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APPLICABILITY OF BGO TO CONTINUUM GAMMA-RAY MEASUREMENTS OF HEAVY-ION REACTION PRODUCTS

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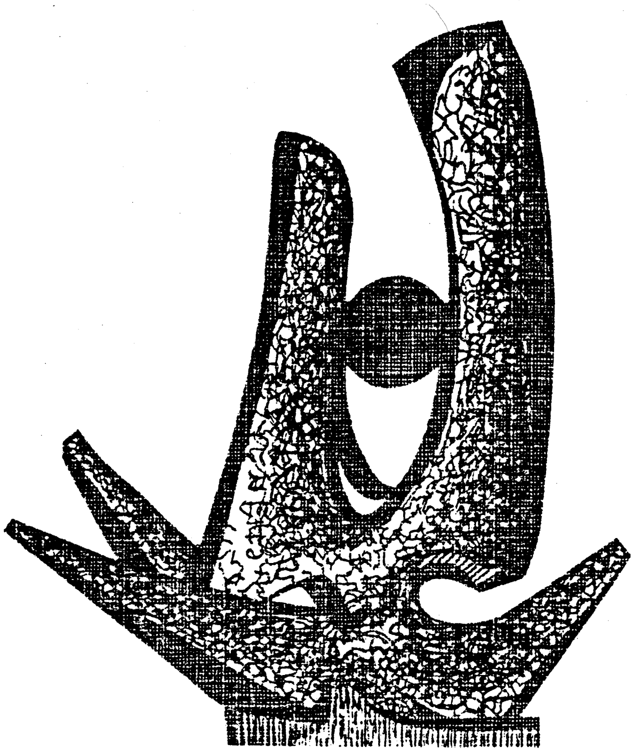

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Applicability of BGO to Continuum Gamma-ray Measurements of Heavy-ion Reaction Products

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The study of continuum gamma-rays emitted during heavy-ion reactions has made extensive use of large volume NaI(Tl) detectors. These studies have contributed the bulk of the information currently available on the role of angular momentum in these reactions, and recently have indicated an additional component of relatively high energy gamma-rays (approximately 15 MeV). The studies have been hampered by the necessity of unfolding the response function of the NaI(Tl) detectors and by the sensitivity of the detectors to neutrons created during the nuclear reaction. BGO detectors offer the advantages of a better response function (peak to total ratio) and a lower sensitivity to slow neutrons. However, BGO detectors also bring the disadvantages of poorer resolution and poorer timing. Discrimination against neutrons commonly employs time-of-flight techniques so the tradeoff of timing against neutron sensitivity is crucial. Some results of initial comparisons of the sensitivity of NaI(Tl) and BGO detectors to fast neutrons will be presented.

Angular momentum plays a prominent part in the overall scheme of heavy-ion reactions. Its importance has been established by relatively simple measurements of continuum gamma-rays emitted by the reaction products. These reactions create nuclei which typically have 100 MeV of excitation energy and 50 $\hbar$ of spin angular momentum. Such nuclei have extremely high level densities and thus follow a similarly large number of deexcitation pathways toward their ground states. The early transitions are unresolvable because of their large variety and are dubbed continuum gamma-rays. These gamma-rays are used in nuclear structure physics as triggers for discrete line detectors, i.e. germanium, which follow the nuclei through the latter stages of the deexcitation cascade [1]. There are several contributions to this conference dealing with such filter or trigger devices and I will not speak further on that subject. In nuclear reaction mechanism studies we are interested in the highly excited nuclei as they are produced at the top of the cascade. Thus, we must work with the continuum gamma-rays.

The general technique that is employed requires the detection of a reaction product in coincidence with the gamma-rays. The reaction is then studied in terms of kinetic energy transfer and the product nuclear charge, and the detection of a scattered beam particle defines the reaction plane. In the early experiments the number of coincident gamma-rays was recorded in simple arrays of small volume (7.6 x 7.6 cm) NaI(Tl) detectors [2]. Notable extrapolations of this technique are the Oak Ridge Spin Spectrometer [3] and the Heidelburg -Darmstadt Crystal Ball [4] with 72 and 162 discrete detectors, respectively. In other recent experiments small numbers of larger volume NaI(Tl) detectors (12.7 x 15.2 cm) have been used to record the pulse height as well as the number of gamma-rays [5]. This allowed a deconvolution of the rotational and statistical components in the spectrum, as shown in figure 1a. Once the rotational transitions, centered near 0.5 MeV, were separated from the broad statistical transitions a much better measurement of the fragments' average spins could be obtained than in the earlier work. Also the angular distributions of the continuum gamma-rays contain information on the average orientations of the fragments' spin vectors. The two classes of transitions have different multipolarities and hence different angular distributions. In figure 1b the difference between the numbers of rotational transitions observed in-plane and out-of-plane with respect to the scattered particles can be easily seen.

A third component in the continuum spectra from heavy-ion induced reactions has been identified recently at about 15 MeV [6]. These events have been tentatively identified as giant E1 transitions which, if true, would yield information on the shapes of the emitting nuclei. An example of experimental data from such a study using 12.7 x 15.2 cm NaI(Tl) detectors is shown in figure 2 [7]. As the nature of the transitions becomes established, further work on this subject will require detectors that have sufficient resolution to study these transitions in detail. The information on the shape of the emitting nuclei is contained in the shape of the gamma-ray distribution around 15 MeV. The detector should have a resolution on the order of 0.5

MeV or better so that it can separate the components of the spectrum at these energies. The most recently reported studies have used a 24 x 36 cm NaI(Tl) detector at Brookhaven [8].

A nagging problem in the study of moderate energy continuum gamma-rays (a few MeV) is the broad response function of NaI(Tl). The raw pulse height spectra, such as those shown in figures 1 and 2, have to be unfolded from the detector pulse height response. Evans has pointed out that the relative fraction of gamma-ray events that lie in the full energy peak is far larger for a BGO detector than for a NaI(Tl) detector of the same volume [9]. For this reason we have explored the usefulness of bismuth germanate (BGO) detectors. However, one has to pay a price for this full energy absorption in energy resolution and in timing characteristics (for the presently available BGO material). The fact that the energy resolution with BGO is poorer than with NaI(Tl) is relatively unimportant in continuum studies, especially when compared to the improved full energy response. However, the timing characteristics of BGO are critical in determining its usefulness in heavy-ion reaction studies.

The importance of the timing characteristics of the gamma-ray detectors used in heavy-ion reaction studies is easy to understand. The excited reaction products emit neutrons as well as gamma-rays, and the best method to discriminate between the neutrons and the gamma-rays is to measure the difference in their times of flight (over a constant flight path). If the BGO detectors are as sensitive to fast neutrons as NaI(Tl) detectors, and if the timing properties of BGO are poorer, then longer flight paths will be required. Typical timing results for a large volume NaI(Tl) detector are shown in figure 3. The curve labled (c) represents a calibration of the timing with a ^{249}Cf source (alpha particle plus 390 keV gamma). Curve (b) is a time spectrum obtained with a NaI(Tl) in the presence of coincident neutrons. The interplay between resolution and time-of-flight should be obvious. The time spectrum obtained with a Ge detector under similar circumstances, but with a shorter flight path, is also shown for reference. In this case the neutrons are not resolved. At present BGO detectors lie inbetween the latter two curves.

As we have heard at this conference the timing properties of the BGO material are mostly beyond the control of the end user of the detectors. They are determined by light collection and depend on the purity of the BGO material, indices of refraction, and surface effects. However, the optimization of the photomultiplier tube (PMT) maybe in the realm of control. Up to the present a common ploy has been to use two different PMT's with BGO [10], one optimized for timing (e.g. Hamamatsu R-329-2), and another optimized for energy resolution (e.g. Hamamatsu R-1306). This is an unacceptable situation. A PMT which should provide both good timing and good energy resolution is the Amperex-2312B. We will explore the response of BGO coupled to this PMT in the near future.

Capture of slow neutrons by NaI(Tl) creates important problems that should be absent in BGO. However, we need to consider the effects of the neutrons that are present in heavy-ion reactions which are predominently fast, approximately 5 MeV. We have investigated the relative sensitivity of BGO and

NaI(Tl) to fast neutrons in a simple experiment which we shall describe. A 7.6 x 7.6 cm BGO detector integrally mounted to a Hamamatsu R-1307 PMT was obtained form the Harshaw Chemical Co. The energy resolution and response function of the detector were measured by cascade gamma-ray sources. This technique requires a coincidence between a narrow gate in a high resolution detector as a trigger and any signal from the detector being calibrated. This generates a spectrum from a monoenergetic photon that is essentially free from background. The calibration results of the full energy peak to total ratio of the BGO and a 7.6 x 7.6 cm NaI(Tl) are shown in figure 4a. The full-width at half-maximum (FWHM) of the two detectors are shown in figure 4b. The BGO detector can be seen to contain a reasonably good quality large volume BGO crystal (FWHM = 14 % at 662 keV). The highest energy data point was measured with a Pu-Be source, a neutron-gamma emitter (the trigger neutron was detected in a NE-213 scintillator with pulse shape discrimination). The difference in full energy absorption between the two materials is quite dramatic for the 4.4 MeV gamma-rays emitted by this source as shown in figure 5.

We turned the table on the Pu-Be source calibration in order to obtain an estimate of the response of the detectors to fast neutrons. If we observe a 4.4 MeV gamma-ray in the NaI(Tl) detector there is a neutron emitted isotropically in prompt coincidence. The ungated neutron spectrum from a Pu-Be source is shown in figure 6 [11]. However, when we require the 4.4 MeV gamma-ray (i.e. require excitation of the first excited state of ^{12}C) only a limited range of neutron energies is available. The higher excited states are unbound towards alpha particle emission and do not lead to the gamma-ray emitting state. Neutrons with energies in the range of 4 to 6 MeV are exactly the sort that will be created in heavy-ion reactions. Thus the Pu-Be source gives us a direct check of the relative sensitivity to neutrons of the appropriate energy.

The results of the neutron tests are shown in figure 7. The pulse height created by the neutron is shown as a function of probability, normalized to the total number of neutrons expected to strike each detector. The curves are very similar in shape and magnititude. The only large difference is at low pulse heights where the probability of an interaction in NaI(Tl) is larger. If we integrate the spectra over pulse height, then we find that the probability of an interaction in the NaI(Tl) is 0.40 and in the BGO is 0.33, for the same unit volume. The results of measurements at Chalk River of the sensitivity of BGO to fast neutrons [12] also suggest that there is only a minor difference between NaI(Tl) and BGO to neutrons at these energies. Thus, we cannot ignore the response of BGO to fast neutrons in estimating the operating characteristics of any new heavy-ion reaction product spectrometer system. Rather, we should take it to be the same as that of a NaI(Tl) detector of the same volume.

The conclusions from our study of the applicabilbity of BGO to heavy-ion continuum gamma-ray spectroscopy are simple and straightforward. The timing properties of the off-the-shelf detectors are unacceptable. We need, first, to find a PMT that can simultaneously optimize both the energy resolution and fast timing characteristics (a possibility is the Amperex-2312B).

And, second, we must attempt to bring the fast timing characteristics of BGO into the range of those of large volume NaI(Tl) detectors. We have found that BGO is nearly as sensitive to fast neutrons as NaI(Tl) and so time-of-flight separation of neutrons from gamma-rays will be needed in any device that replaces NaI(Tl) with BGO (of the same volume). However, if one replaces NaI(Tl) with BGO of the same stopping power then the overall neutron sensitivity will be lower.

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References

1. R. M. Diamond and F. S. Stephens, Annl. Rev. Nucl. Part. Sci. 30 (1980) 85.
2. S. Y. van der Werf, Nucl. Instru. Meth. 153 (1978) 221, and references therein.
3. D. G. Sarantites, M. Jääkeläinen, J. T. Hood, R. Woodward, J. H. Barker, D. C. Hensley, M. L. Halbert, and Y. Chan, J. de Phys. C10 (1980) 269.
4. R. S. Simon, J. de Phys. C10 (1980) 281.
5. A. J. Pacheco, G. J. Wozniak, R. J. McDonald, R. M. Diamond, C. C. Hsu, L. G. Moretto, D. J. Morrissey, L. G. Sobotka, and F. S. Stephens, Nucl. Phys. A (1982), in press.
6. J. O. Newton, B. Herskind, R. M. Diamond, E. L. Dines, J. E. Draper, K. H. Lindenberger, C. Shuck, S. Shih, and F. S. Stephens, Phys. Rev. Lett. 46 (1981) 1383.
7. J. E. Draper, J. O. Newton, L. G. Sobotka, H. Lindenberger, G. J. Wozniak, L. G. Moretto, F. S. Stephens, R. M. Diamond, and R. J. McDonald, Phys. Rev. Lett. 49 (1982) 434.
8. M.T. Collins, A. M. Sandorfi, D. H. Hoffmann, and M. K. Salomaa, Phys. Rev. Lett. 49 (1982) 1553.
9. A. E. Evans, Jr., IEEE Trans. Nucl. Sci. NS-27 (1980) 172.
10. K. Okajima, K. Takami, K. Ueda, and F. Kawaguchi, Rev. Sci. Instru. 53 (1982) 1285.
11. D. Slaughter and R. Strout, Nucl. Inst. Meth. 198 (1982) 349.
12. M. A. Lone, contirbution G-1 to this conference.

Figure captions

1. Continuum gamma-ray spectra obtained in coincidence with a heavy-ion reaction product [5]. In part (a) the rotational transitions are indicated by the cross hatched area. In part (b) the difference between the angular distributions of the rotational and statistical transitions can be seen.

2. Recent results that show the presence of an additional component at about 15 MeV in the continuum gamma-ray spectra [7]. The reaction was ^{136}Xe + ^{165}Ho at 1150 MeV, the five bins correspond to increasingly more negative Q-values.

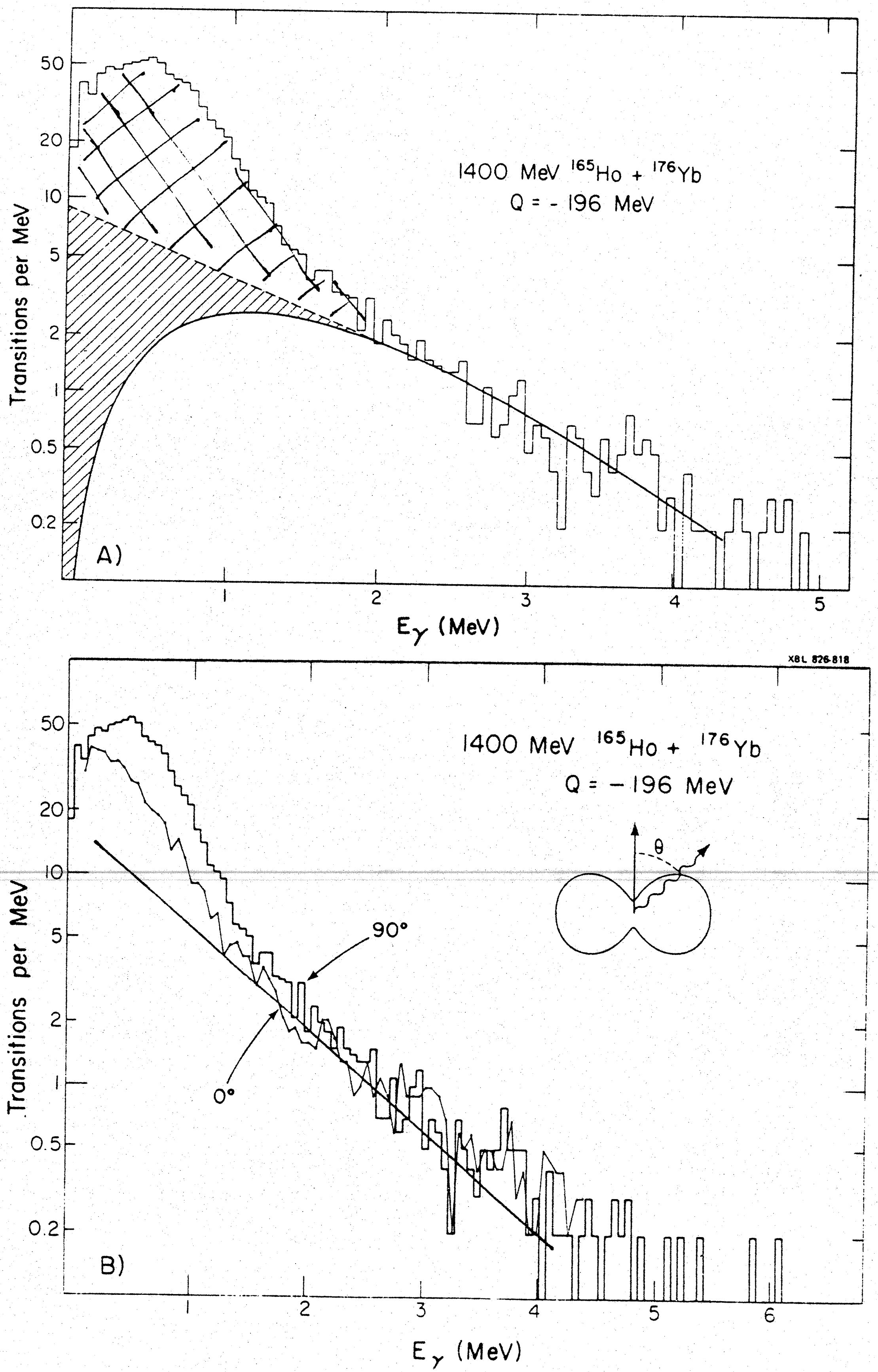
3. The timing characteristics of a large volume NaI(Tl) detector that were obtained with an alpha-gamma source, (c), and in-beam, (b), are shown. Also for reference the timing characteristics of an intrinsic Ge detector obtained in-beam,(a), are also shown.

4. Calibration results for 7.6 x 7.6 cm BGO and NaI(Tl) detectors. In part (a) the peak-to-total ratios (in percent) are compared. And in part (b) the energy resolution of the full energy peaks are compared (also in percent).

5. Pulse height distributions obtained for a 4.4 MeV gamma-ray, in 7.6 x 7.6 cm NaI(Tl) and BGO detectors.

6. The ungated neutron spectrum from a Pu-Be source from [11]. The energy levels of the ^{12}C reaction product are indicated along the top, only the first excited state leads to the emission of the 4.4 MeV gamma-ray.

7. Pulse height spectra of the gated neutrons in BGO and NaI(Tl). The data have been normalized to the total fluence of neutrons, and the BGO data has been shifted up by a factor of 2 to separate it from the NaI(Tl) data.


50
20
10
5
2
1
0.5
0.2
Transitions per MeV
1400 MeV ^{165}Ho + ^{176}Yb
Q = - 196 MeV
A)
1
2
3
4
5
E_γ (MeV)
50
20
10
5
2
1
0.5
0.2
Transitions per MeV
1400 MeV ^{165}Ho + ^{176}Yb
Q = −196 MeV
θ
90°
0°
B)
1
2
3
4
5
6
E_γ (MeV)

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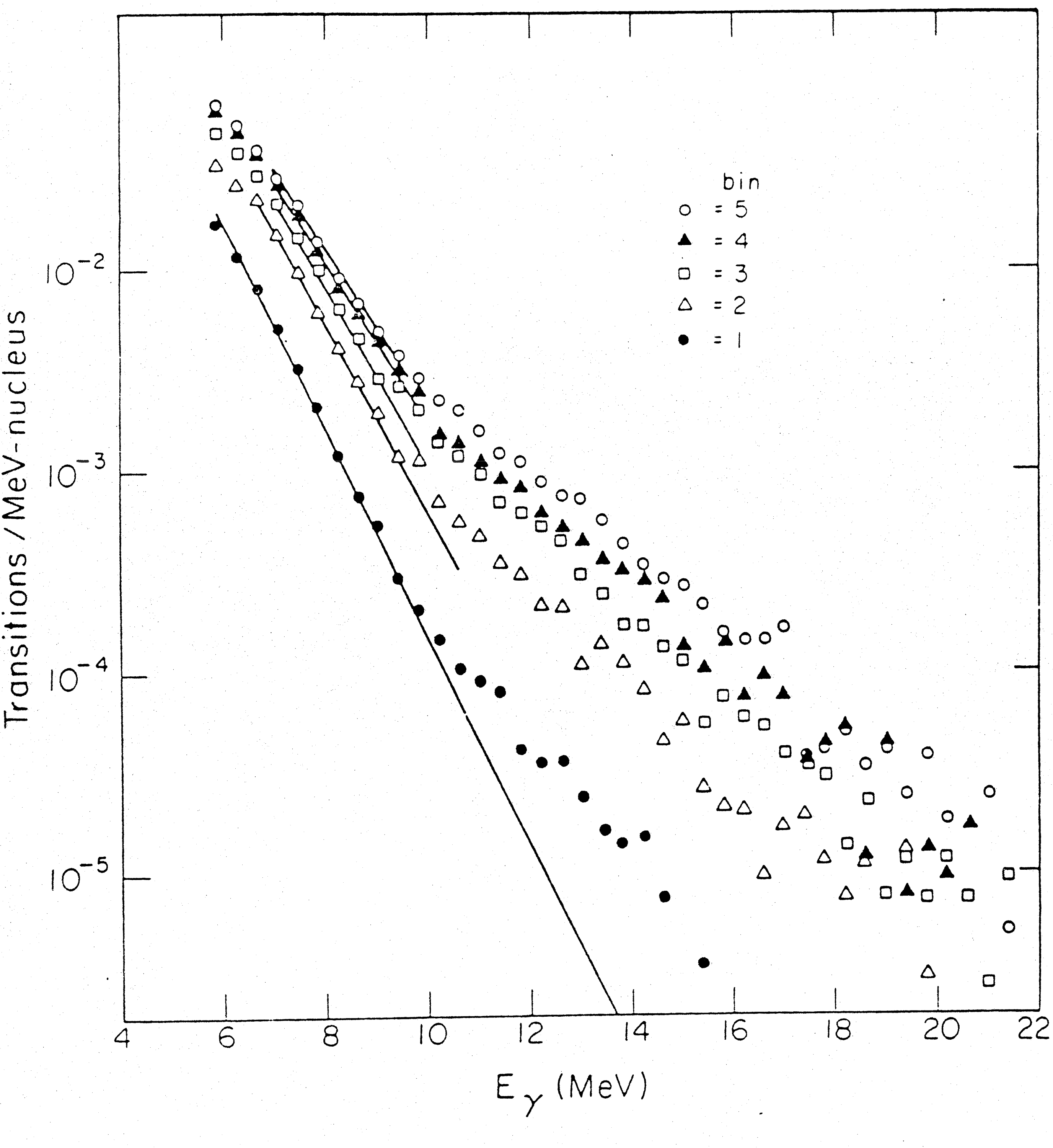

bin
○ = 5
▲ = 4
□ = 3
△ = 2
● = 1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Transitions / MeV-nucleus
4
6
8
10
12
14
16
18
20
22
E_γ (MeV)

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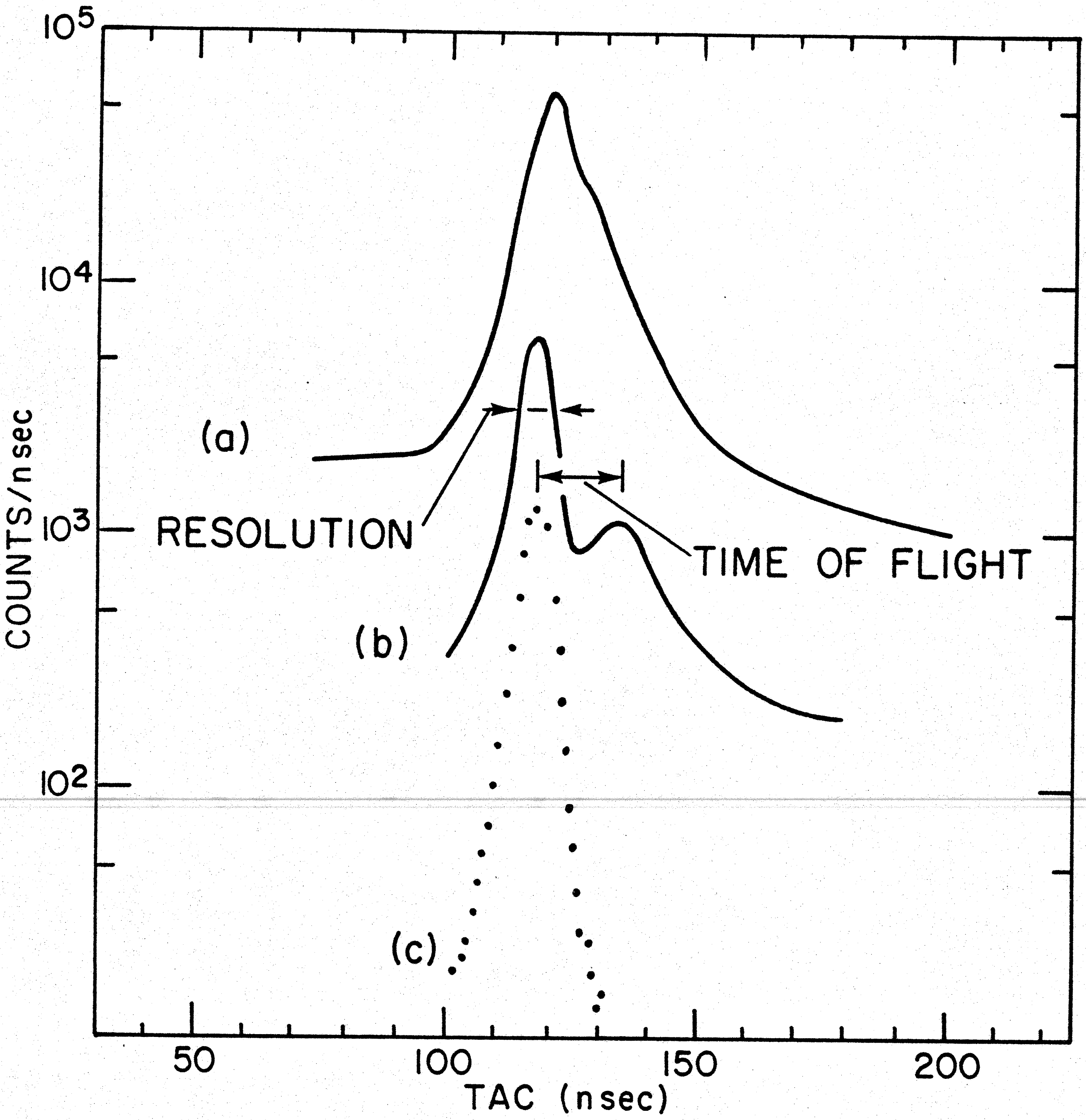
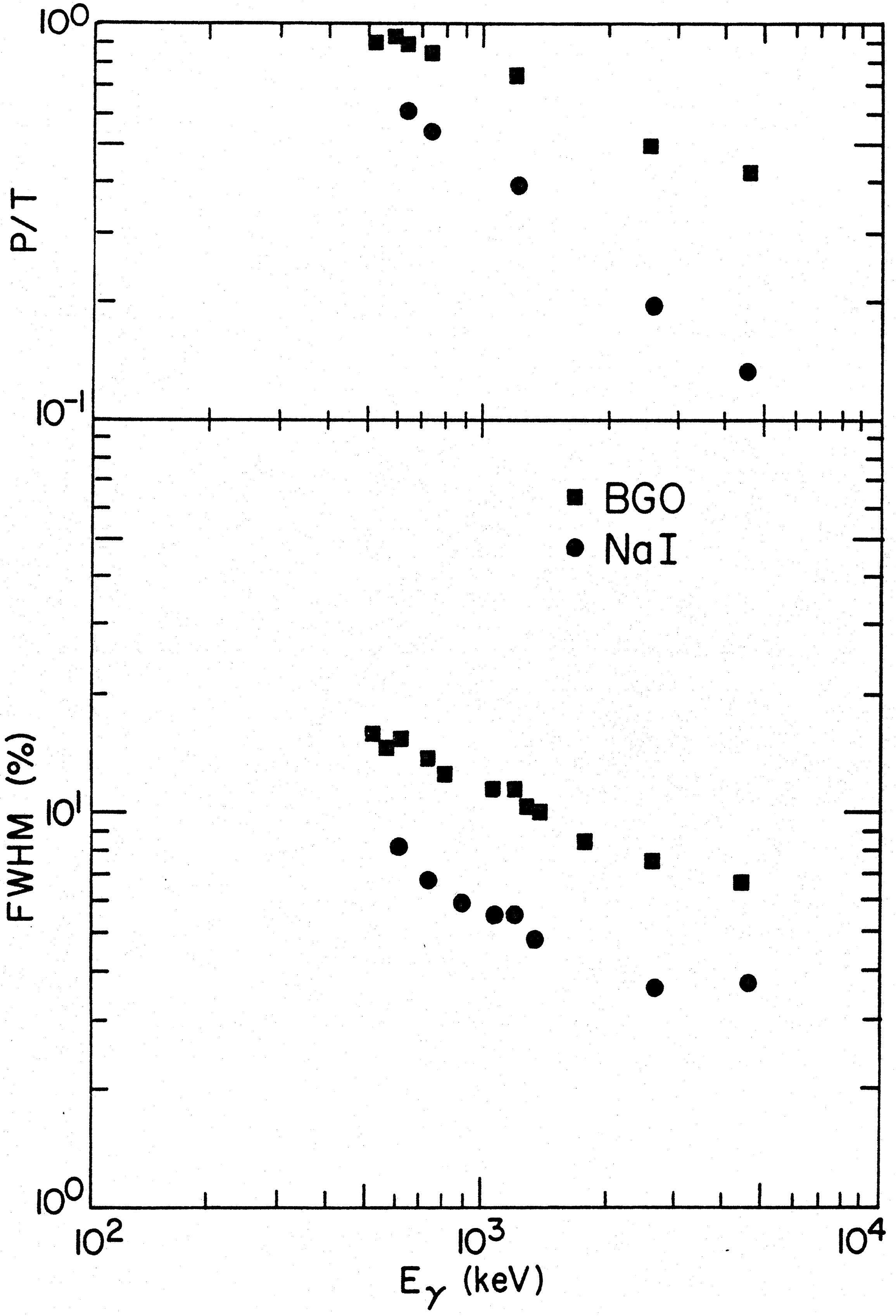
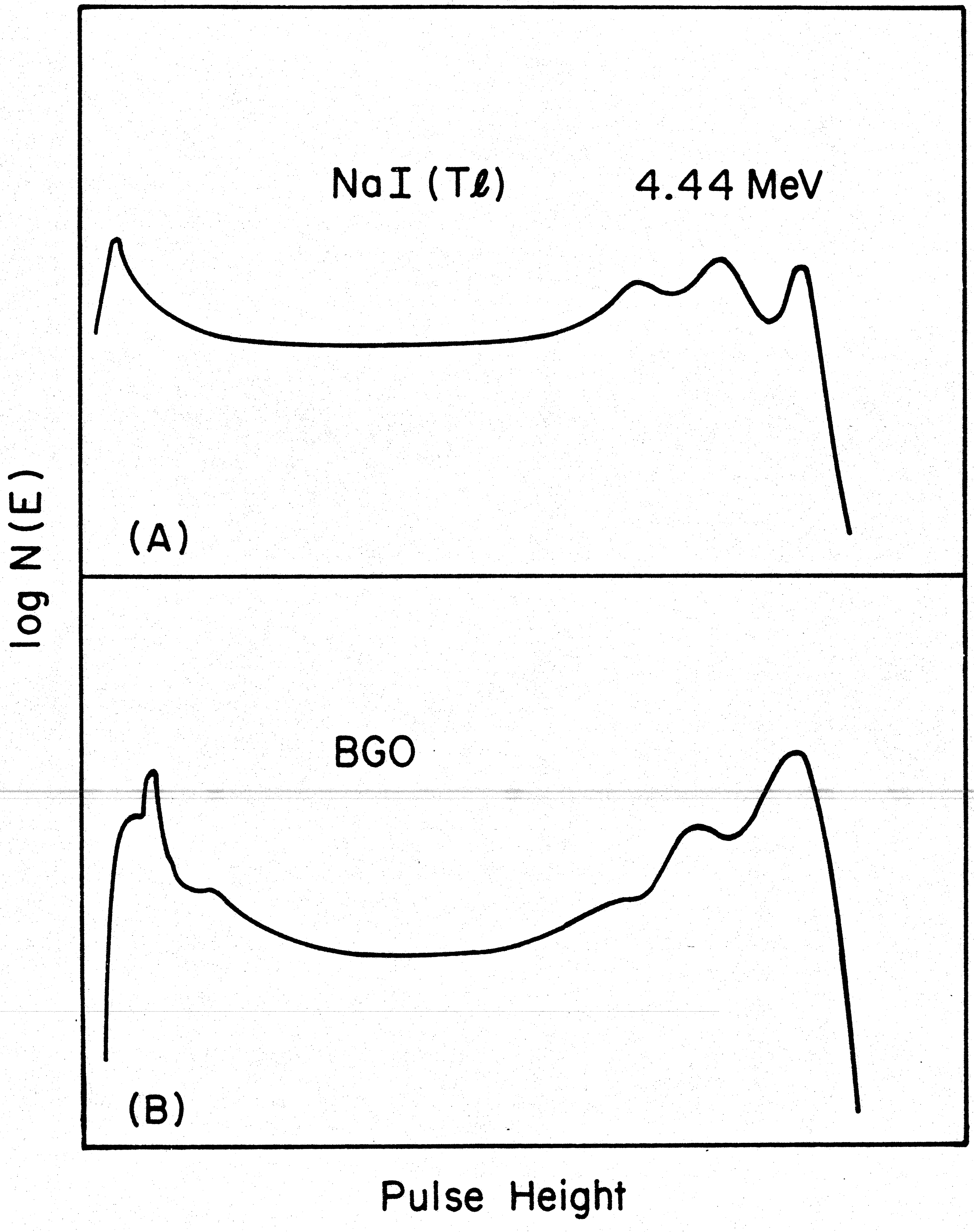


10^5
10^4
10^3
10^2
COUNTS/nsec
(a)
(b)
(c)
RESOLUTION
TIME OF FLIGHT
50
100
150
200
TAC (nsec)


10^0
10^{-1}
P/T
■ BGO
● NaI
FWHM (%)
10^1
10^0
10^2
10^3
10^4
E_γ (keV)

MSUX-82-424



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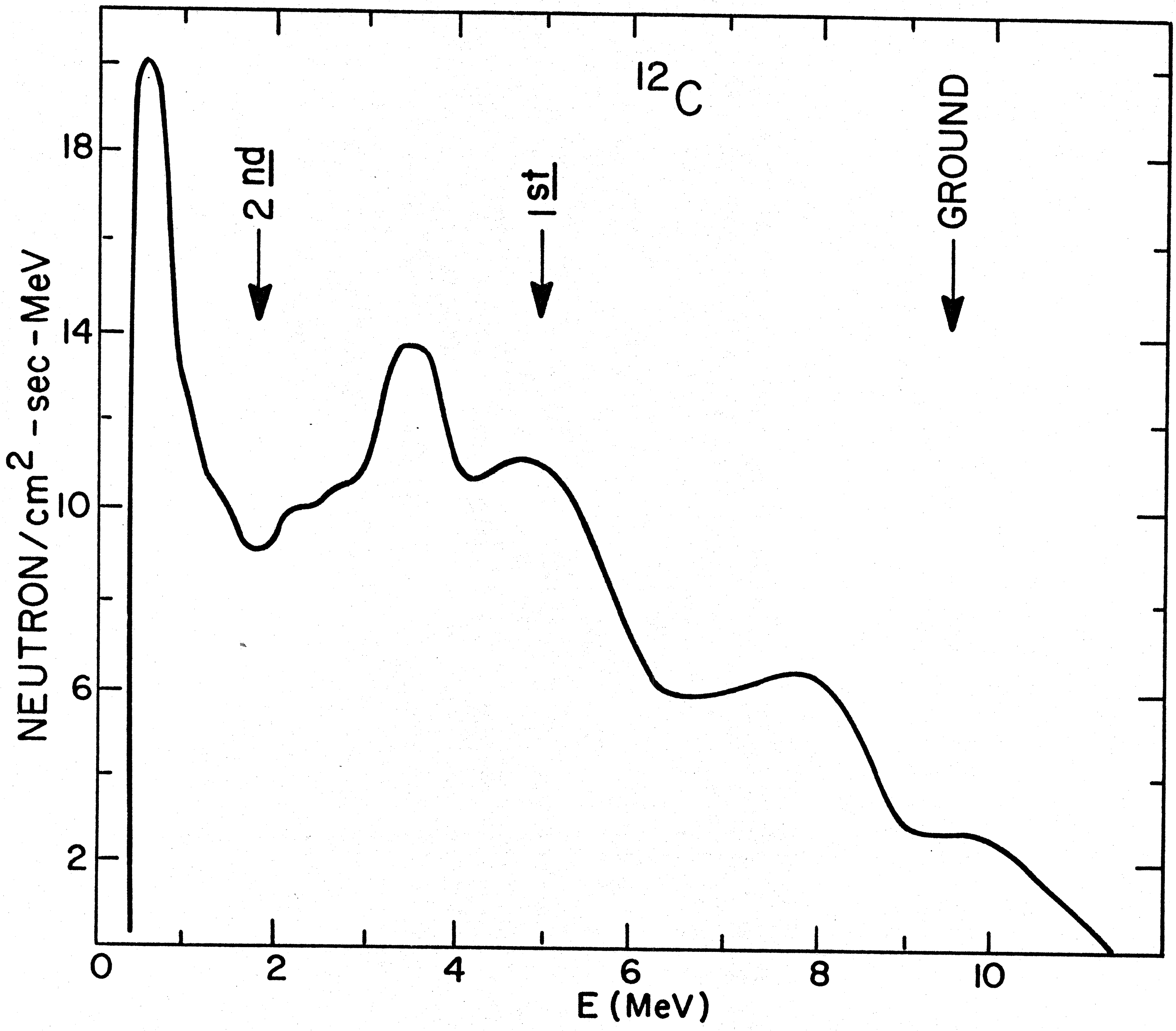
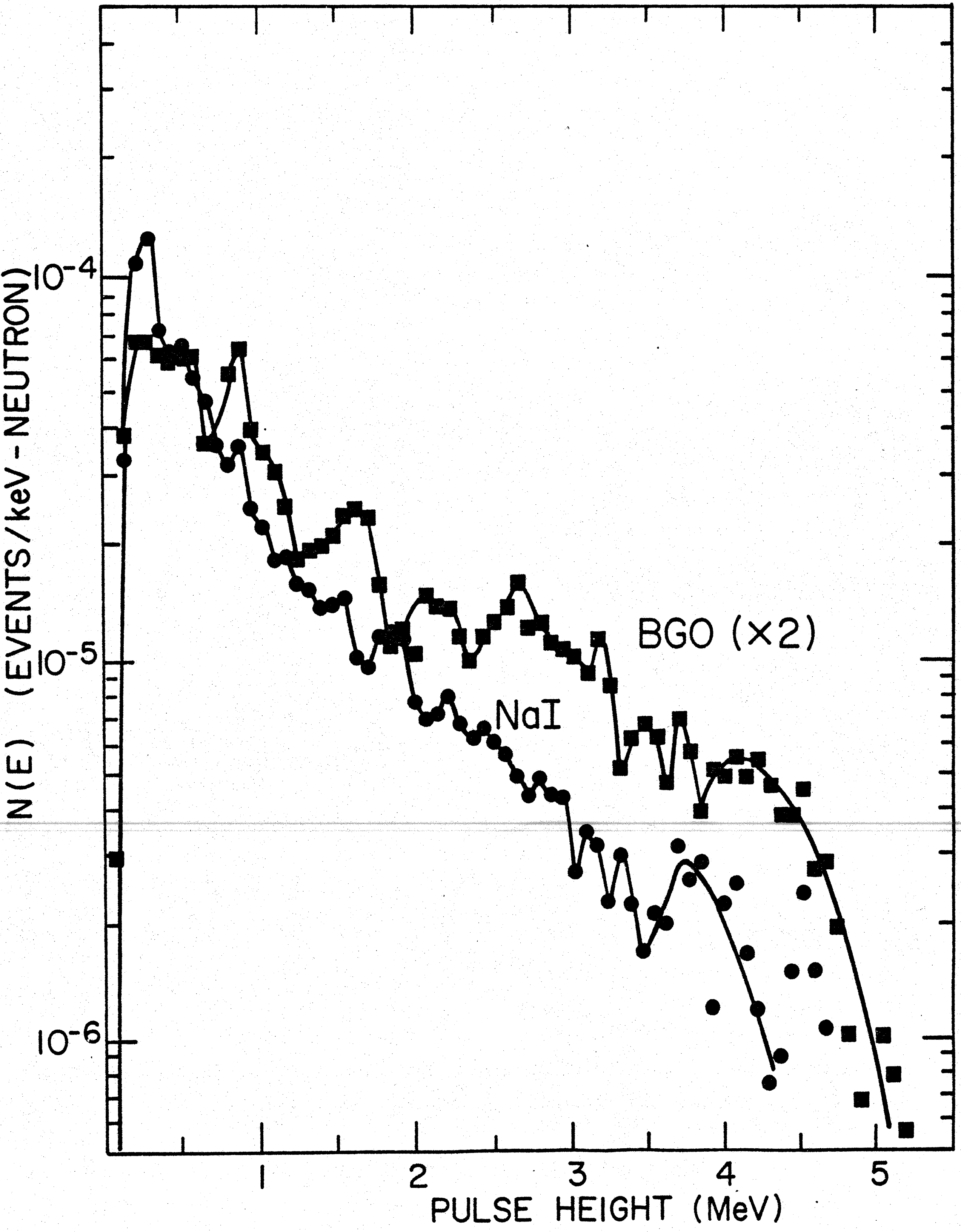


^{12}C
2 nd
1st
GROUND
NEUTRON/cm^2-sec-MeV
18
14
10
6
2
0
2
4
6
8
10
E (MeV)


N(E) (EVENTS/keV - NEUTRON)
10-4
10-5
10-6
1
2
3
4
5
PULSE HEIGHT (MeV)
BGO (×2)
NaI