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# GAMMA-RAY PRODUCTION DUE TO NEUTRON INTERACTIONS WITH $^{68}Zn$ AND THE LEVEL STRUCTURE OF $^{68}Zn$

J. K. Dickens

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22151
Price: Printed Copy $5.45; Microfiche $1.45

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ORNL-4985
UC-34a — Physics
Atomic & Molecular

Contract No. W-7405-eng-26

Neutron Physics Division

# Gamma-Ray Production Due to Neutron Interactions with $^{68}Zn$ and the Level Structure of $^{68}Zn$

J. K. Dickens

SEPTEMBER 1974

NOTE: THIS WORK FUNDED BY DEFENSE NUCLEAR AGENCY UNDER SUBTASK No. PC101

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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Abstract

Numerical values of differential cross sections for gamma rays produced by neutron interactions with $^{68}Zn$ have been measured for an incident energy of 5.4 MeV and gamma-ray scattering angle of 55 deg. The $d\sigma/d\omega$ data were obtained using a 60 $cm^3$ Ge(Li) detector. The data consist of cross section values for 164 gamma rays or gamma-ray groups having gamma-ray energies between 413 and 4998 keV. These data were analyzed to obtain information on the level structure of $^{68}Zn$, and 131 transitions were assigned among 78 known or postulated new levels in $^{68}Zn$.

## Introduction

The element zinc is made up of five stable isotopes as follows: $^{64}Zn$ (48.9%), $^{66}Zn$ (27.8%), $^{67}Zn$ (4.1%), $^{68}Zn$ (18.6%), and $^{70}Zn$ (0.6%). Thus, an understanding of the radiation transport through elemental zinc will require knowledge of the various reactions induced by neutrons on each of the isotopes, or at least on the three major isotopes $^{64}Zn$, $^{66}Zn$, and $^{68}Zn$. At the present writing, data on neutron interactions with elemental zinc have been requested.[1] As a consequence two measurements have recently been completed and reported upon. The first was the measurements of gamma-ray production with a sample of elemental zinc utilizing a large volume NaI detector.[2] This experiment ascertained gamma-ray production for $E_\gamma$ between 0.7 and 10 MeV and $E_n$ between 1.0 and 20 MeV. These data are in the best form for direct application for current transport problems, but cannot easily be used to deduce nuclear properties of isotopes of Zn. The second experiment consisted of measuring excitation functions for 31 gamma rays due to neutron interactions with elemental zinc utilizing a Ge(Li) detector.[3] In this experiment the excellent gamma-ray energy resolution of the detector allowed study of the strongest individual gamma rays, although placement of these gamma rays as transitions among levels of the three major isotopes required other corroborating information.

A complete neutron cross section evaluation for zinc will benefit from knowledge of the level structures and decay gamma rays of all of the isotopes of Zn. In this regard, a very recent evaluation[4] of Si showed that information on the two minor isotopes of Si was required to adequately complete the evaluation, even though the two minor isotopes

together make up only 8% of elemental Si. It is clear that cross-checking evaluated neutron-scattering files with gamma-ray production files will require a more detailed knowledge of the level structures of the zinc isotopes than is presently available.

With these considerations in mind, a study of gamma-ray production related to any single isotope of zinc is certainly desirable. It happens, however, to be the case that the data reported herein were accumulated[5] during the period 1970 to 1971, i.e., several years prior to obtaining the data reported for neutron interaction with elemental zinc.[2,3] At the time we were involved in a program[6] to measure cross sections for the production of gamma rays using a Ge(Li) photon detector and neutrons produced using a pulsed deuteron beam from a Vande Graaff generator. A variety of nuclei were studied,[5] the choices being restricted to available isotopes of elements having high priorities assigned to (n,xγ) measurements in the then current request lists. Among the nuclei studied was $^{68}$Zn, since at the time, very little was known about the gamma decay of levels in $^{68}$Zn. (The current Nuclear Data Project compilation[7] shows only 7 gamma rays emanating from 5 low-lying states and 9 primary gamma rays from the capture reaction $^{67}$Zn(n,γ). A total of 33 levels having $E_x < 6$ MeV are "adopted.") Data reduction was initiated shortly after the accumulation of the data but was not completed due to other priorities.

Since then the two sets of data on elemental Zn discussed above were taken, reduced, and reported.[2,3] In addition, a careful study of the $^{67}$Zn(n,γ)$^{68}$Zn reaction was reported by Ottmar *et al.*[8] These authors were able to place more than 100 gamma-ray transitions among 49 known or

postulated new levels in $^{68}Zn$, thus considerably extending the knowledge of the level structure of $^{68}Zn$. The major catalyst for the resumption of data reduction of the present data, however, was the initiation of a new Nuclear Data Project compilation[9] for $^{68}Zn$. The present data would, if available, materially benefit the new compilation, not only corroborating the $^{67}Zn(n,\gamma)$ results, but providing new information on levels in $^{68}Zn$ not populated by the capture reaction.

## Experimental Information

The experimental system was quite straightforward and has been discussed in prior reports.[6] A nearly monoenergetic neutron beam was produced by accelerated deuterons interacting with deuterium. The neutrons impinged on a sample enriched to 98.4% in $^{68}Zn$, which was in the form of zinc oxide encapsulated in a thin-walled aluminum can. A dummy sample of BeO similarly encapsulated was used to provide information on background radiation. The resulting gamma rays were detected using a 60 $cm^3$ Ge(Li) detector. Fast-timing electronics were used to discriminate against background radiation, which was reduced substantially, but not entirely eliminated. The advantage of the large volume diode was its efficiency for the full-energy mode of detection, such that all the large, and many of the remaining peaks could be ascribed to the full-energy detection mode. (Only for $E_\gamma > 5$ MeV was the double-escape peak larger than the full-energy peak.) However, the detector was susceptible to neutron damage, moreso than previously suspected.[10] In addition, for the higher-energy gamma rays the recoil motion of the excited Zn nucleus (Doppler effect) helped worsen the observed resolution. The overall

photon energy resolution for the data obtained at $E_n$ = 5.4 MeV was ∿4 keV full width at half maximum (FWHM) for $E_\gamma$ ∿ 1 MeV, increasing to ∿8 keV FWHM for $E_\gamma$ ∿ 4 MeV. Gamma-ray energy calibration was provided by the known background lines in the spectrum, e.g., 511 keV, 843 and 1013 keV due to Al, and 2615 and 4084 keV full-energy and escape peaks due to Pb, from the shielding material. The total spectrum obtained is shown in expanded form in 20 graphs in the appendix. Gamma-ray energies were assigned to observed peaks based on analyses using a light-pen oriented routine written for the PDP-10 graphics display system. These energies were determined to ∿1 keV with respect to the photon-energy calibration. However, in addition to uncertainties associated with the energy calibration, particularly for the larger-energy gamma rays, the observed energies are Doppler shifted some unknown amount depending upon the lifetimes of the excited states and angular distributions of the residual excited $^{68}$Zn nuclei with respect to the angle of photon observation. As discussed below, the observed gamma-rays were not corrected for their Doppler shift, but instead were paired where possible with the more exact gamma-ray energies of Ottmar, *et al.*[8] Relative intensities ($I_\gamma$) were obtained from the raw data for 164 gamma ray peaks, some of which were due to more than a single gamma ray. The $I_\gamma$ were later normalized to the isotopic cross section for the $E_\gamma$ = 1077 keV, obtained in a subsequent run using a natural zinc metal sample. A spectrum was also obtained at $E_n$ = 5.9 MeV; however, the overall photon-energy resolution was worse for this $E_n$, and the spectrum was not analyzed. However, the $E_n$ = 5.9 MeV spectrum provided information for four gamma rays which aided in their placement in the level structure of $^{68}$Zn. The final

reduced isotopic differential cross sections for 164 gamma rays or groups of nearly degenerate gamma rays, are tabulated in Table 1, along with comparison data from the $^{67}Zn(n,\gamma)$ report.[8]

As mentioned above the present photon energies have uncertainties $\Delta E_\gamma$ of ≈1 keV. The $^{67}Zn(n,\gamma)$ data are more precise.[8] It was assumed that many of the presently observed gamma rays corresponded to gamma rays observed in the $^{67}Zn(n,\gamma)$ experiment, and therefore an attempt was made to match up as many of the present gamma rays with those reported in the $^{67}Zn(n,\gamma)$ experiment as possible. This matching procedure had also the benefit of ensuring that the present photon-energy calibration was probably correct to the quoted uncertainties. Additional information was also obtained from the branching ratios obtained from the $I_\gamma$ of the $^{67}Zn(n,\gamma)$ experiment when compared to the cross section ratios obtained from the present $I_\gamma$. Strictly speaking the two ratios are not equivalent, but to within the uncertainties associated with the present $I_\gamma$, and the fact that the present $\theta_\gamma = 55$ deg was chosen because $P_2$ (cos $\theta_\gamma$) ≃ 0, the present cross section ratios are probably adequate branching ratios, at least for those levels not otherwise reported upon.

## Results and Discussion

Nearly 200 peaks were observed and analyzed to obtain $E_\gamma$ and $I_\gamma$ values. Altogether ∿80% of the gamma rays associated with observed peaks were ultimately placed as transitions among 78 known or postulated levels in $^{68}Zn$. To keep the following discussion reasonably brief the following abbreviations will be used without continuous further reference: $(n,\gamma)$ refers to the gamma-ray data of Ottmar, *et al.*;[8] $(\gamma,\gamma')$ refers to the

Table 1. Gamma Rays Produced by Neutron Interaction with $^{68}Zn$

The present data are compared with similar data from the $^{67}Zn(n,\gamma)$ report (ref. 8). Photon energies are in keV. The present $I_\gamma$ are laboratory isotopic cross sections for a gamma-ray scattering angle of 55 degrees and for $E_n$ = 5.4 MeV.

| Gamma-Ray Energy | | Intensity | | Assignment[a] | |
|---|---|---|---|---|---|
| Present[b] | $^{67}Zn(n,\gamma)$ | Present[c] | $^{67}Zn(n,\gamma)$[d] | Present | $^{67}Zn(n,\gamma)$[e] |
| 413 | 412.5 | 1.26 (0.35) | 5.6 | 2751-2338 | 2751-2338 |
| 418 | | 0.20 (0.12) | | | |
| 443 | | 0.24 (0.12) | | | |
| 483(W) | 483.4 | 0.40 (0.18) | 1.1 | 2822-2338 | 2822-2338 |
| 493(B) | | 0.18 (0.10) | | | |
| 500(B) | | 0.62 (0.20) | | | |
| 542(B) | 542.1 | 0.21 (0.11) | 1.8 | 2959-2417 | 2959-2417 |
| 570(B) | 568.6 | 0.60 (0.25) | 0.84 | | |
| 579 | 578.5 | 4.47 (0.88) | 30 | 1656-1077 | 1656-1077 |
| 622 | 621.0 | 0.40 (0.15) | 0.59 | 3630-3009 | 3630-3009 |
| 630(W) | 629.3 | 0.29 (0.12) | 1.2 | 3451-2825 | (3911-3282) |
| 634 | | 0.11 (0.07) | | | |
| 671(C) | 670.9 | 0.96 (0.18) | 3.1 | 3009-2338 | 3009-2338 |
| 735 | 733.7 | 0.25 (0.11) | 1.2 | | |
| 747(W) | 744.8 | 0.31 (0.13) | 0.8 | 3164-2417 | 3496-2751 |
| 807 | 805.8 | 12.7 (1.9) | 121 | 1883-1077 | 1883-1077 |
| 837(B) | 836.4 | 1.62 (0.28) | 6.2 | 3587-2751 | 3587-2751 |
| 865(B) | 864.2 | 3.56 (0.76) | 20 | 3282-2417 | 3282-2417 |
| 874 | 873.6 | 0.69 (0.35) | 2.9 | | |
| 880(B) | 879.6 | 0.86 (0.30) | 9.5 | 3630-2751 | 3630-2751 |
| 937 | 936.7 | 0.18 (0.10) | 1.7 | 3896-2959 | 3896-2959 |
| 955(W) | | 0.22 (0.12) | | | |
| 964(C) | | 1.45 (0.30) | | | |
| 969 | | 0.20 (0.12) | | | |
| 978(W) | 975.4 | 0.30 (0.17) | 1.3 | | (3726-2751) |
| 992 | | 0.65 (0.20) | | $^{64}Zn(n,n')$ | |
| 1027 | 1025.6 | 0.20 (0.13) | 3.9 | | |
| 1041(G) | 1041.3 | 4.10 (1.00) | 6.9 | 3458-2417 | (3458-2417) |
| 1063 | | 0.45 (0.23) | | | |
| 1077 | 1077.4 | 127 | 1000 | 1077-0 | 1077-0 |
| 1114(C) | 1113.3 | 0.60 (0.25) | 2.4 | 3451-2338 | 3935-2822 |
| 1126 | 1126.1 | 5.32 (0.80) | 65 | 3009-1883 | 3009-1883 |
| 1158(W) | 1159.2 | 0.54 (0.24) | 1.6 | | |
| 1170 | 1171.3 | 0.81 (0.18) | 7.3 | | |
| 1214 | 1212.7 | 0.18 (0.11) | 2.2 | 3630-2417 | 3630-2417 |

Table 1 (continued)

| Gamma-Ray Energy | | Intensity | | Assignment[a] | |
|---|---|---|---|---|---|
| Present[b] | $^{67}Zn(n,\gamma)$ | Present[c] | $^{67}Zn(n,\gamma)$[d] | Present | $^{67}Zn(n,\gamma)$[e] |
| 1220(W) | 1219.4 | 0.70 (0.17) | 5.1 | 3104-1883 | |
| 1261 | 1261.0 | 11.7 (1.8) | 113 | 2338-1077 | 2338-1077 |
| 1268(W) | | 0.53 (0.28) | | 3685-2417 | |
| 1276(W) | 1276.9 | 0.50 (0.28) | 1.5 | 4028-2751 | 4028-2751 |
| 1300(W) | 1300.9 | 0.52 (0.18) | 5.1 | 3184-1883 | 3184-1883 |
| 1313 | 1313.1 | 0.48 (0.17) | 1.4 | | |
| 1340 | 1340.0 | 26.1 (3.9) | 126 | 2417-1077 | 2417-1077 |
| 1366(U) | | 0.35 (0.22) | | | |
| 1372 | 1372.3 | 1.00 (0.32) | 1.6 | 3712-2338 | |
| 1387(W) | 1387.2 | 0.66 (0.23) | 6.3 | 3726-2338 | 3726-2338 |
| 1398 | 1397.7 | 0.80 (0.21) | 3.2 | (3282-1883) | |
| 1433 | 1431.9 | 1.4 (0.50) | 7.1 | 3849-2417 | 3849-2417 |
| 1438(B) | 1437.8 | 0.7 (0.40) | 5.1 | 3776-2338 | 3776-2338 |
| 1452(B) | 1451.8 | 0.23 (0.11) | 1.3 | | (3335-1883) |
| 1462(G) | 1463.3 | 0.49 (0.18) | 2.2 | (3346-1883) | |
| 1479 | 1478.3 | 1.11 (0.20) | 7.7 | 3896-2417 | 3896-2417 |
| 1493 | 1493.5 | 0.35 (0.18) | 3.9 | 3911-2417 | 3911-2417 |
| 1518 | 1518.3 | 0.80 (0.20) | 1.9 | 3401-1883 | |
| 1542(R) | 1541.7 | 0.70 (0.25) | 6.9 | 3425-1883 | 3425-1883 |
| 1547 | 1546.1 | 1.63 (0.28) | 20.0 | 3430-1883 | 3430-1883 |
| 1559(W) | 1557.1 | 0.52 (0.22) | 0.6 | | 3896-2338 |
| 1598 | 1596.3 | 0.46 (0.22) | 1.9 | (3935-2338) | 3935-2338 |
| 1608 | | 0.20 (0.13) | | | |
| 1612 | 1612.2 | 0.20 (0.13) | 1.4 | 3496-1883 | 3496-1883 |
| 1617(U) | | 0.20 (0.13) | | | |
| 1626(W) | {1624.2, 1627.7} | 2.26 (0.39) | 5.5<br>2.2 | | |
| 1633(W) | 1630.9 | 1.0 (0.4) | 7.1 | (3287-1656) | 3287-1656 |
| 1673 | 1673.3 | 16.5 (2.5) | 73 | 2751-1077 | 2751-1077 |
| 1697 | 1698.0 | 0.35 (0.20) | 1.9 | (4521-2822) | |
| 1724(W) | 1723.5 | 1.81 (0.41) | 1.9 | 4060-2338 | (4733-3009) |
| 1745 | 1744.2 | 5.46 (0.82) | 41 | 2822-1077 | 2822-1077 |
| 1778(U) | 1777.6 | 1.03 (0.25) | 4.5 | | |
| 1780(U) | 1781.5 | 1.03 (0.25) | 8.8 | 3665-1883 | 3665-1883 |
| 1883 | 1883.1 | 26.4 (3.9) | 187 | 1883-0 | 1883-0 |
| 1933(W) | 1932.1 | 0.94 (0.35) | 7.6 | 3009-1077 | 3009-1077 |
| 1969(W) | | 0.67 (0.22) | | | |
| 2027 | 2027.9 | 0.40 (0.18) | 4.1 | 3911-1883 | 3911-1883 |
| 2055(S) | | 0.75 (0.25) | | | |
| 2062 | | 0.78 (0.25) | | | |

Table 1 (continued)

| Gamma-Ray Energy | | Intensity | | Assignment[a] | |
|---|---|---|---|---|---|
| Present[b] | $^{67}Zn(n,\gamma)$ | Present[c] | $^{67}Zn(n,\gamma)$[d] | Present | $^{67}Zn(n,\gamma)$[e] |
| 2081 | | 0.44 (0.18) | | 3158-1077 | |
| 2094(U) | 2094.6 | 0.20 (0.14) | 5.1 | | 4512-2417 |
| 2108(B) | 2106.8 | 1.74 (0.60) | 20 | 3184-1077 | 3184-1077 |
| 2122(U) | | 0.26 (0.15) | | (4871-2751) | |
| 2161 | | 0.25 (0.13) | | | |
| 2182 | 2181.7 | 0.52 (0.22) | 3.5 | 4521-2338 | 4521-2338 |
| 2212(H) | 2209.8 | 2.6 (1.4) | 49 | 3287-1077 | 3287-1077 |
| 2259(W) | 2257.2 | 0.62 (0.20) | 2.1 | | (3335-1077) |
| 2270 | | 0.62 (0.20) | | 3346-1077 | |
| 2300(U) | | 0.25 (0.20) | | (4639-2339) | |
| 2310(R) | | 0.60 (0.28) | | (3383-1077) | |
| 2322(W) | | 0.90 (0.35) | | (3401-1077) | |
| 2339 | | 0.35 (0.14) | | 2339-0 | |
| 2348(R) | 2347.4 | 0.97 (0.19) | 12.7 | 3425-1077 | 3425-1077 |
| 2352 | 2352.8 | 0.90 (0.18) | 12.1 | 3430-1077 | 3430-1077 |
| 2374(W) | | 0.63 (0.16) | | (3451-1077) | |
| 2392 | (2390.2) | 0.58 (0.16) | 3.0 | | 5400-3009 |
| 2420(W) | 2418.6 | 2.67 (0.40) | 26 | 3496-1077 | 3496-1077 |
| 2428(U) | | 0.25 (0.15) | | | |
| 2442 | 2438.9 | 0.27 (0.10) | 0.8 | | |
| 2470(U) | | 0.15 (0.10) | | | |
| 2508(W) | {2506.3, 2512.7} | 0.73 (0.20) | 8.3<br>5.7 | 3584-1077 | 4851-2338 |
| 2548 | (2547.0) | 0.86 (0.21) | 5.4 | 3626-1077 | 5298-2751 |
| 2563(W) | | 0.35 (0.18) | | | |
| 2591(W) | {2587.2, 2591.3} | 1.38 (0.23) | 4.4<br>5.0 | 3665-1077 | 3665-1077 |
| 2650(W) | {2648.1, 2652.1} | 1.00 (0.22) | 7.8<br>6.0 | 3726-1077 | 3726-1077 |
| 2699(W) | {2695.8, 2699.5} | 0.20 (0.14) | 2.4<br>2.2 | 3776-1077 | 3776-1077 |
| 2732(Y) | 2730.0 | 3.23 (0.48) | 1.47 | (5146-2417) | |
| 2739 | 2737.7 | | 11.2 | 3816-1077 | |
| 2822(W) | {2821.4, 2824.7} | 0.56 (0.15) | 3.2<br>1.9 | 2822-0 | 2822-0 |
| 2845(U) | | 0.50 (0.30) | | | |
| 2852(R) | 2851.0 | 0.98 (0.33) | 3.7 | 3928-1077 | |
| 2861 | 2857.6 | 1.64 (0.28) | 19.0 | 3935-1077 | 3935-1077 |

Table 1 (continued)

| Gamma-Ray Energy | | Intensity | | Assignment[a] | |
|---|---|---|---|---|---|
| Present[b] | $^{67}Zn(n,\gamma)$ | Present[c] | $^{67}Zn(n,\gamma)$[d] | Present | $^{67}Zn(n,\gamma)$[e] |
| 2953 | | 0.45 (0.13) | | | |
| 2985 | 2982.9 | 2.38 (0.50) | 5.0 | 4060-1077 | |
| 2990(Y) | | | | 4871-1883 | |
| 3009(W) | | 1.34 (0.31) | | | |
| 3065(Z) | 3062.4 | 1.05 (0.44) | 6.9 | | (4140-1077) |
| | 3068.8 | | 2.6 | (4145-1077) | 4952-1883 |
| 3140(W) | 3137.8 | 0.81 (0.14) | 5.9 | 4215-1077 | 4215-1077 |
| 3152(R) | 3151.9 | 0.35 (0.18) | 2.5 | 4229-1077 | |
| 3157 | 3154.6 | 0.70 (0.30) | 3.8 | 4232-1077 | |
| 3183(R) | 3184.3 | 0.50 (0.33) | 4.9 | 3184-0 | 3184-0 |
| 3187 | | 1.07 (0.33) | | | |
| 3207(B) | 3206.4 | 0.13 (0.09) | 3.7 | 4284-1077 | 4284-1077 |
| 3286(U) | 3287.2 | 0.14 (0.10) | 18.1 | 3287-0 | 3287-0 |
| 3332 | 3331.0 | 0.15 (0.07) | 9.5 | 4408-1077 | 4408-1077 |
| 3348 | 3345.9 | 1.76 (0.27) | 8.8 | 3346-0 | |
| 3360 | 3358.2 | 0.69 (0.12) | 4.8 | 4437-1077 | |
| 3383(U) | 3380.2 | 0.18 (0.10) | 2.1 | (3383-0) | (3380-0) |
| 3402(W) | 3399.8 | 0.22 (0.11) | 2.4 | 3401-0 | 5283-1883 |
| 3427(W) | | 0.31 (0.14) | | (4504-1077) | |
| 3430(U) | 3430.0 | | 1.8 | (3430-0) | 3430-0 |
| 3442 | | 0.43 (0.18) | | | |
| 3456(W) | 3452.6 | 0.46 (0.21) | 1.5 | | |
| | 3458.1 | | 9.5 | 4535-1077 | 4535-1077 |
| 3511(W) | 3509.9 | 1.10 (0.18) | 3.4 | 4587-1077 | |
| 3520(Y) | 3519.4 | <0.15 | 3.2 | 5403-1883 | 5403-1883 |
| 3567(W) | 3563.2 | 0.67 (0.12) | 6.1 | 4640-1077 | |
| | 3569.0 | | 1.4 | | |
| 3592 | (3595.2) | 0.32 (0.18) | 0.9 | (4670-1077) | |
| 3626 | (3630.2) | 0.22 (0.10) | 1.9 | 3625-0 | 3630-0 |
| 3666(W) | 3664.8 | 1.22 (0.19) | 2.5 | 3665-0<br>(4744-1077) | 3665-0 |
| 3706 | 3703.5 | 0.80 (0.13) | 2.4 | | |
| 3718 | 3716.5 | 1.46 (0.21) | 3.4 | 3717-0 | |
| 3773(W) | 3772.3 | 0.80 (0.30) | 5.6 | | |
| | (3777.0) | | 6.3 | 3776-0 | 3776-0 |
| 3817 | 3816.3 | 0.54 (0.14) | 4.3 | 3816-0 | |
| 3832 | 3833.1 | 0.60 (0.21) | 10.0 | 4910-1077 | 4910-1077 |
| 3883 | 3885.5 | 0.44 (0.15) | 2.8 | | 4963-1077 |

Table 1 (continued)

| Gamma-Ray Energy | | Intensity | | Assignment[a] | |
|---|---|---|---|---|---|
| Present[b] | $^{67}Zn(n,\gamma)$ | Present[c] | $^{67}Zn(n,\gamma)$[d] | Present | $^{67}Zn(n,\gamma)$[e] |
| | 3946.7 | | 1.1 | | |
| 3954 | 3951.8 | 1.1 (0.19) | 2.6 | | |
| | 3958.6 | | 3.1 | | |
| 3989(W) | | 0.30 (0.15) | | (3989-0) | |
| 4027 | 4028.3 | 1.14 (0.16) | 4.3 | 4028-0 | 4028-0 |
| 4069(Y) | 4069.4 | <0.1 | 5.6 | 5146-1077 | |
| 4102 | | 0.67 (0.14) | | (4102-0) | |
| 4282(U) | 4281.7 | 0.17 (0.17) | 2.7 | (4282-0) | |
| 4325 | 4325.5 | 0.39 (0.14) | 5.4 | 4325-0 | (4326-0) |
| 4338(W) | 4334.0 | 0.70 (0.15) | 6.1 | 4334-0 | P,G |
| 4414 | 4411.2 | 0.54 (0.14) | 2.4 | 4414-0 | |
| 4444(W) | 4437.5 | 0.98 (0.15) | 2.7 | 4437-0 | |
| | 4448.7 | | 4.0 | 4449-0 | |
| 4465 | 4466.2 | 0.74 (0.11) | 4.1 | 4466-0 | |
| 4496 | 4493.9 | 0.30 (0.12) | 1.9 | 4496-0 | |
| 4502 | 4500.0 | 0.30 (0.12) | 6.3 | 4500-0 | |
| 4523(U) | 4521.0 | 0.17 (0.11) | 5.8 | 4521-0 | 4521-0 |
| 4578 | 4579.8 | 0.35 (0.10) | 1.4 | 4579-0 | |
| 4585 | | 0.31 (0.10) | | 4586-0 | |
| 4608 | 4609.1 | 0.77 (0.13) | 2.0 | 4609-0 | |
| 4639 | 4639.4 | 0.28 (0.12) | 2.1 | 4639-0 | |
| 4670(U) | 4670.7 | 0.20 (0.13) | 1.8 | 4671-0 | |
| 4680 | 4681.6 | 0.52 (0.11) | 3.3 | 4682-0 | P,G |
| 4718 | 4716.5 | 0.18 (0.09) | 2.5 | 4717-0 | G,P |
| 4792(W) | 4789.8 | 0.45 (0.13) | 2.6 | 4790-0 | |
| 4855 | 4858.4 | 0.29 (0.10) | 2.6 | 4855-0 | |
| 4982 | 4977.8 | 0.23 (0.07) | 2.3 | 4978-0 | P,G |
| 4998 | 4998.0 | 0.23 (0.08) | 2.0 | 4993-0 | 4991-0 |

Footnotes

a. Uncertain assignments in parenthesis.

b. Present photon energy uncertainty given by $\Delta E_\gamma = 0.5 + 0.0012 \times E_\gamma$, in keV, where the second factor accounts for the Doppler motion. The following comments are associated with the symbols appearing adjacent to some of the gamma-ray energies:

(B) Coincident with background radiation.
(C) Coincident with known lines in copper.
(G) Coincident with known lines in Germanium, due to neutron interactions with the detector.
(H) Underlying this peak is a broad peak believed associated with n + p capture gamma ray, $E_\gamma \approx 2.22$ MeV.
(R) Peak is not clearly resolved from a stronger nearby peak.
(S) Wide group barely resolved from the 2062-keV peak.
(U) Uncertain peak extraction due to odd peak shape.
(W) Peak is wide, probably due to two or more gamma rays.
(Y) Peak is much larger for $E_n = 5.9$ MeV.
(Z) Peak is coincident with 4084 keV double-escape peak, a known background line from Pb.

c. In mb/sr, with errors in parentheses.

d. $^{67}Zn(n,\gamma)$ intensities are relative to $E_\gamma = 1077$ keV; for $E_\gamma > 2210$ keV, the data in Table 3 of ref. 8 were renormalized to agree with the data in Table 2 of ref. 8.

e. Assignment of "P,G" or "G,P" for high-energy gamma rays indicate that either primary (i.e., from the capture state) or ground-state transitions were the probable assignments.

gamma-ray scattering data of Metzger;[11] ($\beta$-$\gamma$) refers to the decay studies of $^{68}$Cu isomers by Swindle *et al.*;[12] (t,p) refers to the charged-particle data of Hudson and Glover;[13] ($\alpha$,$\alpha'$) refers to inelastic alpha scattering data of Alpert, *et al.*;[14] and NDS refers to the published Nuclear Data Project compilation[7] (not the compilation in progress). Each subheading below refers to one or more levels to be discussed. Levels not observed in the present experiment are enclosed in parentheses. The presently assigned transitions and branching ratios are shown schematically in Fig. 1 for $E_x < 4$ MeV, and in Fig. 2 for $E_x > 4$ MeV.

$E_x$ = 1077, 1656, 1883, and 2338 keV. The present data agree very well with prior gamma-ray data. Additional verification of the placement of gamma rays among the low-lying levels of $^{68}$Zn was provided by the data of ref. 3 cited above. In that experiment data were obtained using a natural zinc metal sample and the Oak Ridge Electron Linear Accelerator as the neutron source. Incident-neutron-energy thresholds were observed for $E_\gamma$ = 583, 1077, 1261, 1673, and 1883 keV gamma rays which are in agreement with the present assignments.

($E_x$ = 2369 keV). This level is reported in the ($\beta$-$\gamma$) experiment having $J^\pi = 2^+$ and decaying via a 1292-keV gamma ray. There is no indication of a 1292-keV photon in the present experiment. The existence of this level is doubtful.

$E_x$ = 2417 keV. A strong 1340-keV gamma ray is observed in agreement with (n,$\gamma$) and ($\beta$-$\gamma$). $J^\pi = 4^+$ has strongest support from gamma-gamma coincidence measurements of ($\beta$-$\gamma$).

($E_x$ = 2.5 MeV). NDS shows a level at 2.49 MeV based only on a $^{67}$Zn(d,p) measurement, and ($\beta$-$\gamma$) reports a level at 2511 keV having

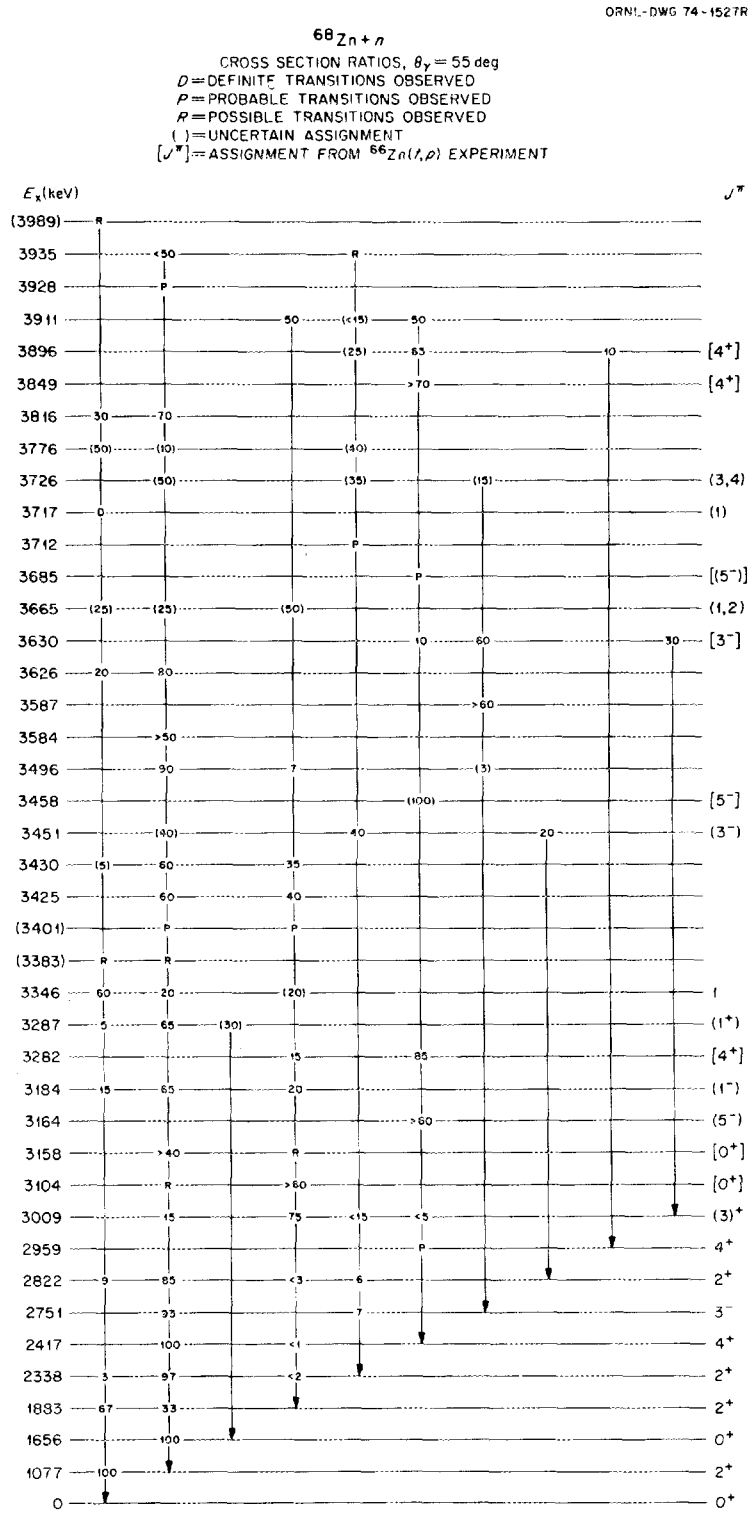


Fig. 1. Level structure for $^{68}$Zn for $E_x$ < 4 MeV as deduced from the present experimental data. The small numbers at the intersections of the lines indicated cross-section ratios for gamma-ray scattering angle of 55 deg.

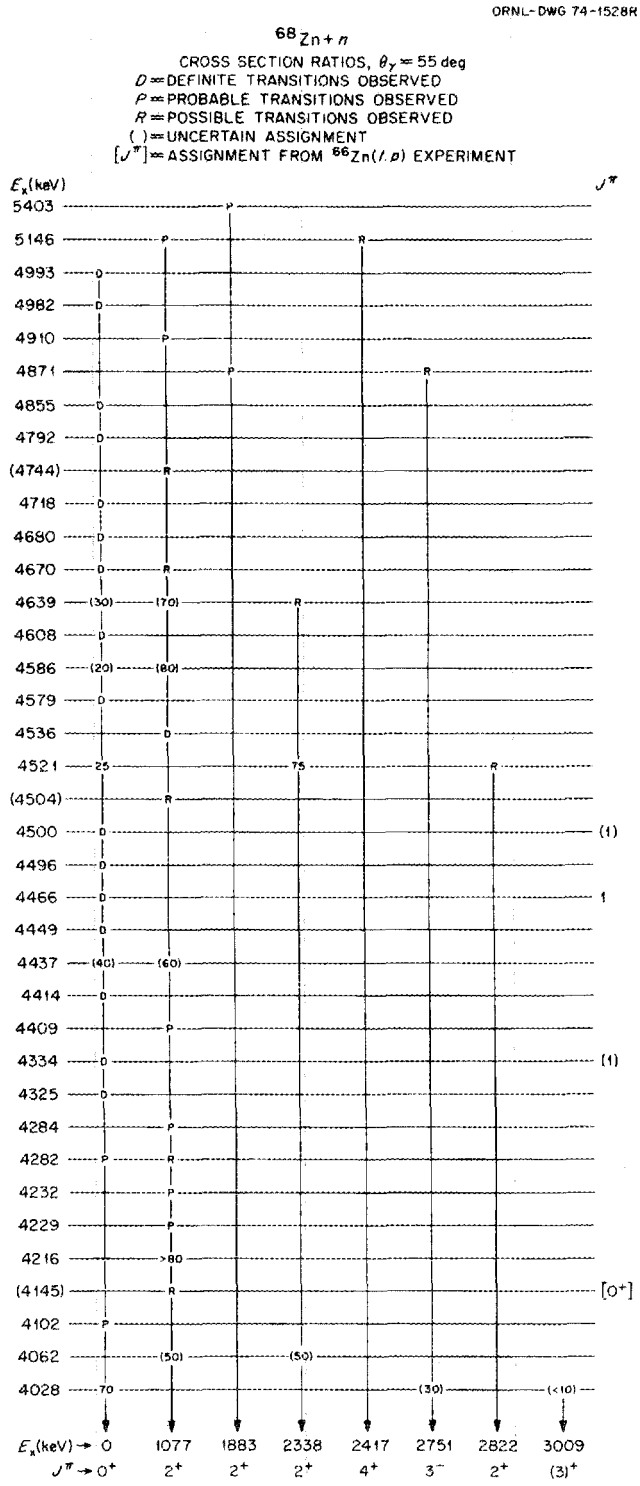


Fig. 2. Levels in $^{68}Zn$ for $E_x$ > 4 MeV observed in the present experiment.

J = (2) and decaying via a 1433-keV photon. A 1433-keV gamma ray is observed in the present experiment as well as in the (n,γ) report. The (n,γ) assignment is as a transition between $E_x$ = 3849 and 2417 keV levels based upon their gamma-gamma coincidence measurements. The present assignment in agreement with (n,γ) reflects doubt as to the existence of a level vic $E_x$ = 2.5 MeV.

$E_x$ = 2751 and 2822 keV. The present data confirm prior gamma-ray assignments. In addition, as mentioned above, the data of ref. 3 indicate a threshold for $E_\gamma$ = 1673 keV consistent with assignment as decay from $E_x$ = 2751 keV. A strong $J^\pi = 3^-$ level is observed in (α,α') at $E_x$ = 2.75 MeV, and a $J^\pi = 2^+$ level is indicated in (t,p) at $E_x$ = 2821 keV.

$E_x$ = 2959 keV. A very weak 542-keV photon is observed and given the same assignment as (n,γ). A $J^\pi = 4^+$ level is indicated in (t,p) at $E_x$ = 2955 keV.

$E_x$ = 3009 keV. Photons are observed corresponding to decay to $E_x$ = 1883 and 2338 keV, in agreement with (n,γ). No comparable level is observed in (α,α') or (t,p) suggesting an unnatural parity state. Parity is positive and J = (2,3) according to (n,γ); present data prefer spin of 3.

($E_x$ = 3081 keV). Level reported in (β-γ) not confirmed by present experiment.

$E_x$ = 3104 and 3158 keV. Two $J^\pi = 0^+$ levels are observed in (t,p) at $E_x$ = 3100 and 3157 keV, the higher energy level very strongly observed. $J^\pi = 0^+$ excited states tend to be weakly observed in nucleon inelastic scattering[15] so the present data were scanned for possible weak transitions to J = 2 levels. Two likely and two possible transitions were

observed, for $E_\gamma$ = 2081 and 1220 keV and $E_\gamma$ = 2027 and 1275 keV, respectively. The latter two were observed and assigned differently by (n,γ).

$E_x$ = 3164 keV. A weak $J^\pi = (5^-)$ level was reported in (α,α') at $E_x$ = 3.17 MeV. Such a level having $J^\pi = 5^-$ should decay only to a $J^\pi = 4^+$ level, probably the $E_x$ = 2417 keV level. The 747-keV gamma ray observed in the present experiment may include the 745-keV transition observed and assigned in (n,γ); however the present $I_\gamma$ is about four times larger than expected from the (n,γ) assignment. Other possible transitions from the postulated $E_x$ = 3164 keV level were sought, and the branching ratio assignment in Fig. 1 is based upon a cumulation of upper limits to the unobserved transitions.

$E_x$ = 3184 keV. Present data confirm (n,γ) assignments, with no objection to $J^\pi = (1^-)$ assignment of (n,γ). This level is probably the $E_x$ = 3.20 MeV level of NDS.

$E_x$ = 3282 and 3287 keV. Present data essentially confirm a doublet reported by (n,γ). A $J^\pi = 4^+$ level is observed in (t,p) at $E_x$ = 3278 keV and NDS and (n,γ) suggest $J^\pi = (1,2)^+$ for the $E_x$ = 3287 keV level. Neither level is observed by (α,α'), suggesting $J^\pi$ for the upper level is $1^+$ rather than $2^+$.

$E_x$ = 3346 keV. Present assignment confirms (γ,γ'). A similar energy photon was observed by (n,γ), unplaced by (n,γ); however, (n,γ) doesn't report a 2270-keV gamma ray observed in the present experiment.

$E_x$ = 3383 keV. NDS has a level at 3382 keV based on (p,p'). Present experiment has two weak gamma rays which could be transitions from this level. The $E_\gamma$ = 3383-keV gamma ray may be the 3380.2-keV gamma ray observed in (n,γ) and tentatively placed by (n,γ) as a ground-state transition. Level is not observed in other experiments.

$\underline{E_x}$ = 3401 keV. Two transitions are observed in the present experiment which suggest a level at this energy. Level is not observed in other experiments.

$\underline{E_x}$ = 3425 and 3430 keV. A doublet is reported by (n,γ), and the present data are in agreement, since the raw spectra show almost resolved doublets for peaks corresponding to $E_\gamma \simeq 2350$ and 1547 keV. NDS has $J^\pi = (3,4)^+$ for a level at $E_x = 3424$ keV. A level having $J^\pi = 2^+$ is indicated by (t,p) for $E_x = 3427$ keV. The (n,γ) experiment suggests $J^\pi = (1,2)^+$ for $E_x = 3430$ keV.

$\underline{E_x}$ = 3451 and 3458 keV. The (t,p) experiment reports a doublet at $E_x = 3451$ keV having L = 5 as the dominant angular momentum. An addition of L = 3 would improve the fit. A level having $J^\pi = 5^-$ is indicated in (α,α') for $E_x = 3.45$ MeV. The (β-γ) experiment supports J = (5,6) for a level at $E_x = 3458$ keV. The NDS level at $E_x = 3424$ keV having $J^\pi = (3,4)^+$ may also be equivalent. As no level in this region of level excitation is shown by (n,γ), possible transitions were sought. A strong $E_\gamma = 1041$ keV photon was observed, equal in $E_\gamma$ to a gamma-ray observed by (n,γ) and tentatively placed as the 3458-2417 keV transition. No other gamma rays are observed which might correspond to transitions from this level. Several other gamma rays were observed, viz., $E_\gamma$ = 630, 1114, and 2374 keV. The first two were also observed by (n,γ) and placed or tentatively placed as transitions among higher-lying states. For both photons the present $I_\gamma$ are too large and both peaks in the raw data appear wide. There are a number of possible placements for $E_\gamma$ = 2374, 1114, and 630 keV gamma rays, but influenced by the suggested possibility for a J = 3 level vic $E_x = 3.45$ MeV and the good agreement for transition energy sums, a level is postulated at $E_x = 3451$.

$\underline{E_x}$ = 3496 keV. The present data agree well with (n,γ) data. A level at $E_\gamma$ = 3492 keV with no $J^\pi$ assignment is reported by (t,p).

$\underline{E_x}$ = 3584 and 3587 keV. An $E_\gamma$ = 836 keV photon is observed in the present experiment assigned to the 3587-2751 keV transition in agreement with (n,γ). A broad peak is observed at $E_\gamma \simeq$ 2508 keV in the present data, with a possible assignment as the 3587-1077 keV transition, a transition not shown in (n,γ). However, the present $I_\gamma$ for $E_\gamma$ = 836 and 2508 keV would not give the same branching ratios as the $I_\gamma$ from (n,γ). Hence, the $E_\gamma$ = 2508 keV gamma ray(s) must be assigned elsewhere. The (t,p) experiment shows a possible doublet at $E_x$ = 3583 keV with L = (4). If the peak is doublet the other L value would likely be 1 or 2. Based on these considerations a doublet is postulated with one of the two levels having $J^\pi = 4^+$.

$\underline{E_x}$ = 3610, 3626, and 3630 keV. A level having $J^\pi = (2^+)$ is indicated by (n,γ) at $E_x$ = 3630 keV. A level having $J^\pi = 3^-$ is indicated by (t,p) at $E_x$ = 3620 keV. A high-spin level, J = 6 or 7 at $E_x$ = 3610 is shown in (β-γ), decaying by a 152-keV transition to the next lower J = (5,6) state. $E_\gamma$ = 152 keV is too small in photon energy to be observed in the present experiment. The (n,γ) report shows five transitions from $E_x$ = 3630 keV, viz., $E_\gamma$ = 3630, 1213, 880, 621, and 349 keV, the last being uncertain. The present data includes gamma rays of approximately these energies. However, in the present data the energy of the "3630-keV" peak is determined to be 3626 keV; in addition a 2548-keV photon is observed in the present experiment. As it is doubtful that a ground-state transition would be observed from a J = 3 level, the high-energy photon, $E_\gamma$ = 3626 keV in the present experiment is postulated as a

ground-state transition, and the 2548-keV photon has the correct energy to be the 3626-1077 keV transition.

$E_x$ = 3665 keV. Gamma rays are observed in agreement with (n,γ) and the present assignments agree with (n,γ).

$E_x$ = 3685 keV. The (t,p) data include a $J^\pi = (5^-)$ level at $E_x$ = 3682 keV. The most likely transition would be 1265 keV to the lowest $4^+$ level. A weak transition is observed for $E_\gamma$ = 1268 keV. Level is not reported in other experiments.

$E_x$ = 3712, 3717, and 3726 keV. Only one of these levels, $E_x$ = 3726 keV, is reported by (n,γ), and the present data include three of four transitions reported by (n,γ). A doublet having $J^\pi = 4^+$ and $J^\pi = 0^+$ is reported at $E_x$ = 3712 keV by (t,p). The (α,α') data include a $J^\pi = 3^-$ at $E_x$ = 3.72 MeV. A J = (4) level at $E_x$ = 3724 keV is reported by (β-γ). The (γ,γ') data include $E_\gamma$ = 3717 keV, assigned as a ground-state transition from a level having J = (1). NDS includes a level having $J^\pi = (4,3)^+$ at $E_x$ = 3712 keV. At least four levels seem required, one with J = 1, one with J = 3 or 4 and positive parity, one with $J^\pi = 3^-$, and one with $J^\pi = 0^+$. Of the five transitions shown for these three levels in Fig 1 only the 3712-2338 keV transition has not previously been reported. The (n,γ) data, however, include an unplaced 1372-keV gamma ray. If the present assignment is correct the $J^\pi$ for $E_x$ = 3712 keV is more likely $3^-$ than $0^+$ since the (n,γ) experiment should not strongly populate $0^+$ levels.

($E_x$ = 3736 keV). A J = (4) level was reported by (β-γ) at $E_x$ = 3736 keV, decaying by a 1225-keV gamma ray to $E_x$ = 2510 keV. As mentioned above there is no indication for a level at $E_x$ = 2510 keV in the present experiment, and the closest energy photon in the present experiment is otherwise assigned. The level is not otherwise reported.

$\underline{E_x}$ = 3776 keV. The present data agree with three reported transitions reported by (n,γ) for a level at this $E_x$.

($\underline{E_x}$ = 3806 keV). A level having $J^\pi = (3^-)$ was reported by (t,p) at this $E_x$. The present experimental data do not support a level of $J^\pi = 3^-$ for $E_x$ = 3806 ± 10 keV.

$\underline{E_x}$ = 3816 keV. Two gamma rays were observed in the present data having $E_\gamma$ = 2739 and 3817 keV, energies close enough to correspond to two unassigned but observed gamma rays by (n,γ) having $E_\gamma$ = 2738 and 3816 keV. The 3816-keV gamma ray could be a 4893-1077 transition; however the energy sum 2738 + 1077 keV and the relative $I_\gamma$ giving similar branching ratios for both experiments supports assignments of these two gamma rays to a level at $E_x$ = 3816 keV.

$\underline{E_x}$ = 3849 and 3896 keV. Two $J^\pi = 4^+$ levels are reported by (t,p) at these $E_x$; two transitions are reported by (n,γ) for decay of $E_x$ = 3849 keV and three transitions are reported for decay of $E_x$ = 3896 keV. Three of these transitions, $E_\gamma$ = 937, 1433, and 1479 keV are definitely observed in the present experiment.

$\underline{E_x}$ = 3911 keV. Four transitions are reported by (n,γ). The present experiment confirms two of them, $E_\gamma$ = 1493 and 2028 keV. The 1572-keV gamma is not observed, and the 636 keV gamma ray is assigned elsewhere.

$\underline{E_x}$ = 3928 keV. A fairly strong 2852-keV photon is observed in the present experiment, corresponding to an unplaced 2851-keV among the data of (n,γ). The transition is not likely ground state, since there is no prior evidence for a level at 2852 keV; the gamma ray could correspond to a 4735-1883 keV. However, (t,p) reports a level at $E_x$ = 3927 keV with no $J^\pi$ assignment, but the reported angular distribution must include

L = 1 or 2. Hence, the present assignment of this gamma ray is as the 3928-1077 keV transition.

$E_x$ = 3935 keV. The present data may include the strongest of the five transitions shown in the level diagram of (n,γ). A 1598-keV transition is observed which may be decay from this level as suggested by (n,γ).

($E_x$ = 3964 keV). A J = (4) level at this $E_x$ is given by (β-γ) decaying by an 1142-keV gamma ray. No gamma ray is observed vic $E_\gamma$ = 1142 keV. The level is not otherwise reported.

$E_x$ = 3989 keV. A wide $E_\gamma$ = 3989-keV gamma ray is observed which is assigned as a ground-state transition based mainly on an NDS level at $E_x$ = 3983 keV. The level is not otherwise reported.

$E_x$ = 4028 keV. Two of three transitions reported by (n,γ) are observed in the present experiment, in particular the strong ground-state transition.

$E_x$ = 4062 keV. A level having $J^\pi = (2^+)$ is indicated at $E_x$ = 4049 keV by (t,p). This level may correspond to a postulated level at $E_x$ = 4062 keV, based on the $I_\gamma$ of two presently observed gamma rays at $E_\gamma$ = 1724 and 2985 keV. The 2985-keV gamma ray does not likely correspond to a ground state transition as there is no other evidence for a level at $E_x$ = 2985 keV, and the $I_\gamma$ seems much too large to correspond to a 4868-1883 keV transition.

$E_x$ = 4102 keV. The observed 4102-keV gamma ray is more likely a ground-state transition than a 5179-1077 keV transtion. NDS shows a 4102-keV level observed only in $^{68}$Zn(p,p').

($\underline{E_x}$ = 4139 keV). A 4139-keV gamma ray observed by (n,$\gamma$) was assigned to a ground-state transition. This gamma ray was not observed in the present experiment.

$\underline{E_x}$ = 4145 keV. A level having $J^\pi = 0^+$ is indicated at this $E_x$ by (t,p). A search for a transition from this level yielded one possible candidate, 4145-1077 keV.

$\underline{E_x}$ = 4216 keV. The present data include a wide peak corresponding to at least one 3140-keV gamma ray which is not likely to be a ground-state transition since there is no other evidence for a level at this $E_x$. Although transitions to the 1656- or 1883-keV levels are energetically possible, the most likely transition is 4217-1077 keV. If so, this assignment is probably the same one as the 4216-1077 keV transition reported by (n,$\gamma$).

$\underline{E_x}$ = 4229 and 4232 keV. The present spectrum exhibits a strong, and rather apparent doublet for $E_\gamma \simeq 3.155$ keV. The lower energy gamma ray, $E_\gamma$ = 3152 keV, may correspond to an unplaced $E_\gamma$ = 3152 keV gamma ray in (n,$\gamma$). The most likely transitions, especially for the stronger 3157-keV gamma ray, are first-excited state transitions. The ($\alpha$,$\alpha'$) data suggest one or more levels vic $E_x$ = 4.23; otherwise there is no other corroborating evidence.

$\underline{E_x}$ = 4282 and 4284 keV. A weak 4282-keV gamma ray is observed in the present experiment, corresponding to an unplaced $E_\gamma$ = 4282 keV by (n,$\gamma$). A weak 3207-keV gamma ray is also observed and the peak shape suggests a doublet. A corresponding 3206-keV photon is placed as the 4284-1077 keV transition by (n,$\gamma$). The (n,$\gamma$) photon energy measurements are precise enough to state that the two gamma rays observed by (n,$\gamma$)

do not emanate from the same level. A doublet is postulated to account for the observed data.

$E_x$ = 4325 and 4334 keV. The present spectra exhibit two statistically significant peaks at $E_\gamma$ = 4325 and 4335 keV. The 4335-keV photon corresponds to a similar energy photon observed in $(\gamma,\gamma')$, and is therefore a ground-state transition from a J = (1) level. The 4325-keV photon might possibly correspond to a 5402-1077 keV transition, but it is much more likely a ground-state transition. NDS shows a $J^\pi = (3)^-$ at $E_x$ = 4.32 MeV, which is not likely either of these two states.

$E_x$ = 4409 and 4414 keV. A level at $E_x$ = 4409 keV decaying primarily by $E_\gamma$ = 3331 keV, was reported by $(n,\gamma)$. The present data include a weak 3332-keV gamma ray and a stronger group at $E_\gamma \sim 4414$ keV. The present $I_\gamma$ are incompatible with assignment of the 4414-keV photon as a 4409-keV ground-state transition. A doublet accounts for the observed data.

$E_x$ = 4437, 4449, 4466, 4496, and 4500 keV. Unresolved groups are observed in the spectrum corresponding to $E_\gamma \sim 4.45$ and 4.50 MeV. The $(n,\gamma)$ data include five unplaced gamma rays in this region of $E_\gamma$. It was assumed that the $(n,\gamma)$-observed photons were also those observed in the present data. They must all be ground-state transitions. An otherwise unplaced 3360-keV gamma ray corresponds to the 4437-1077 keV transition. Two of the five ground-state transitions were already reported by $(\gamma,\gamma')$, viz., $E_\gamma$ = 4466 and 4500 keV, hence the J = (1) or 1 assignments shown.

$E_x$ = 4504 keV. In the present experiment a broad peak is observed corresponding to $E_\gamma$ = 3428 keV. The $(n,\gamma)$ data include a 3430-keV ground-state transition but do not include a slightly lower energy ground-state transition. The present $I_\gamma$ is too large for the observed photon to be

solely the 3430-keV ground-state transition; hence a level at $E_x$ = 4504 keV is postulated.

$E_x$ = 4513 keV. A level at this $E_x$ was postulated by (n,γ) having three decay gamma rays, viz., 4513, 3435, and 2095 keV. The first two were not observed in the present experiment.

$E_x$ = 4521 and 4536 keV. Gamma rays were observed in the present experiment agreeing with three of four transitions deduced by (n,γ). The fourth, $E_\gamma$ = 4535 keV, may correspond to a very weak peak observed in the present spectrum.

$E_x$ = 4579, 4586, 4608, 4639, 4670, 4680, and 4718 keV. Definite, though in some cases weak, gamma rays were observed in the present data which can correspond only to ground-state transitions. Several other gamma rays were observed which are energetically consistent with 4586-1077 keV and 4639-1077 keV transitions.

$E_x$ = 4744 keV. An $E_\gamma$ = 3666 keV gamma ray was observed in the present experiment which was initially assigned as the 3665-keV ground-state transition. However, the present $I_\gamma$ is too large for only this assignment. Hence, a level at $E_x$ = 4744 keV was postulated.

$E_x$ = 4792 and 4855 keV. Gamma rays were observed in the present experiment having $E_\gamma$ = 4792 and 4855 keV, with the lower energy one possibly a doublet. The higher energy gamma ray may correspond to the 4858-keV photon assigned as a ground-state transition by (n,γ).

$E_x$ = 4871 keV. See discussion for $E_x$ = 5146 and 5403 keV below.

$E_x$ = 4910 keV. An $E_\gamma$ = 3832 keV photon was observed in the present experiment, and likely is the 3833-keV gamma ray observed and assigned by (n,γ).

$E_x$ = 4982 and 4993 keV. The highest energy gamma rays observed in the present experiment; both must be ground-state transition. A 4992-keV ground-state transition is given by (n,γ).

$E_x$ = 4871, 5146, and 5403 keV. Four gamma rays had a substantial increase in $I_\gamma$ when $E_n$ was increased to 5.9 MeV, and were therefore assumed to be due to decay from highly-excited levels. The $E_\gamma$ = 4069 keV gamma ray has to be a first-excited-state transition, and the 2732-keV gamma ray is possibly the 5146-2417 keV transition. The 3520-keV gamma ray has the same assignment as given by (n,γ), viz., 5403-1883 keV. Another possible decay transition given by (n,γ) is 5403-1077 keV, i.e., $E_\gamma$ = 4326 keV. A gamma ray of this energy has already been placed as a ground-state transition. The fourth gamma ray of this group, $E_\gamma$ = 2990 keV, doesn't correspond to any (n,γ) gamma ray. It could be due to 4871-1077 keV, 5328-2338 keV, 5407-2417 keV, or even possibly 5741-2751 keV transitions. Other gamma rays were sought which might inidcate other transitions from $E_x$ = 4871, 5328, 5407, or 5741 keV. The only possibility was the weak $E_\gamma$ = 2122 keV gamma ray, corresponding to 4871-2751. NDS suggests a possible level at about $E_x$ = 4.87 MeV and so the 2990-keV gamma ray was placed as the 4871-1077 keV transition, and the 2212-keV gamma ray was placed as the 4871-2751 keV transition.

## Concluding Remarks

It is unlikely that all of the energy levels in $^{68}$Zn have been located even for $E_x$ < 4 MeV, since high-spin and unnatural parity states are not appreciably excited by inelastic neutron scattering.[15] For $E_x$ > 4 MeV the present experiment is able to identify only those states

having transitions for which placement is limited by observed thresholds, and of these only the high energy ground state transitions are firmly established. Placement of other transitions requires "detective" work, and although the section "Results and Discussion" is not brief, not all of the objective nuances or subjective opinions have been detailed. Clearly more experimental information is required to further understand the level structure of $^{68}$Zn. However, for the purpose of a consistent evaluation of the element, the present data combined with other currently available information will be useful.

## Acknowledgments

I am deeply indebted to F. G. Perey for his encouragement, active participation in, and support of this work, and to W. E. Kinney, J. W. McConnell, S. Raman, P. H. Stelson, and W. C. White for their invaluable experimental assistance. I am also indebted to M. B. Lewis for sharing his progress on the current Nuclear Data Compilation and for his detailed study of the present report.

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# APPENDIX

## The Gamma-Ray Spectrum Obtained from Interactions of 5.4-MeV Neutrons with $^{68}Zn$

The total spectrum obtained required about ten hours of bombarding time and was recorded in 2048 channels. The extent of the detail recorded is such that it is impossible to advantageously exhibit the spectrum utilizing a single scale for either abscissa or ordinate. The spectrum was therefore divided into 20 photon-energy groups and an appropriate ordinate scale was chosen for each photon energy group. The following 20 figures show the original spectrum in sufficient detail for comparison with the discussion in the text.

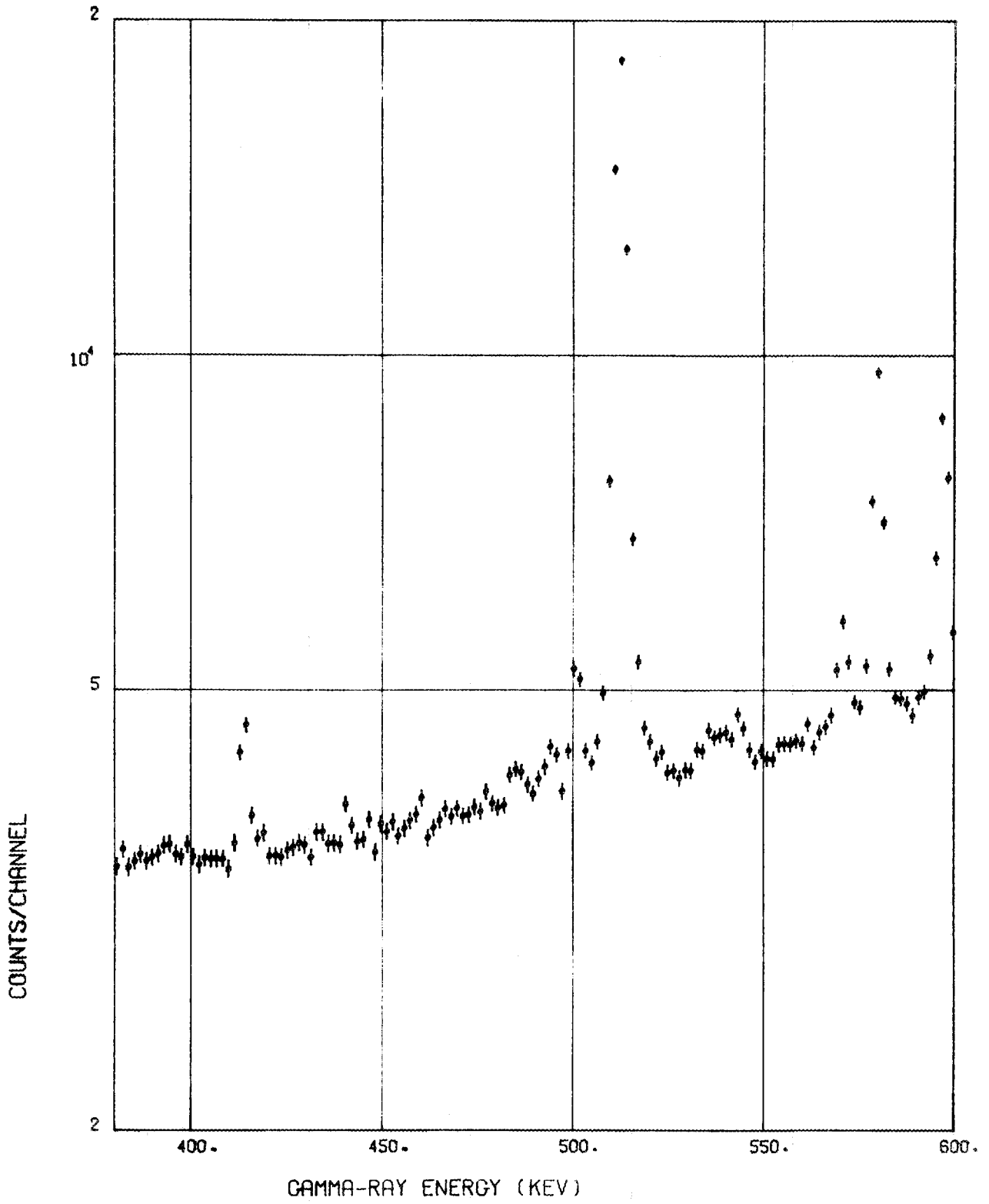


Fig. A1. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 380 and 600 keV. Background lines are observed at $E_\gamma$ = 511, 536 and 597 keV.

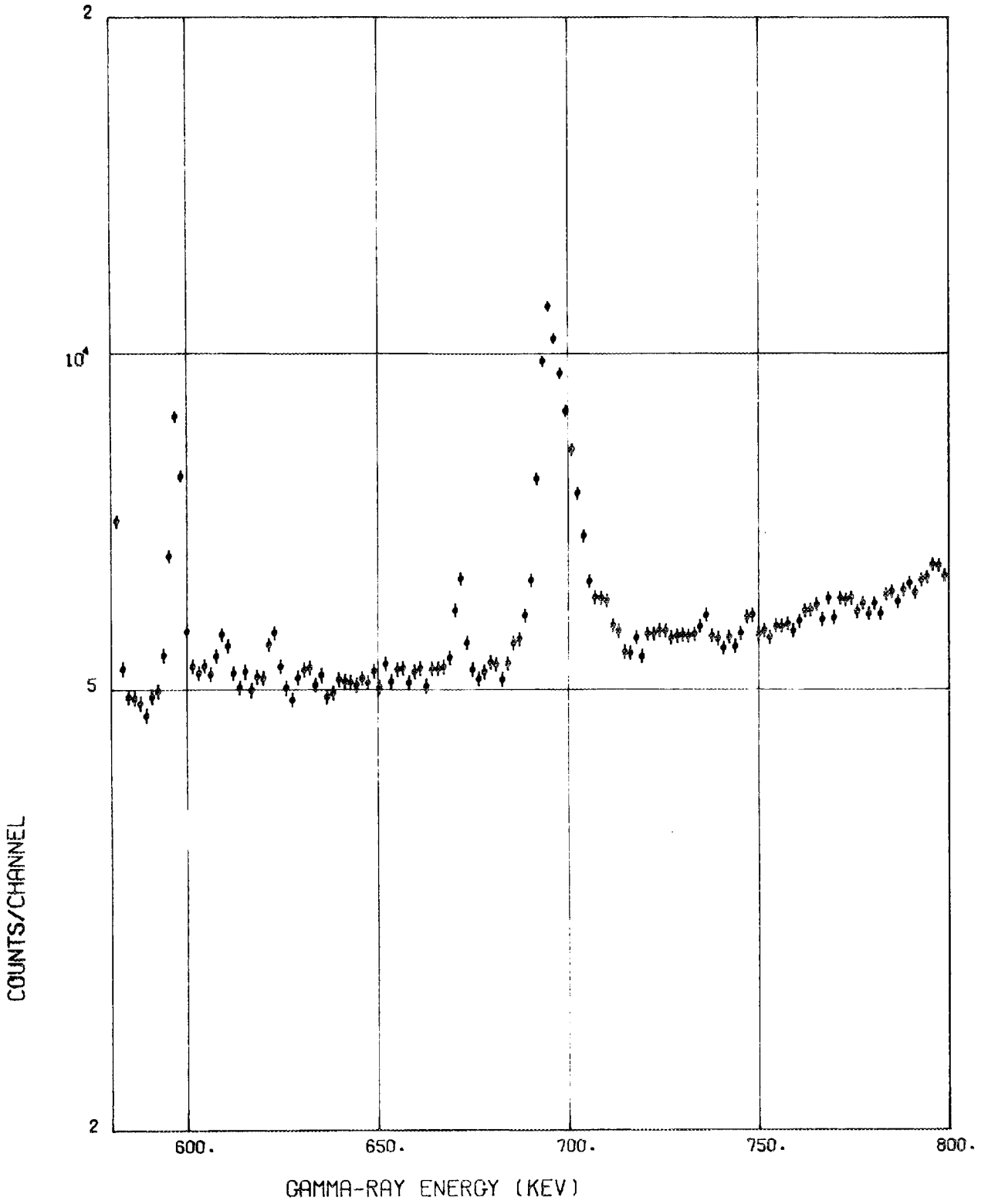


Fig. A2. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 580 and 800 keV. Background lines are observed at $E_\gamma$ = 597, 610 and 696 keV.

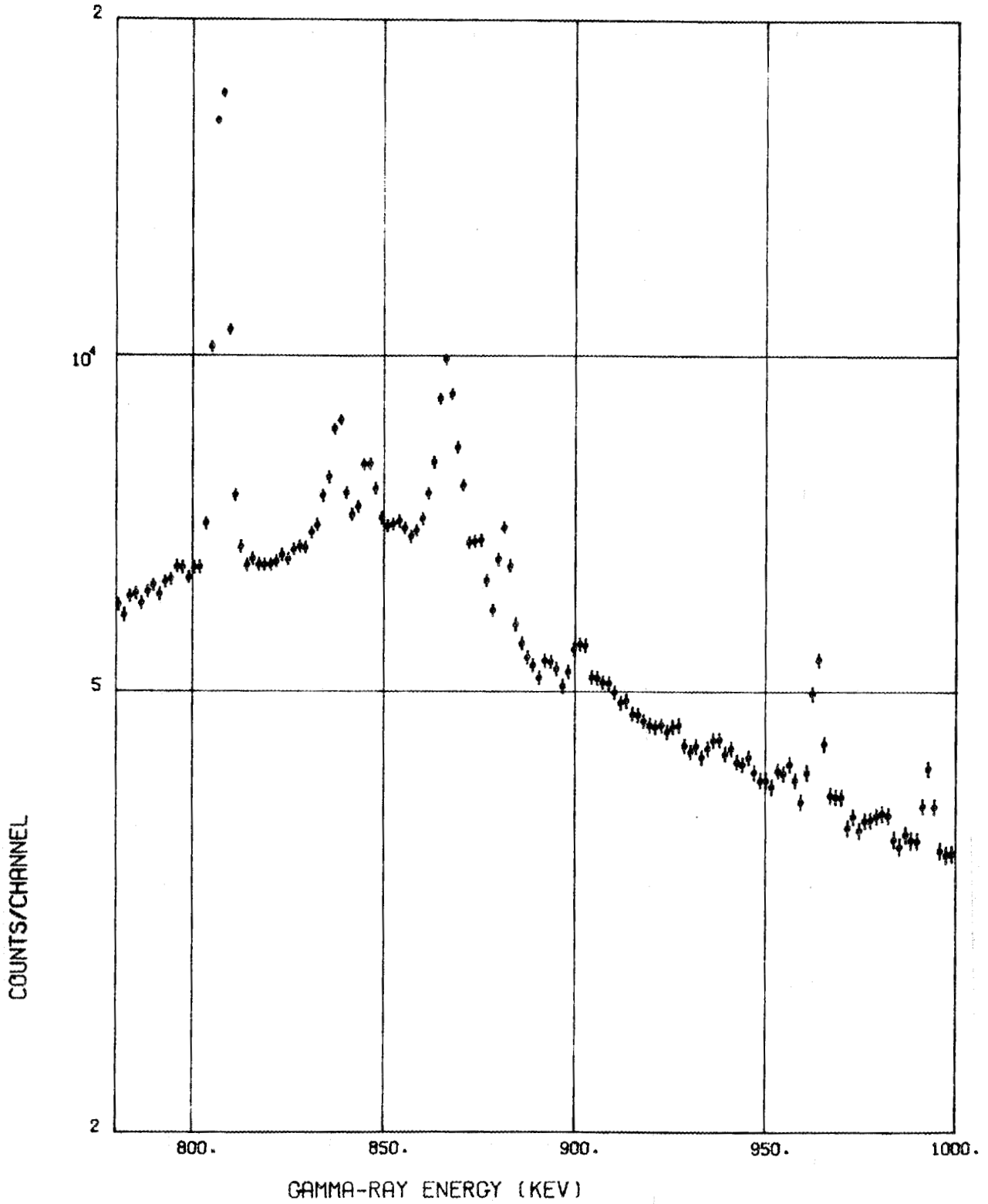


Fig. A3. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 780 and 1000 keV. Background lines are observed at 834, 846, 860, 868, 900 and 962 keV.

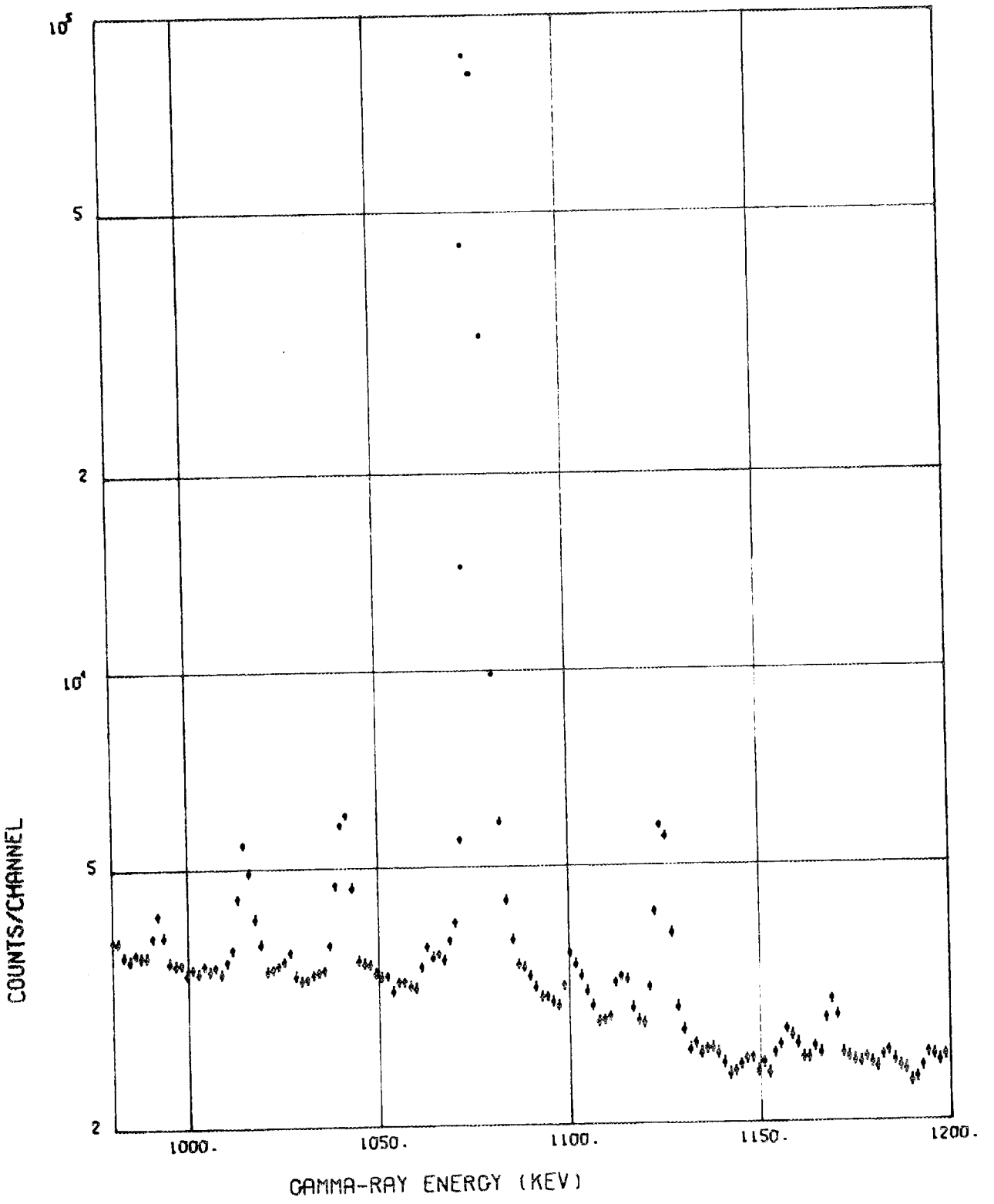


Fig. A4. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 980 and 1200 keV. Background lines are observed at 1014, (1040) and 1101 keV.

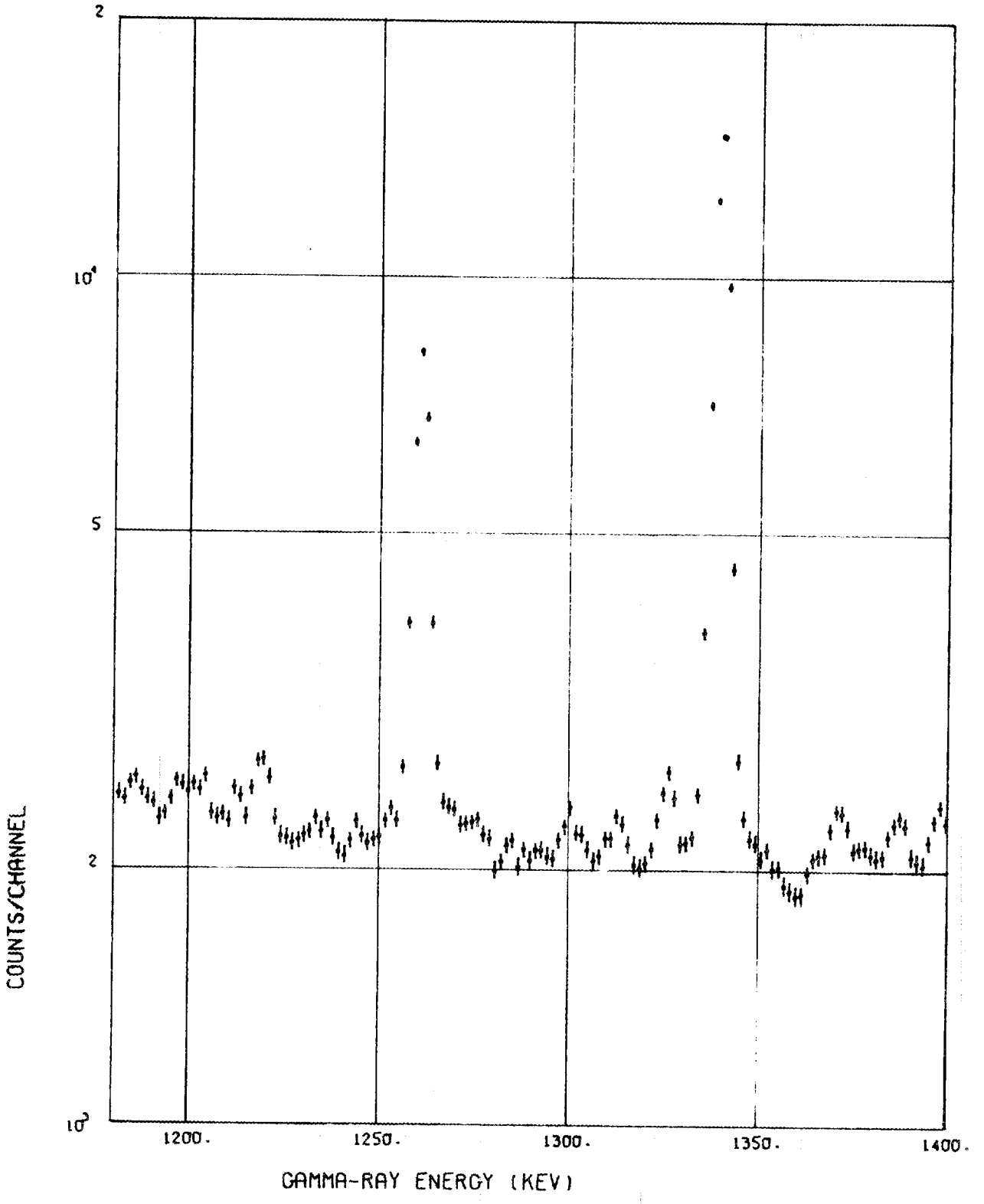


Fig. A5. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 1180 and 1400 keV. Background lines are observed at 1202 and 1345 keV.

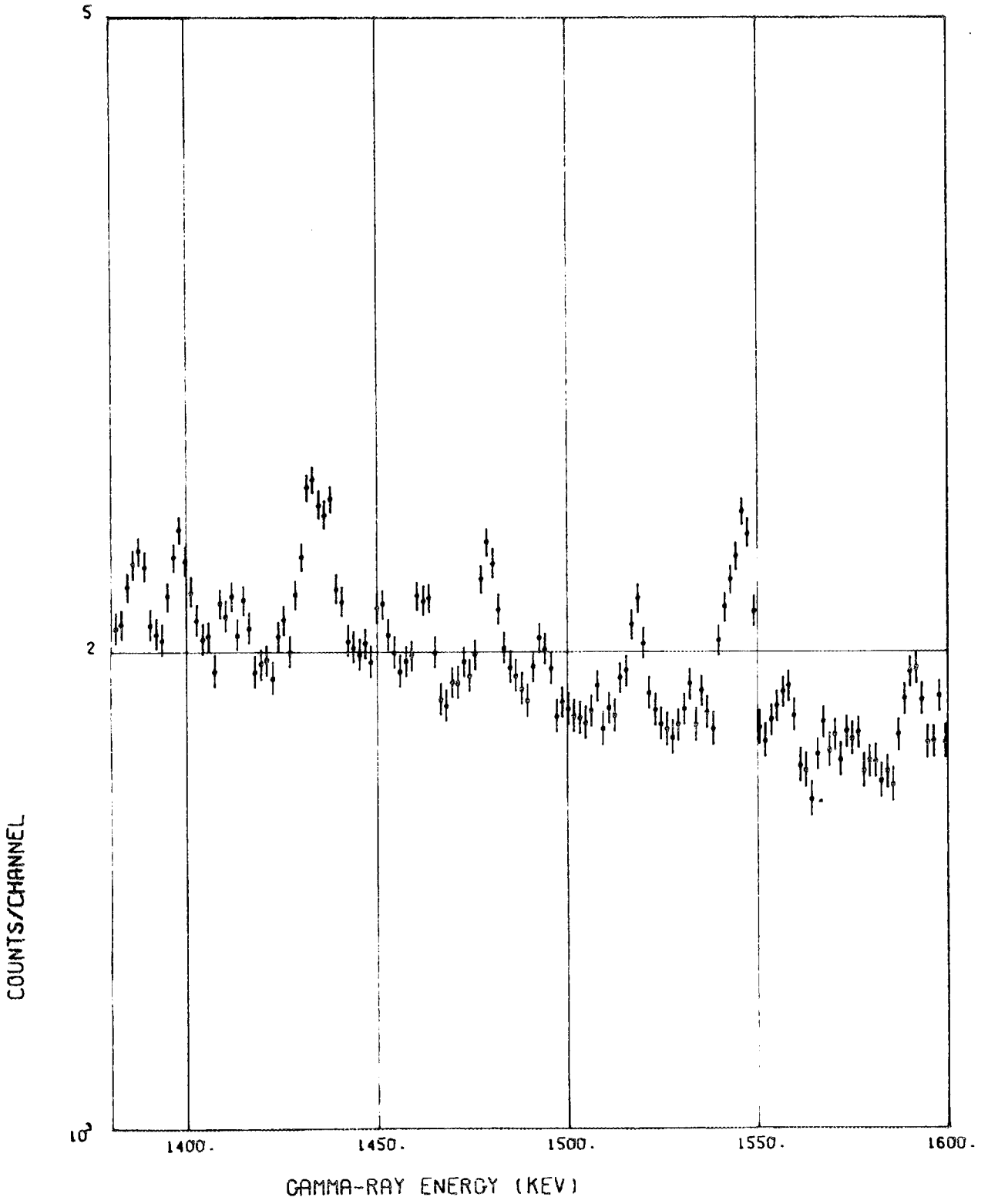


Fig. A6. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 1380 and 1600 keV. A background line is observed at 1592 keV.

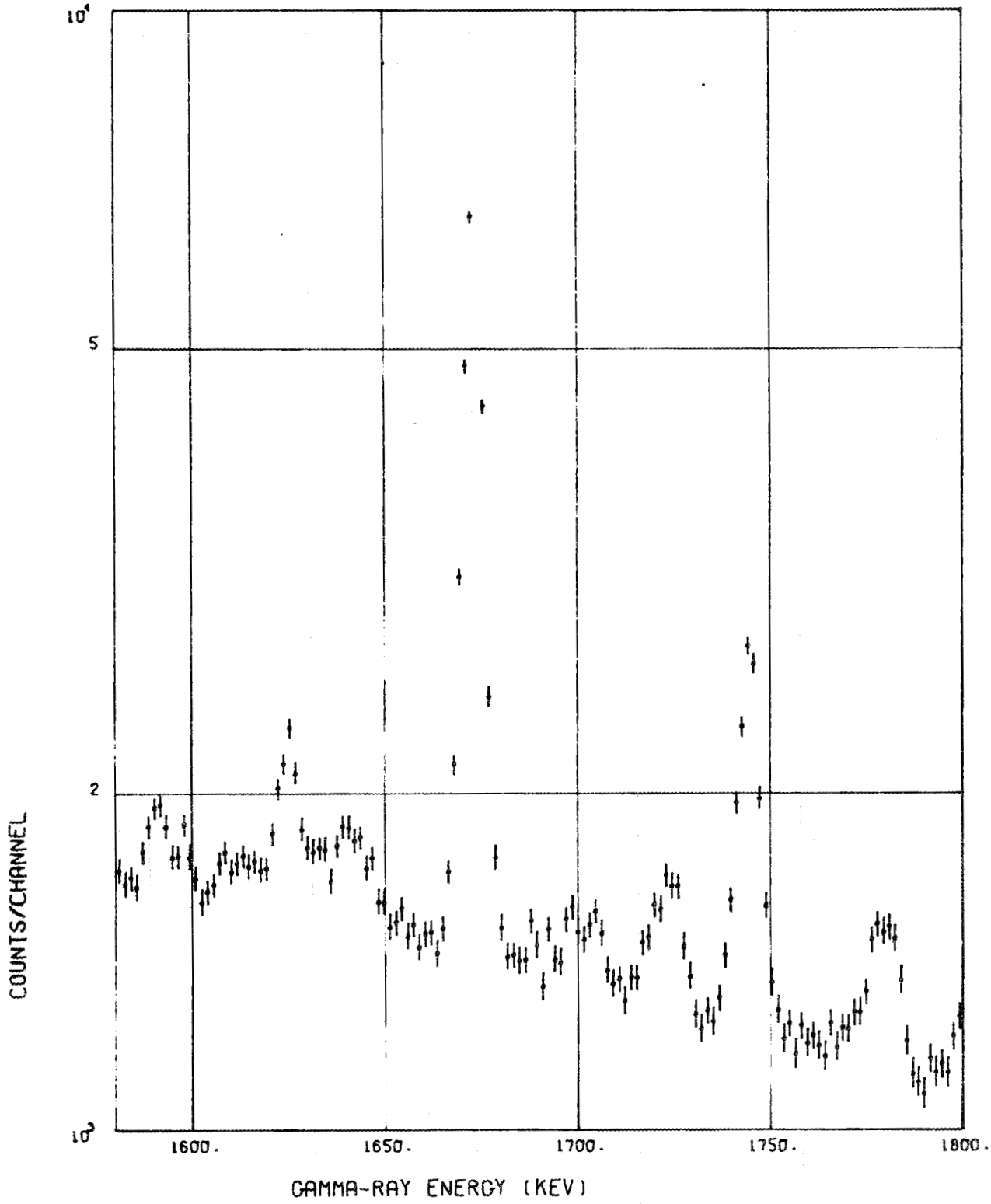


Fig. A7. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 1580 and 1800 keV.

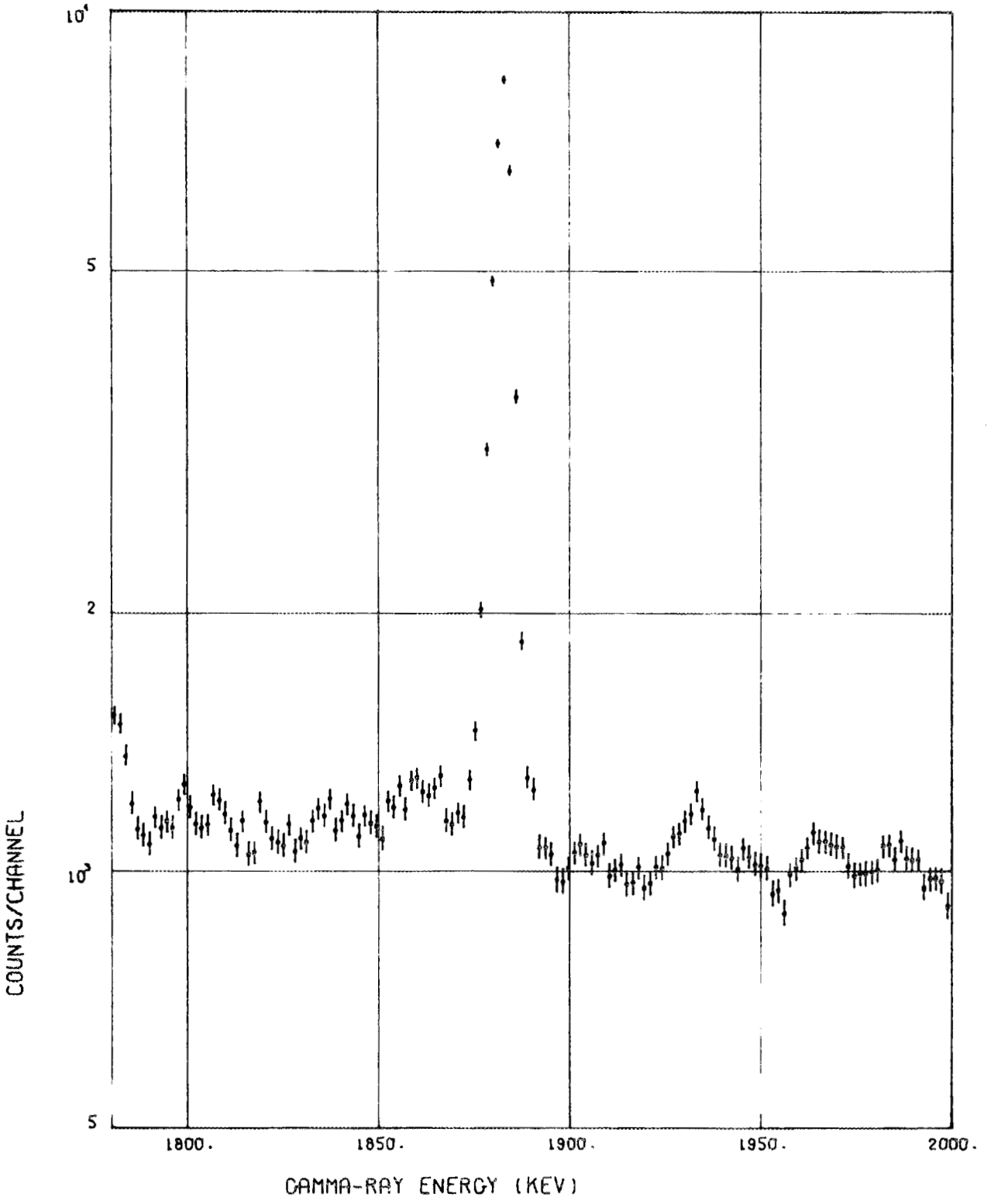


Fig. A8. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 1780 and 2000 keV.

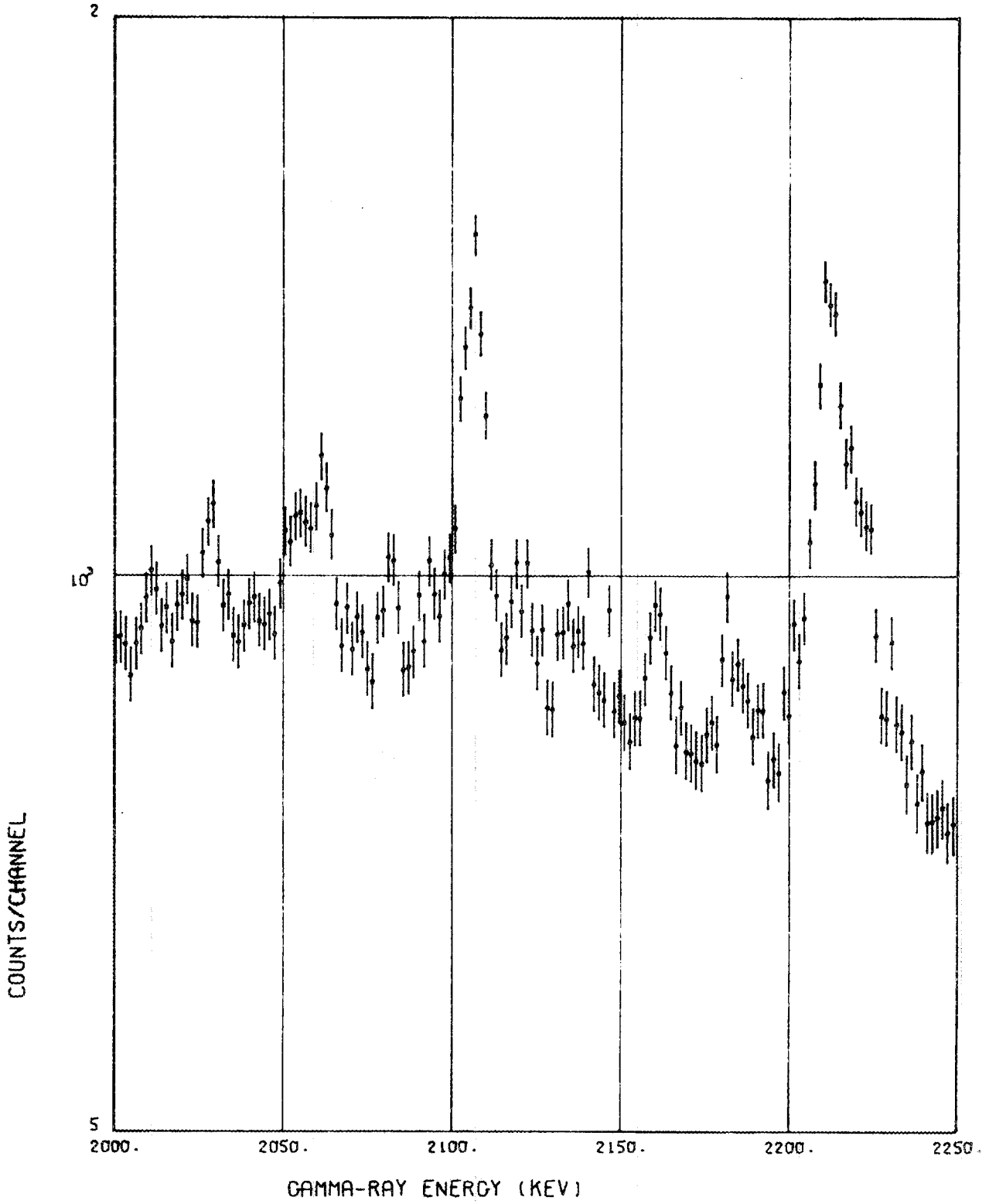


Fig. A9. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 2.00 and 2.25 MeV. A background line is observed at 2102 keV, and a broad peak due to $n + p \rightarrow d + \gamma$ is observed for $E_\gamma \sim 2220$ keV.

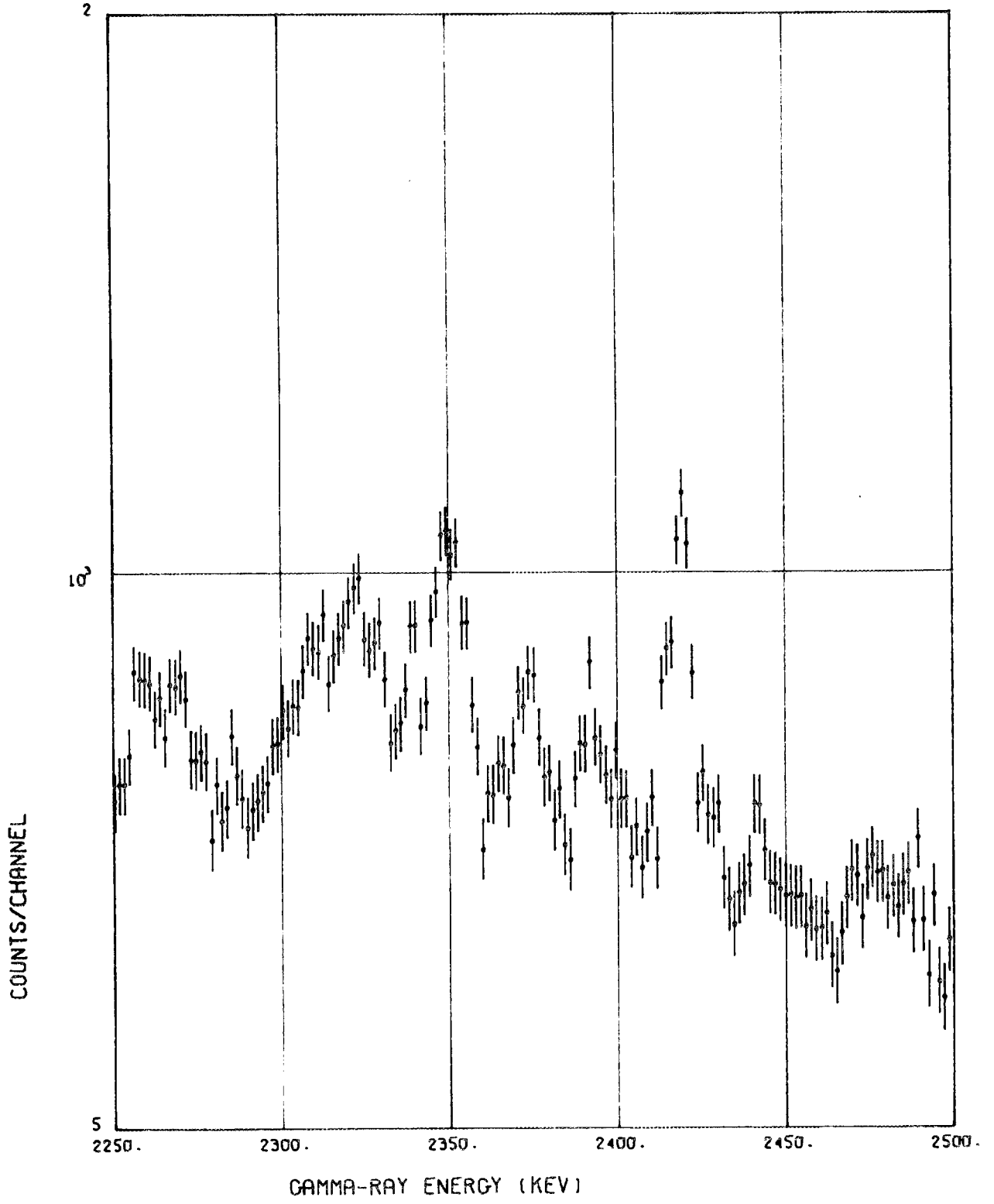


Fig. A10. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 2.25 and 2.50 MeV.

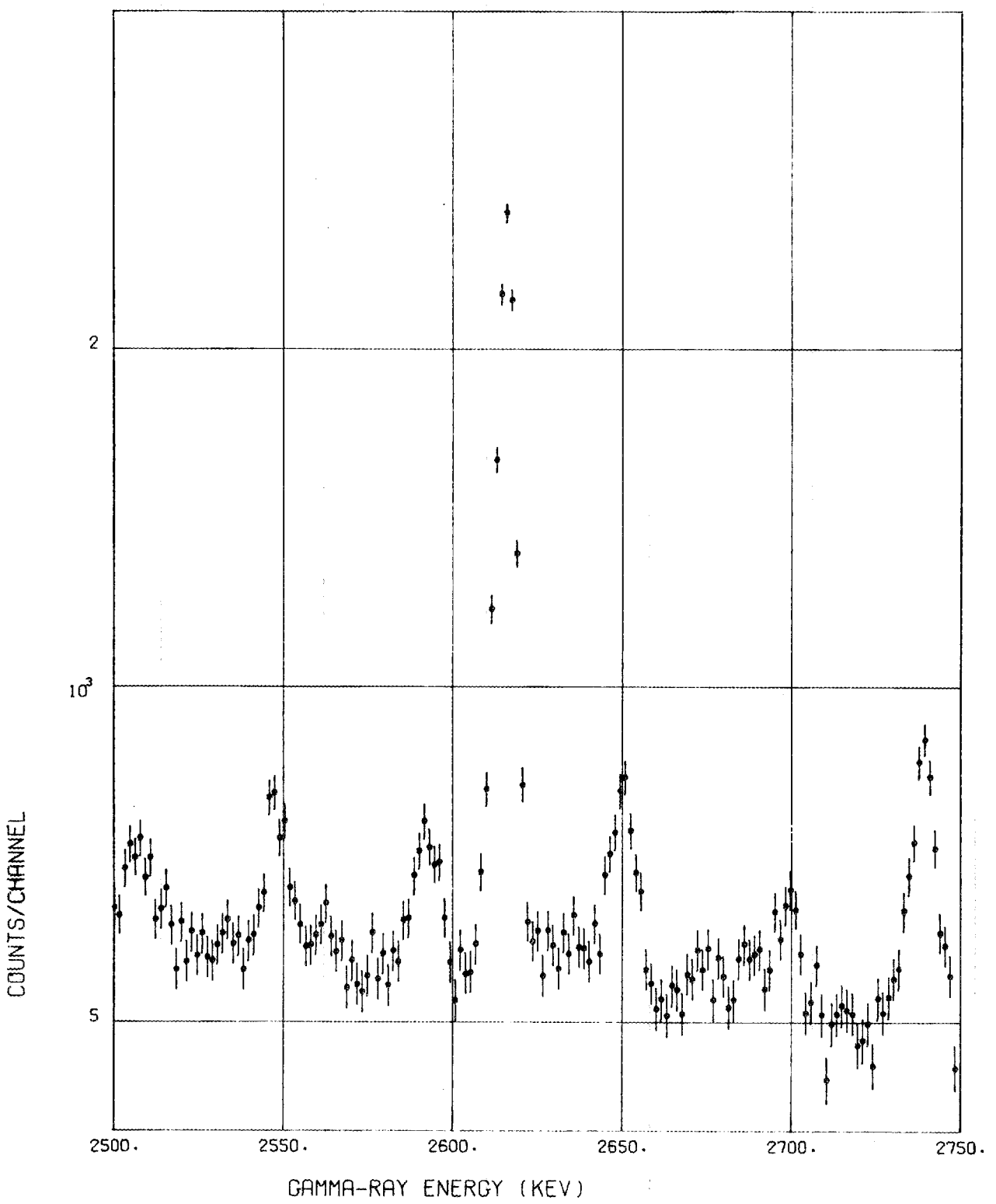


Fig. A11. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 2.50 and 2.75 MeV. A background line is observed at 2615 keV.

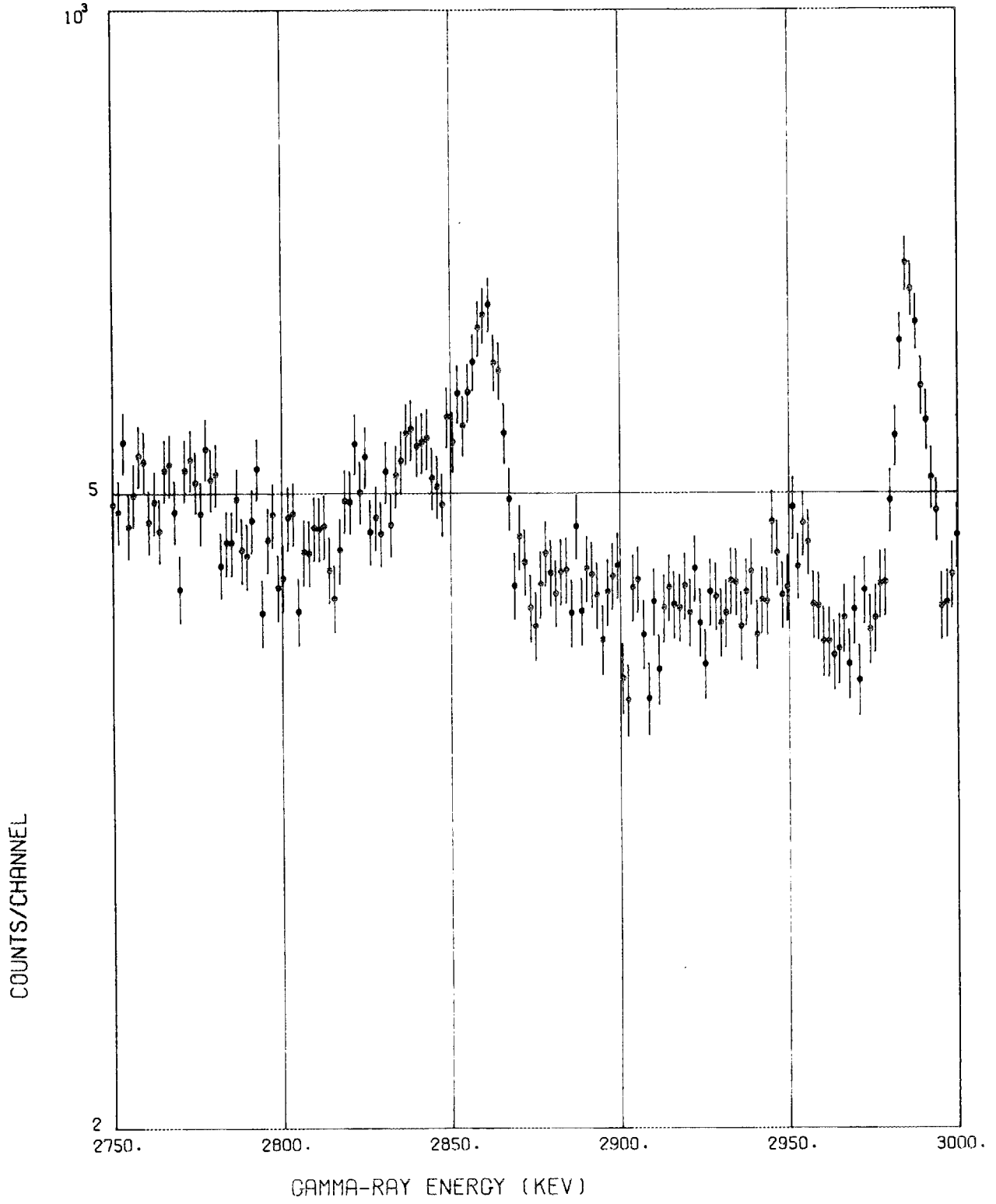


Fig. A12. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 2.75 and 3.00 MeV.

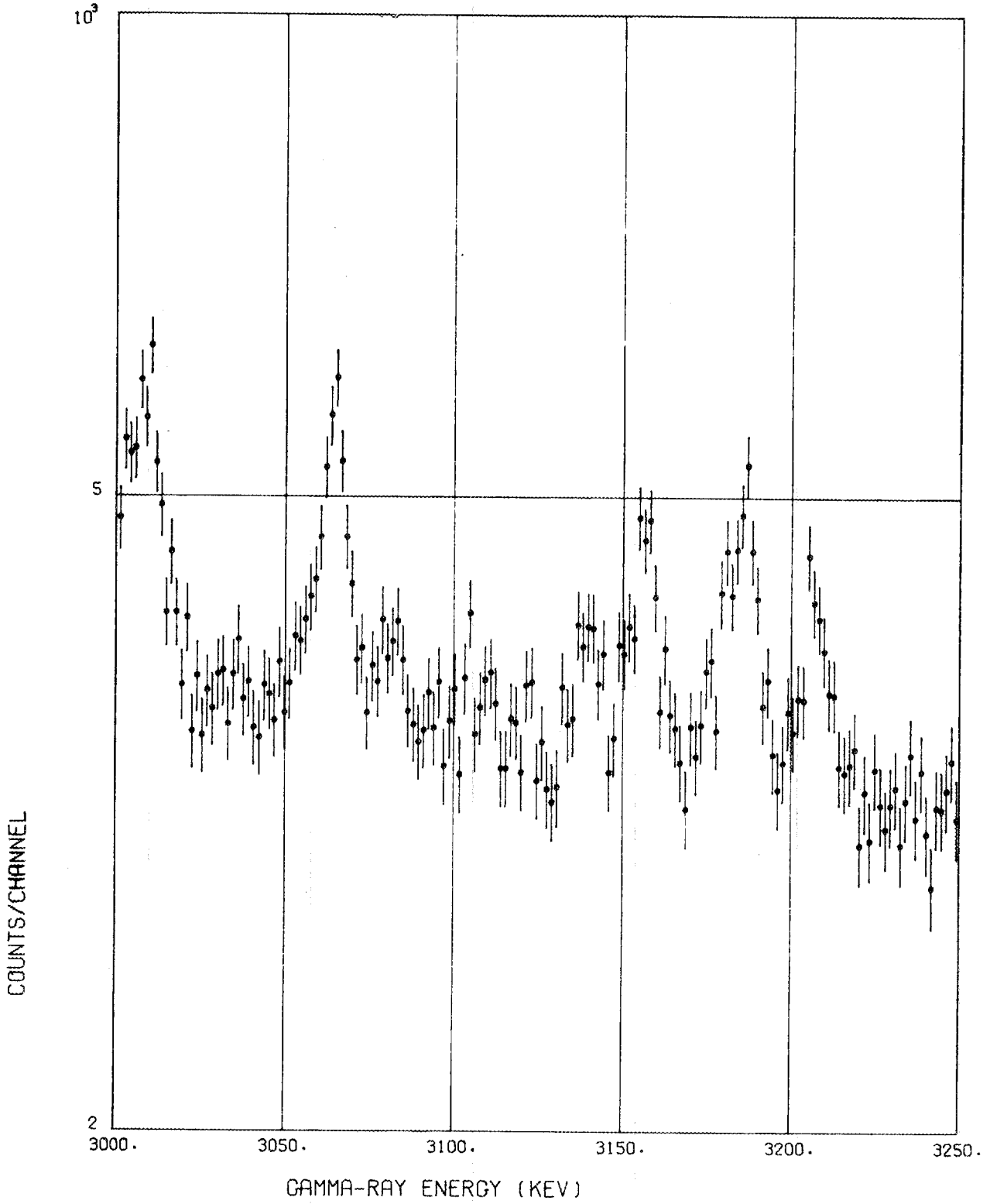


Fig. A13. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 3.00 and 3.25 MeV. A background line is observed at 3062 keV.

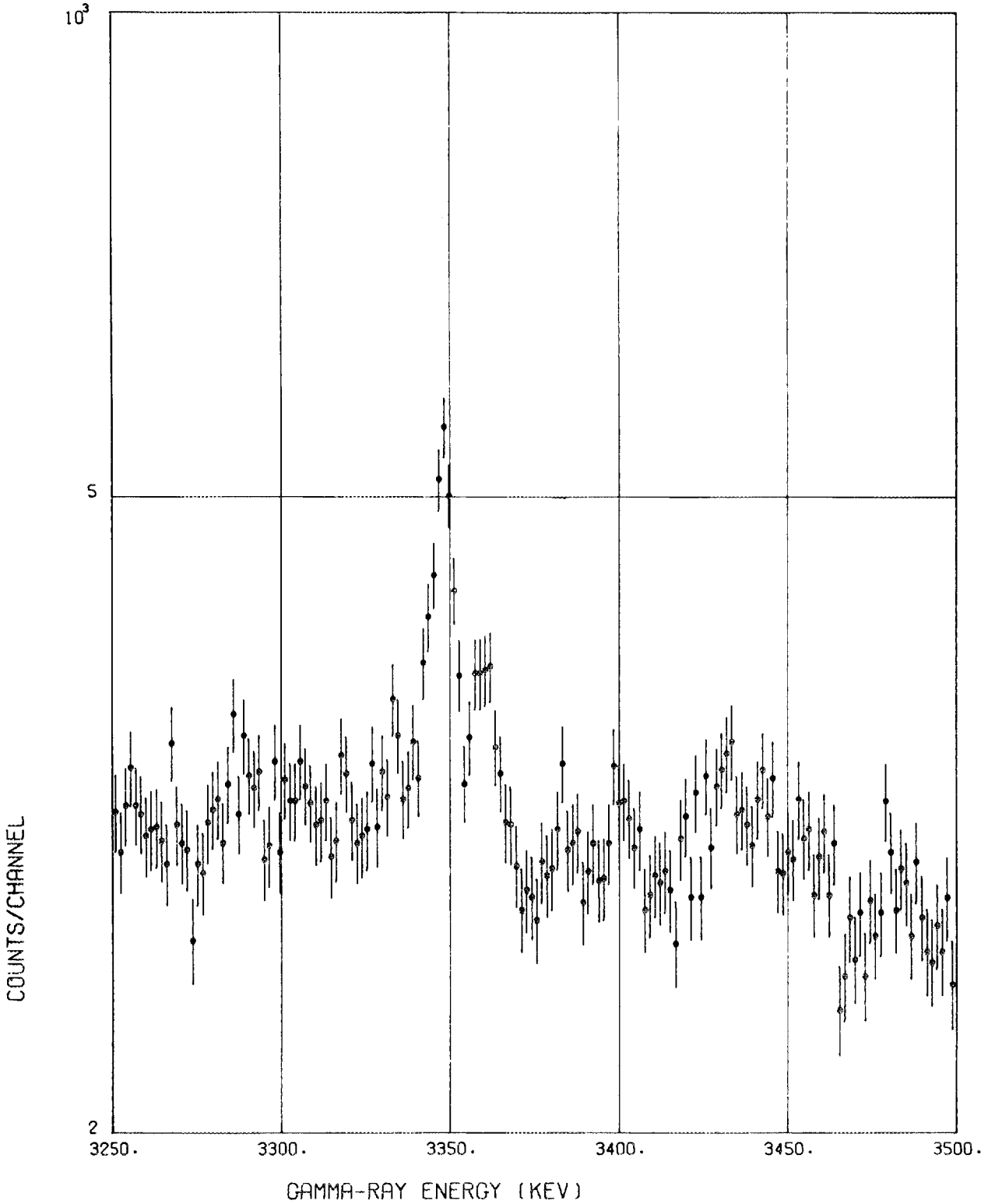


Fig. A14. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 3.25 and 3.50 MeV.

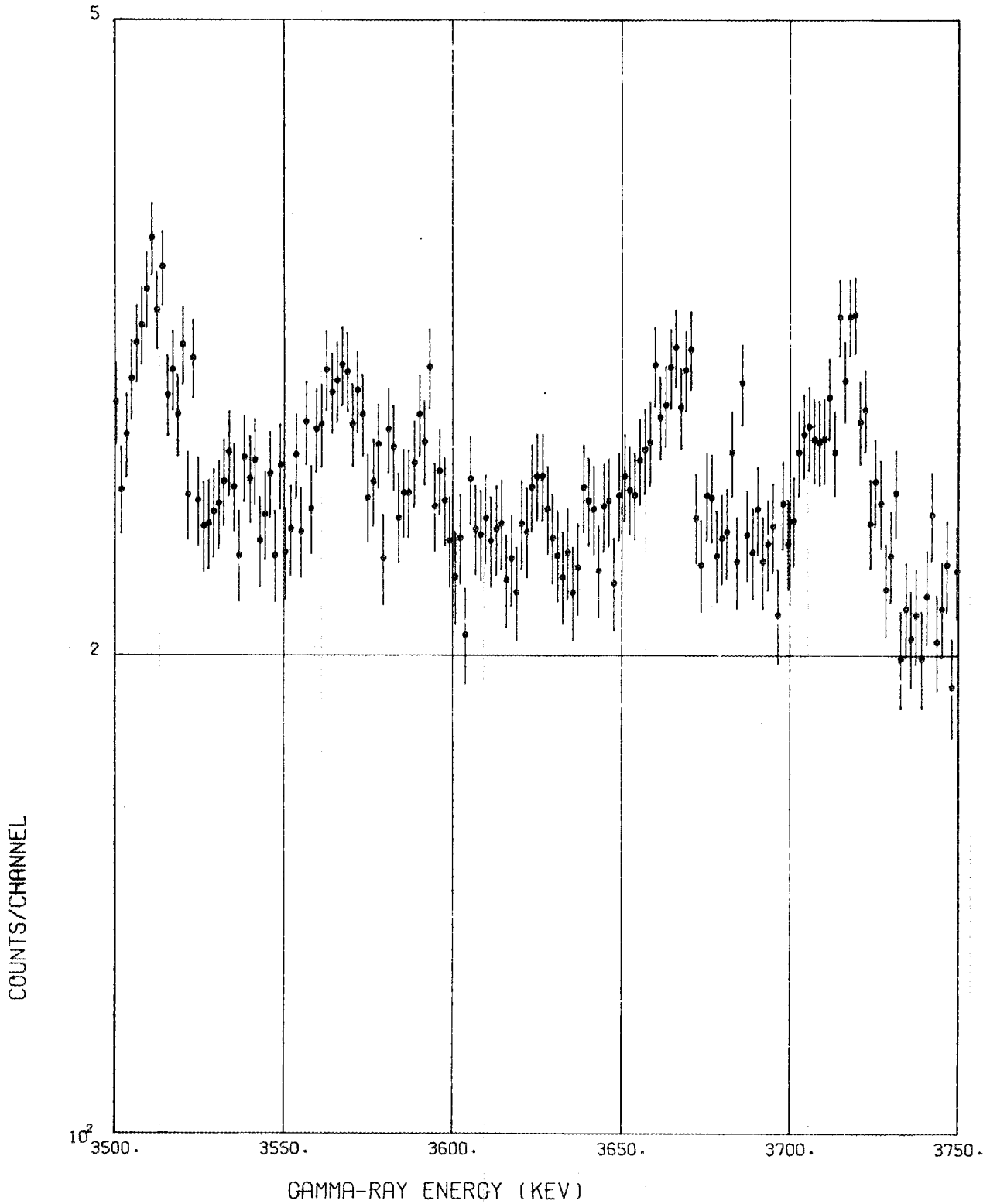


Fig. A15. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 3.50 and 3.75 MeV. A background line is observed at 3573 keV.

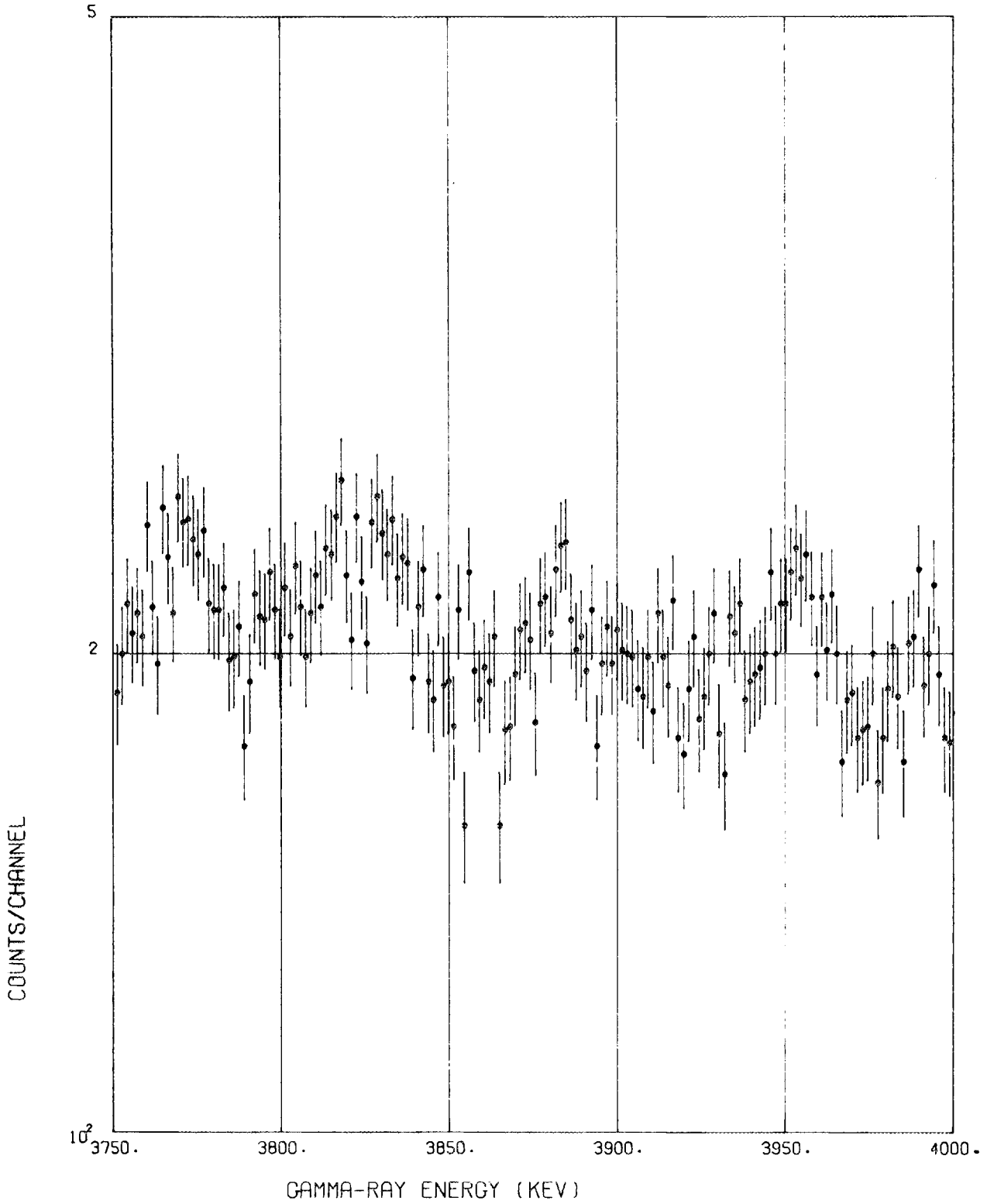


Fig. A16. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 3.75 and 4.00 MeV.

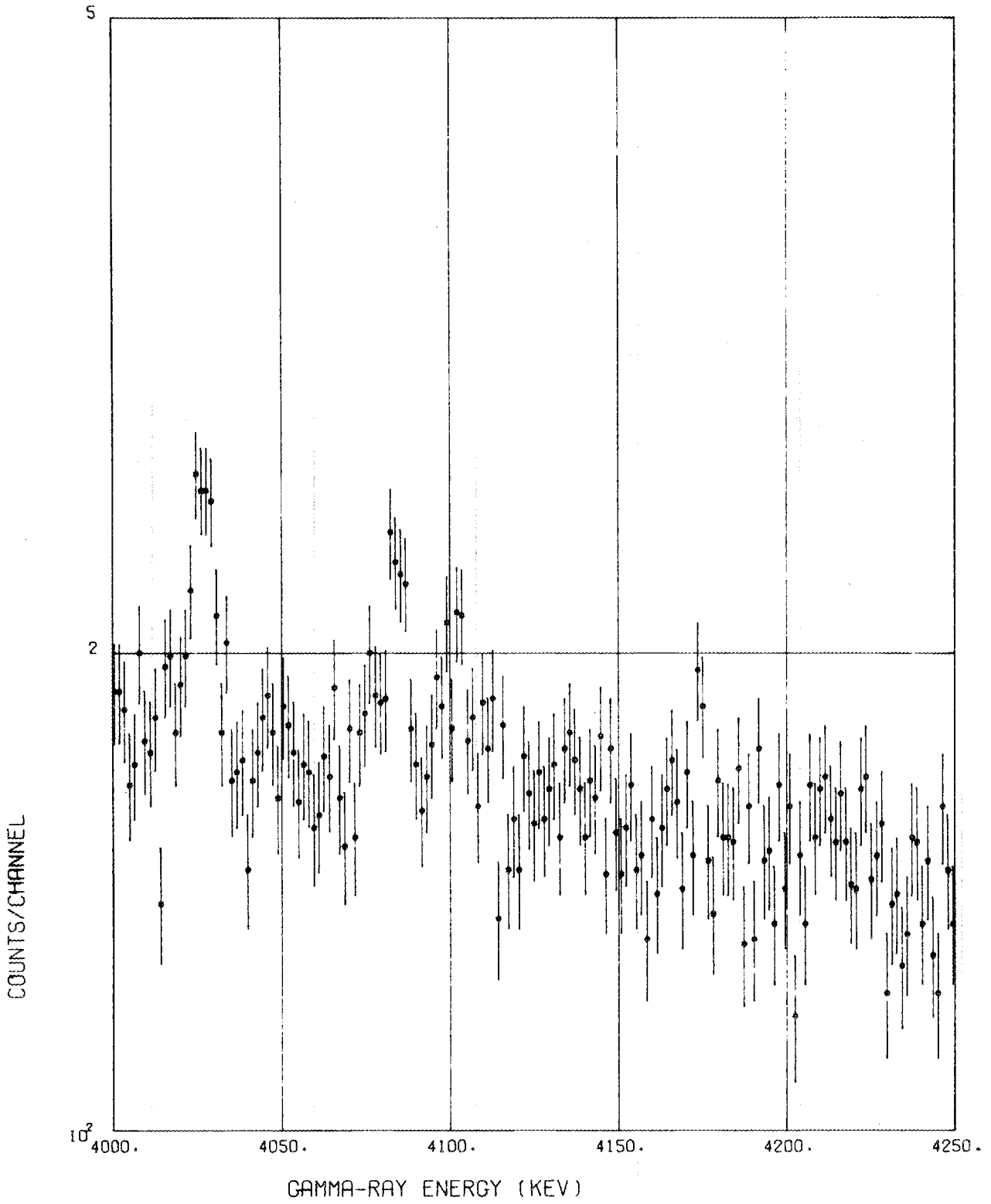


Fig. A17. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 4.00 and 4.25 MeV. A background line is observed at 4084 keV.

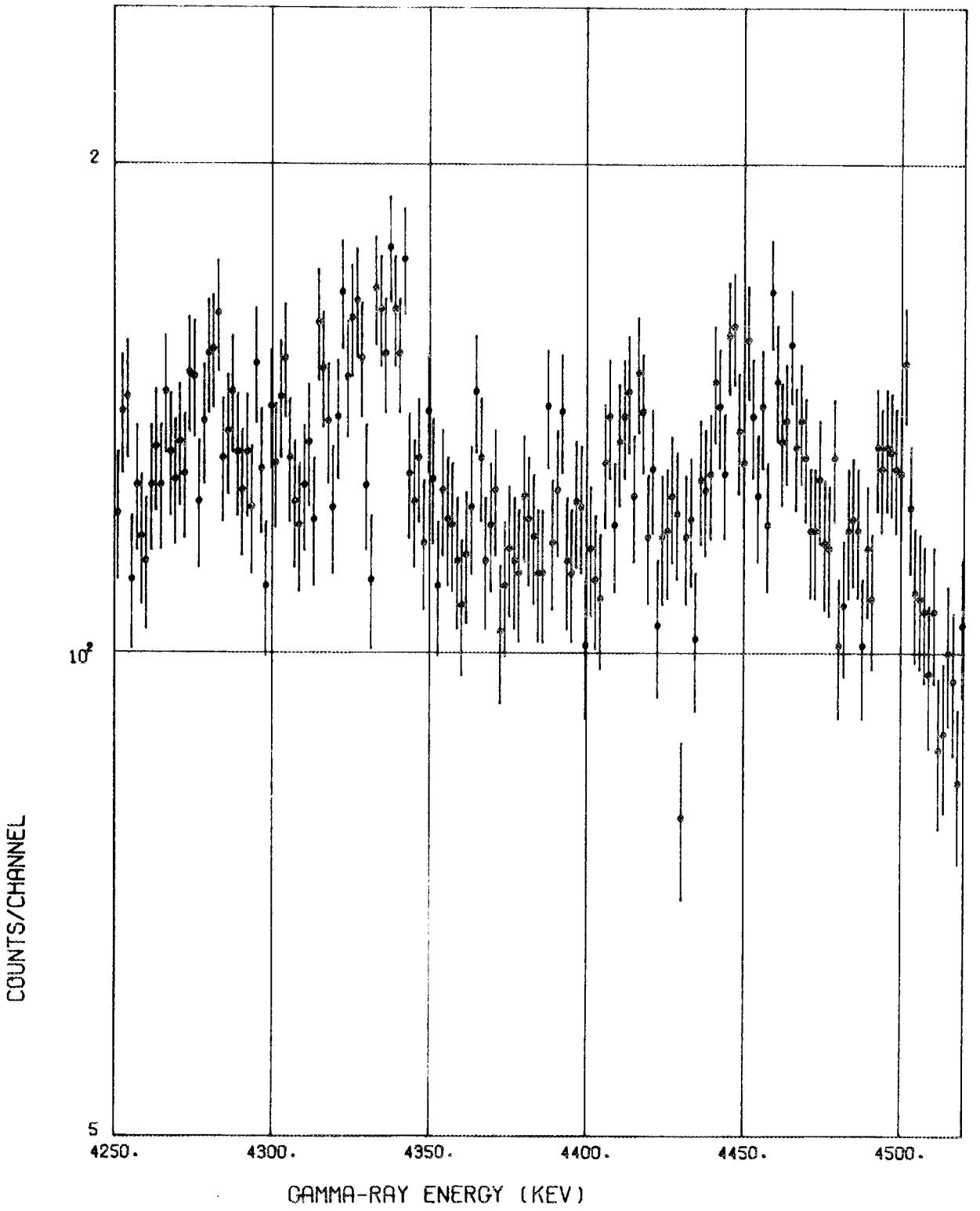


Fig. A18. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 4.25 and 4.50 MeV.

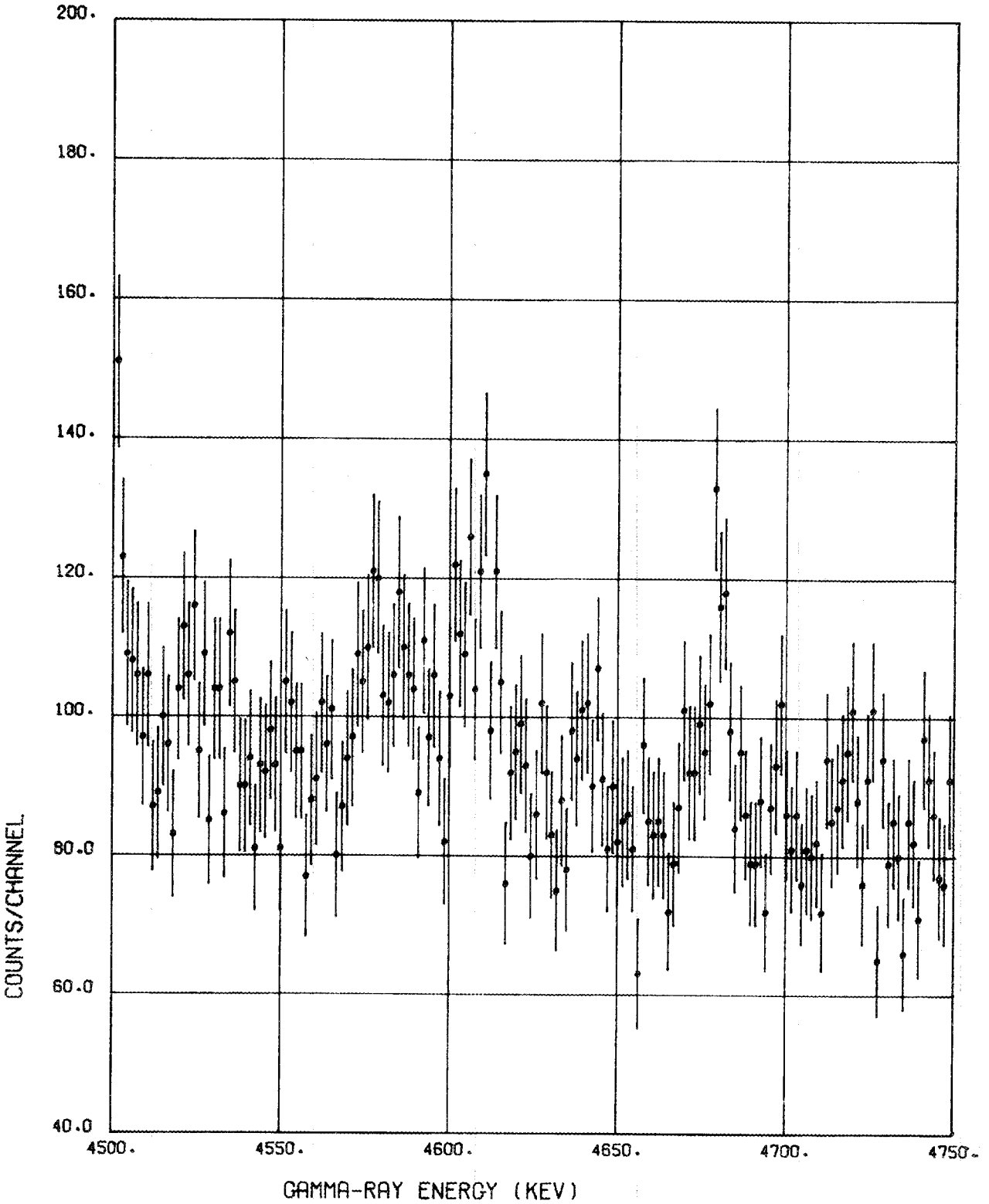


Fig. A19. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 4.50 and 4.75 MeV.

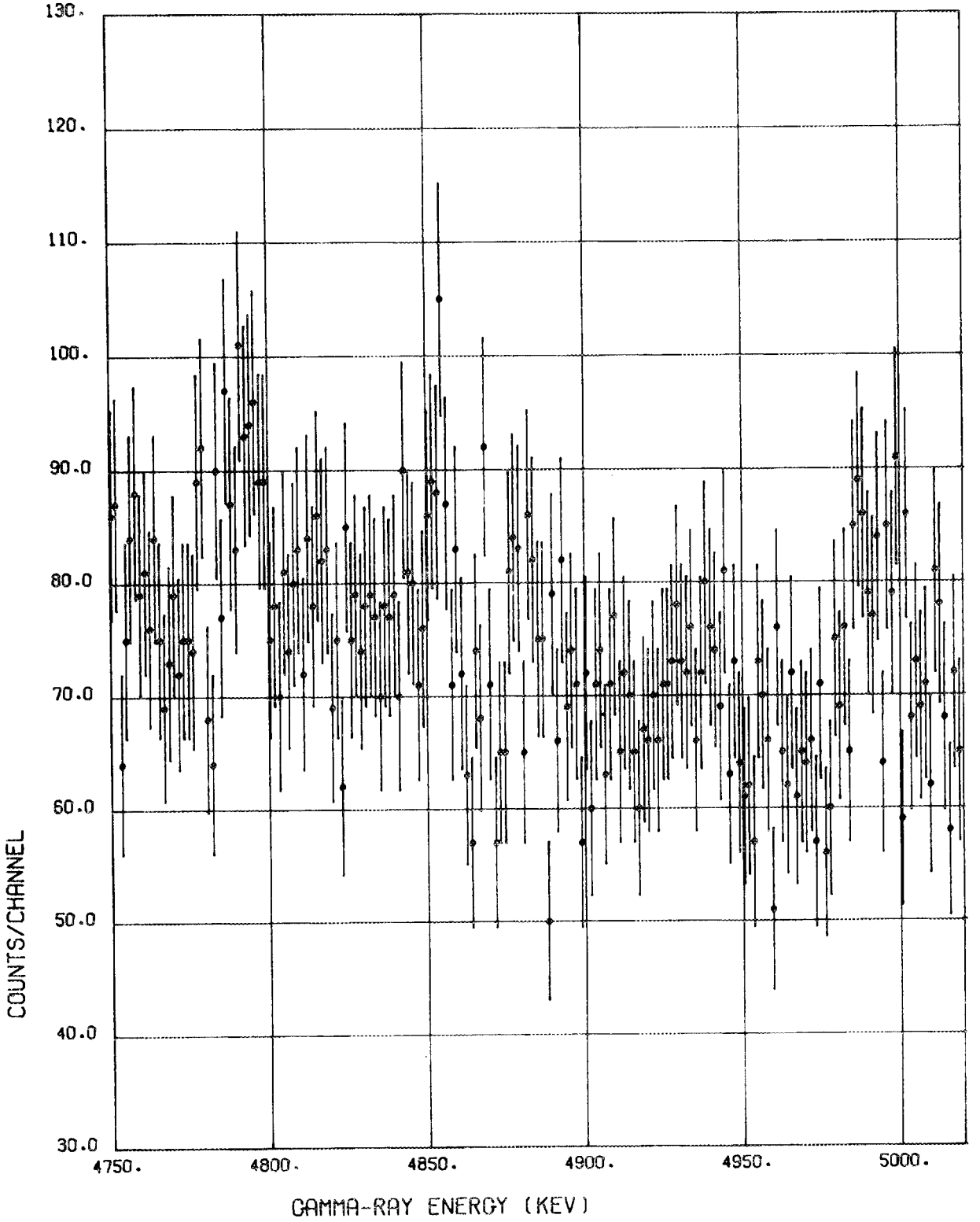


Fig. A20. Gamma-ray spectrum for 5.4-MeV neutron interactions with $^{68}Zn$ for $E_\gamma$ between 4.75 and 5.20 MeV.

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