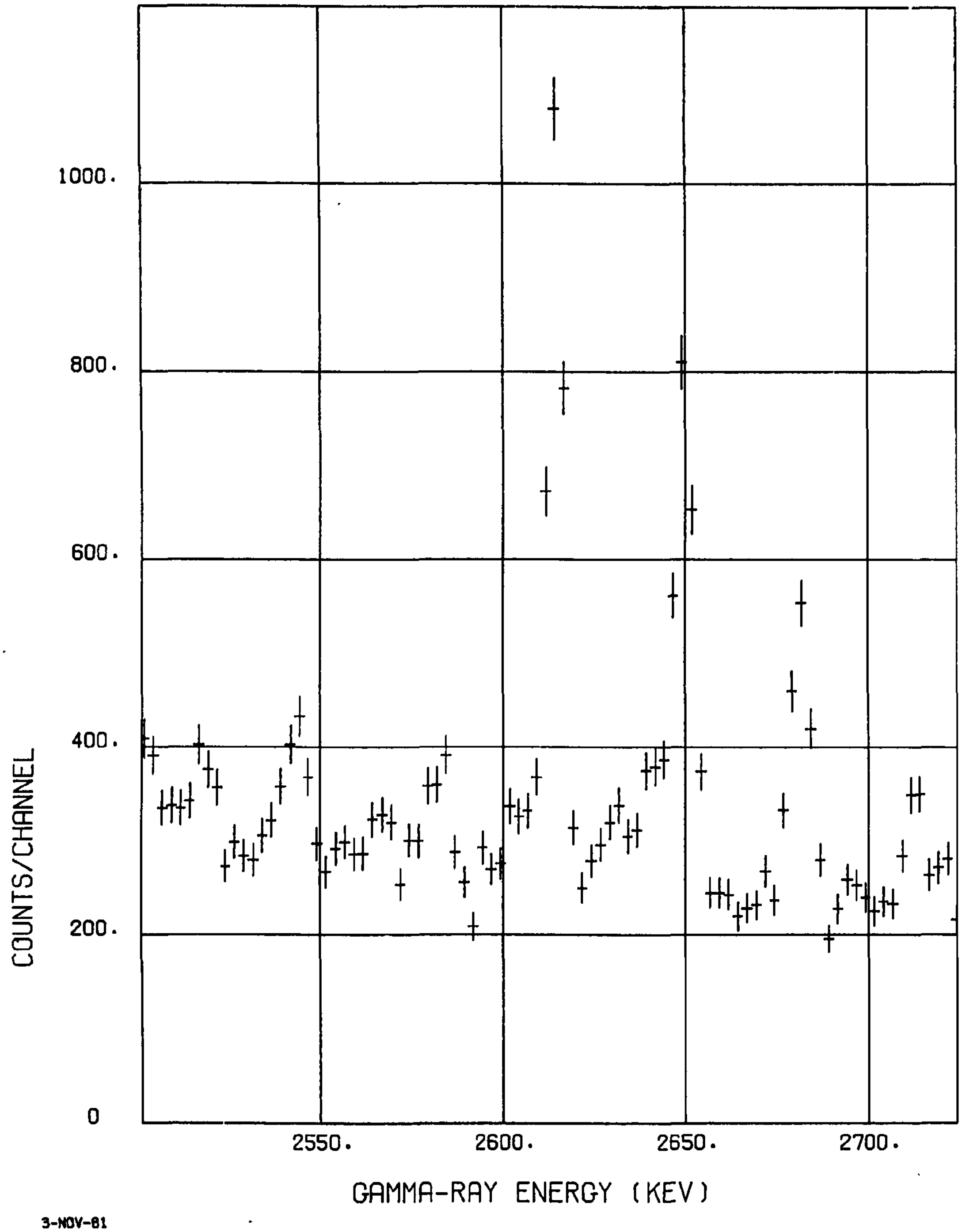


Fig. A-12. Dispersion is 2.5 keV/channel. The peak at $E_\gamma$ = 2614 keV is due to $^{208}Pb(n,n'\gamma)$, and the assumption is made that it is due entirely to this reaction. Peaks corresponding at least partly to escape response include those at $E_\gamma$ = 2556, 2568, 2583, 2602, 2682, and 2695 keV.

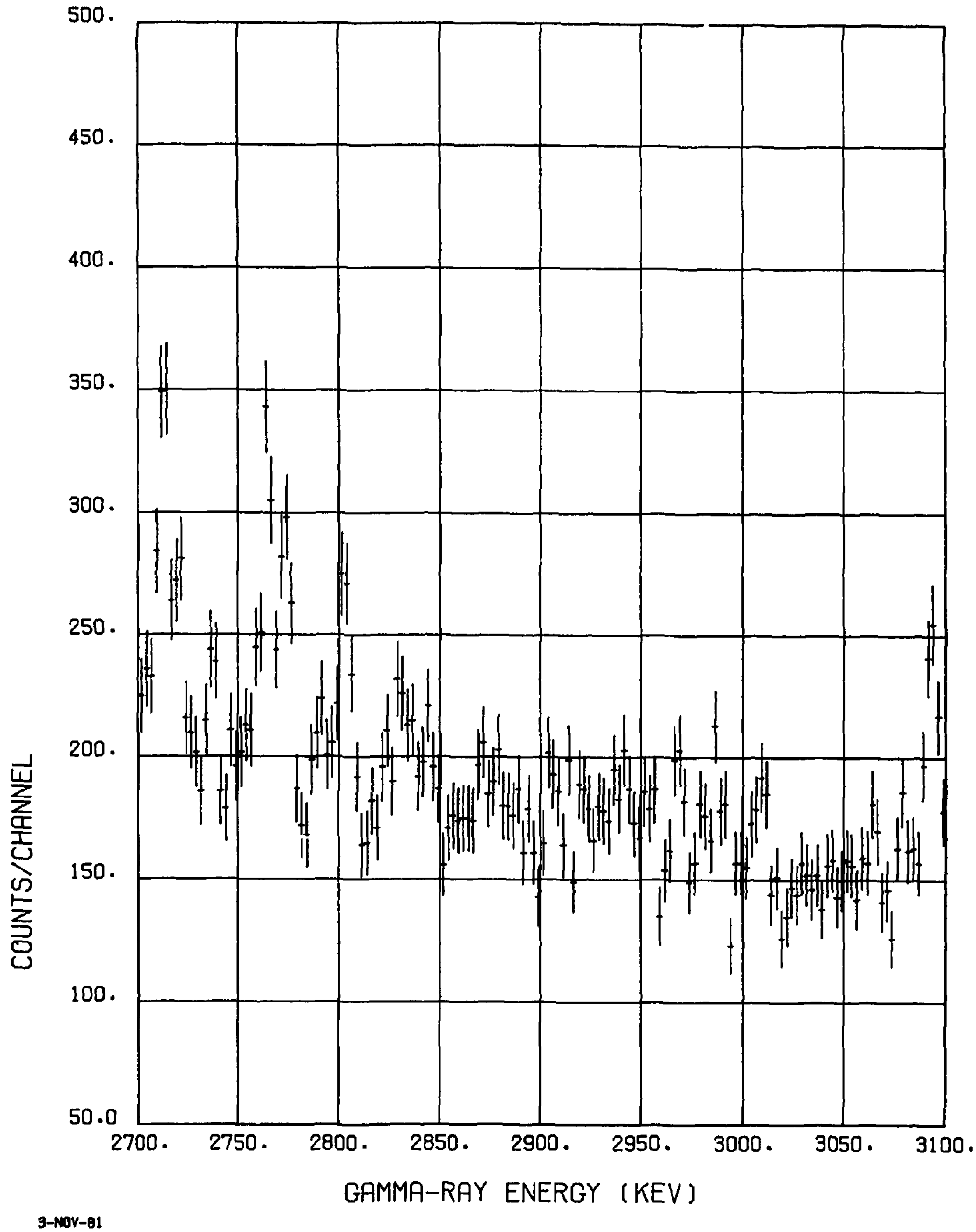


Fig. A-13. Dispersion is 2.5 keV/channel. Peaks corresponding at least partly to escape response include those at $E_\gamma$ = 2722, 2765, 2795, 2832, 2872, 2970, 3064, and 3094 keV.

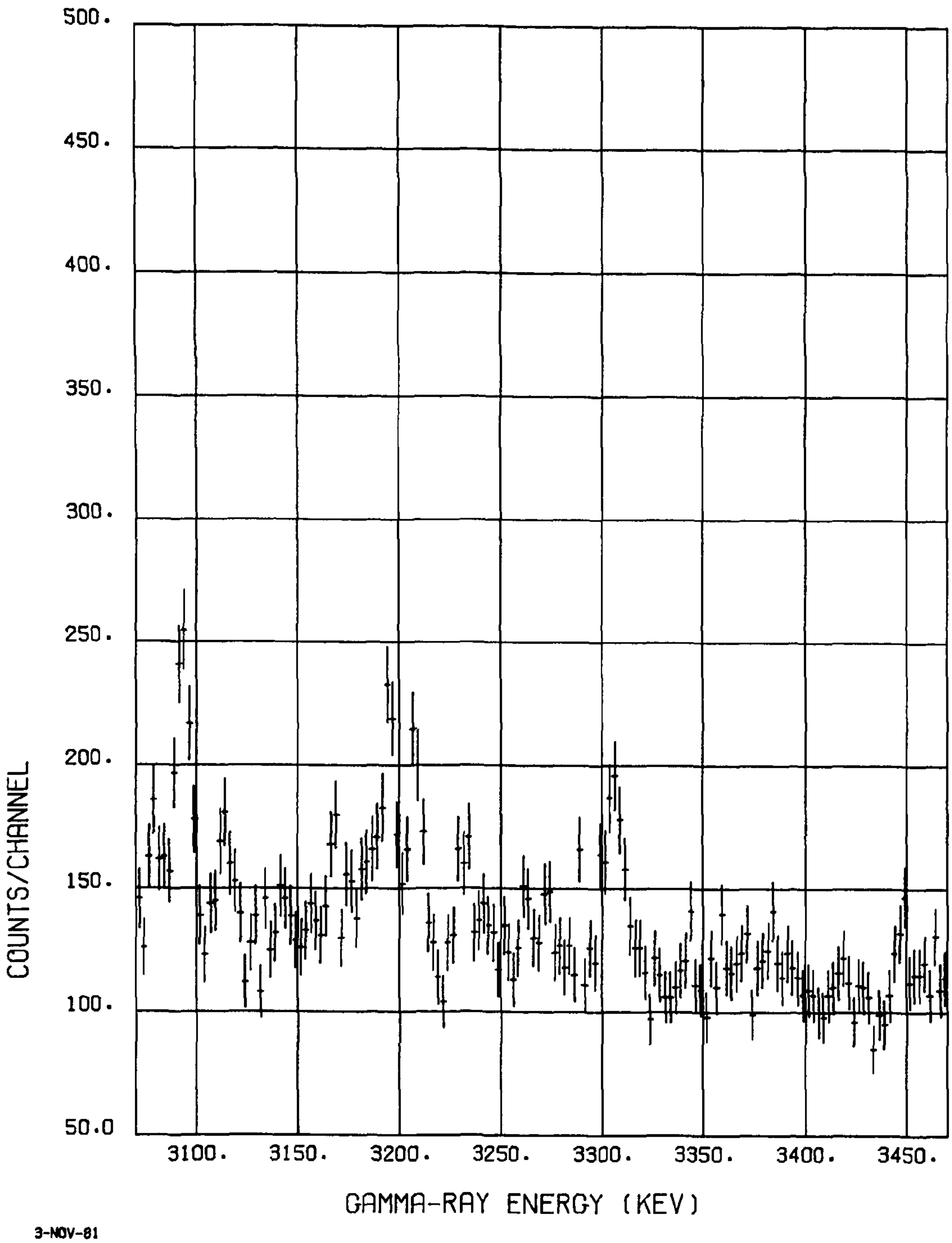


Fig. A-14. Dispersion is 2.5 keV/channel. Peaks corresponding at least partly to escape response include those at $E_\gamma$ = 3094, 3208, 3231, 3307, 3344, and 3448 keV.

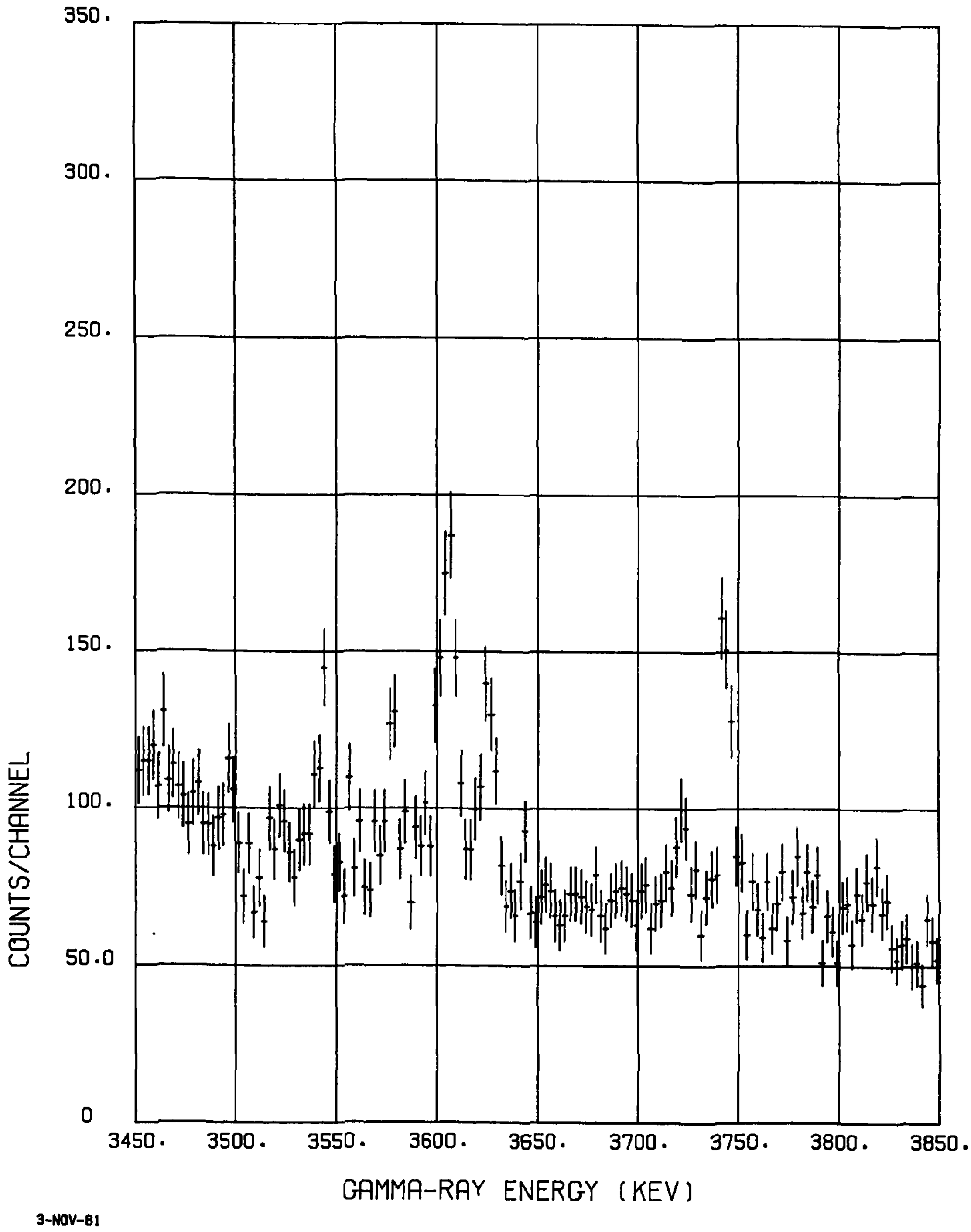


Fig. A-15. Dispersion is 2.5 keV/channel. The large peak near $E_\gamma$ = 3606 keV includes a substantial contribution from the 4117-keV gamma ray.

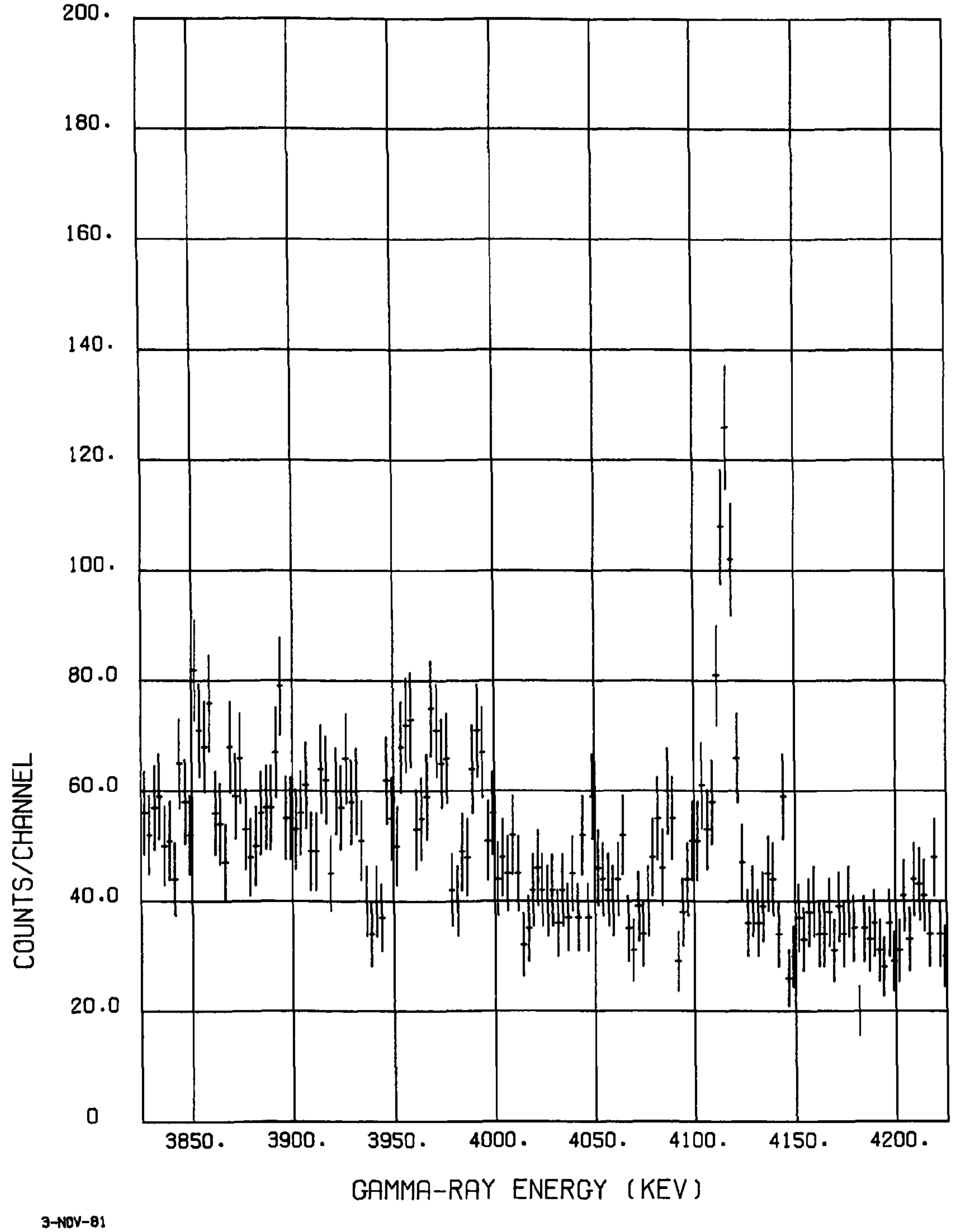


Fig. A-16. Dispersion is 2.5 keV/channel. Escape peaks include peaks observed at $E_\gamma$ = 3957 and 3972 keV. The peak near $E_\gamma$ = 4084 keV is due to a gamma ray from $^{208}Pb(n,n'\gamma)$ and the peaks near $E_\gamma$ = 4104 and 4138 keV are due to $^{207}Pb(n,n'\gamma)$.

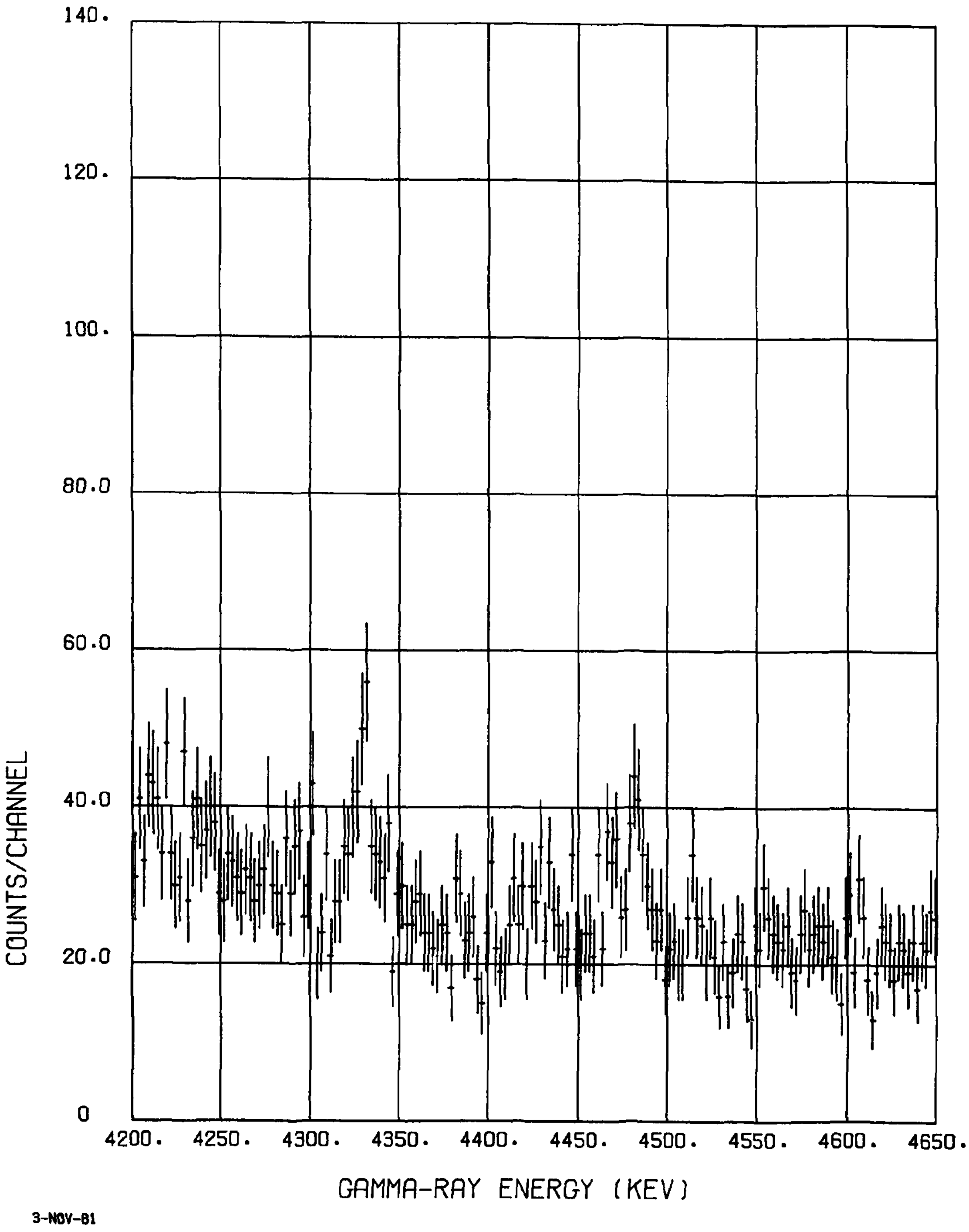


Fig. A-17. Dispersion is 2.5 keV/channel.

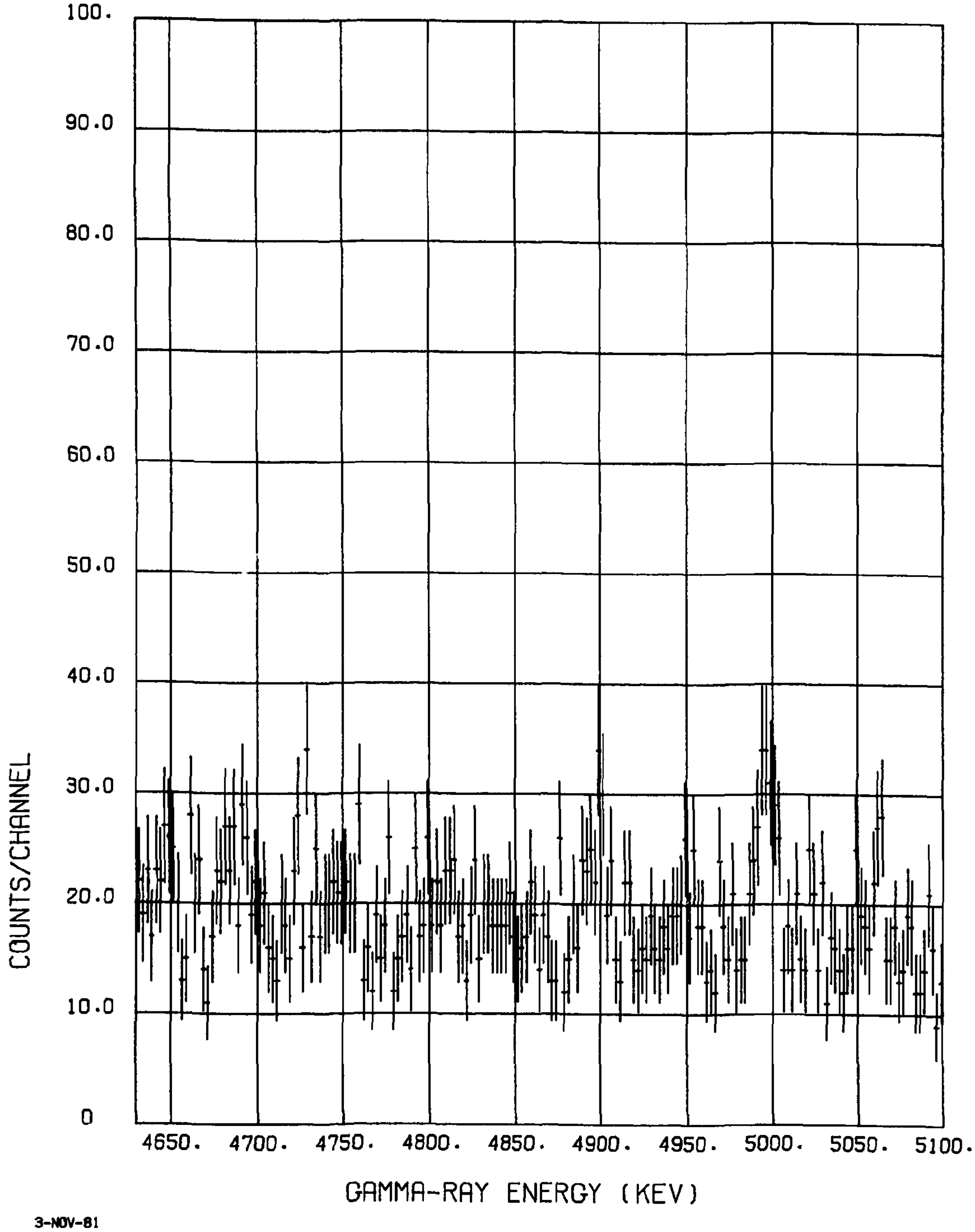


Fig. A-18. Dispersion is 2.5 keV/channel. Peaks near $E_\gamma$ = 4898 and 4996 keV are double-escape peaks from $^{56}Fe(n,\gamma)$ interaction, and these peaks provide the energy calibration for this high-energy portion of the total spectrum.