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THE ENERGY RESOLUTION CAPABILITIES
OF SEMICONDUCTOR DETECTORS FOR PARTICLES
IN THE 10 TO 100 MeV RANGE

F. S. Goulding, D. A. Landis and R. H. Pehl

May 1967

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FOREWARD

This is one of a series of papers presented at the Gatlinburg Conference on Semi-Conductor Detectors and Associated Circuits (May, 1967). Taken together, the papers represent a general summary of some of the recent advances in this area at LRL, Berkeley.

THE ENERGY RESOLUTION CAPABILITIES OF SEMICONDUCTOR DETECTORS FOR PARTICLES IN THE 10 TO 100 MEV RANGE*

By: F. S. Goulding, D. A. Landis and R. H. Pehl

I. Introduction

Many studies of nuclear reactions use beams of medium energy protons, alpha particles and other light nuclei produced by cyclotrons. Recent advances in these machines, in particular the development and use[1] of the variable energy spiral-ridge principle have resulted in the possibility of carrying out experiments with energy resolutions less than .075% (i.e. 37.5 keV FWHM at 50 MeV). For example, the present magnetically analyzed beam from the Berkeley 88" cyclotron is believed to have a beam spread of about .075% FWHM for 50 MeV alphas, and in the near future, with the addition of a higher precision beinding magnet, a beam with a spread of about .02% FWHM will be available. To fully utilize the energy resolution capabilities of these machines, the system analyzing the reaction products (i.e. after the target) must exhibit inherent fluctuations in the .02% FWHM region. Since existing semiconductor detector systems have not demonstrated this performance, we are driven to consider the use of very expensive magnetic analysis systems (which also possess their own limitations). In view of this situation, the following notes have been prepared to make a serious estimate of the performance we can ultimately expect to realize with semiconductor detectors in these applications, and to indicate the conditions necessary for this performance. Some discussion of present performance will also be included.

We will restrict our discussion to the use of silicon detectors; in the energy range of interest this usually implies lithium-drifted silicon detectors 1 to 4mm thick. We will neglect one of the more interesting

*This work was carried out as part of the program of the Nuclear Chemistry Instrumentation Group of the Lawrence Radiation Laboratory supported by AEC Contract No. W-7405-eng-48.

problems posed by this type of cyclotron, namely, the problem of stopping protons up to 60 MeV. Two earlier papers[2,3] have shown the potential of germanium detectors and it will suffice to note here that the results which follow would be somewhat improved by the use of germanium (at 77°K) due to the smaller energy required to produce a hole-electron pair and the smaller measured Fano factor.

II. Sources of Spread

Several factors determine the energy resolution of detector systems and their relative importance changes as a function of particle energy. We will deal with each of these factors in turn:

A. Detector Noise

The relative magnitude of the two components which contribute to detector noise depends upon such factors as temperature, applied voltage, amplifier pulse-shaping network time constants, etc.. The first component, due to bulk leakage current, behaves in a reasonably predictable fashion, the leakage and its associated noise becoming smaller as the temperature is reduced and the mean-square noise voltage increasing linearly with increasing amplifier time constant. The second component, due to surface effects, is more difficult to predict; however, one can say that its value increases with increase in applied voltage, is dependent on the surface treatment of the detector, and that its mean-square value increases very rapidly (i.e. more than linearly) with increasing amplifier time constant.

Obviously, the common factor strongly influencing these two noise sources is the amplifier time-constant, and from this point of view, the shorter the time-constant, the better will be the noise performance. Decreasing the detector temperature decreases the bulk leakage current and also reduces the charge-collection time in the detector (at -75°C the collection time is almost 3 times smaller than at +25°C). This is advantageous in that it permits use of shorter amplifier time constants than would otherwise be necessary*-thereby reducing detector (particularly surface) noise.

Using a shaping network (e.g. one producing a Gaussian-shaped pulse) of about 0.5μsec time constant in the amplifier, and a detector at -75°C, we can realize a total detector noise contribution to energy resolution of << 5 keV (FWHM) with no difficulty. Futher reduction of the temperature is only possible if silicon exhibiting very little charge trapping is available.

B. Input Amplifying Stage Noise

Here we can use results obtained in work on high-resolution germanium and silicon detector systems for lower energy applications and make some reasonable extrapolations to higher energies. The detectors used in high-resolution nuclear reaction experiments exhibit capacities smaller than 5pF (frequently much smaller). For high-energy applications, the feedback capacitor in the charge-sensitive loop must be increased from the small value used in low-energy applications--5pf is a good general purpose value. Therefore, the total input capacity will be about 10pF.

*We will see later that the noise due to the input amplifier stage increases at short time constants but this increase is quite predictable.

A typical F.E.T. preamplifier using an optimally cooled UC250 will exhibit a FWHM energy resolution of (2+0.1C) keV for a Gaussian shaping network peaking at 0.5μsec. (Where C is the added input capacity measured in pF). Therefore an input stage noise contribution of 3 keV can be expected, and together with the detector noise, the total front-end noise should not exceed 5 keV FWHM.

C. Noise Due to Later Stages of Amplification

This is frequently a major source of noise in high-energy applications due to the use of general purpose amplifiers designed for use with all types of radiation from 20 keV X-rays to 100 MeV particles. However, it is a simple matter to design an amplifier especially for the 10-100 MeV range. Moreover, since the number of stages of amplification required is much smaller than in general purpose amplifiers, the gain stability is also much improved.

D. Gain Stability

The very small percentage resolution numbers quoted earlier indicate the importance of amplifier gain stability in these applications. By use of low temperature coefficient resistors and air-conditioned equipment racks we are already achieving gain stabilities which are almost adequate. However, servo stabilization of gain will probably be required for long experiments.

E. Statistics of Charge Production in the Detector

The statistical nature of the sharing of energy between ionizing and other processes results in a spread in the charge signal produced in a detector by the absorption of energy from an ionizing particle. The mean-square fluctuation in the number of hole-electron pairs is given by $\overline{N^2} = F N$ where F is the Fano factor and N is the number of hole-electron pairs produced. This factor has been studied extensively both from a theoretical[4] and experimental point of view. Recent measurements at our laboratory and others indicates that the Fano factor in silicon is smaller than 0.15. This is likely to be an overestimate as trapping and window effects complicate the measurement. We should also bear in mind that the experimental measurements are confined to electrons of energy <1 MeV. However, since it is known that the sharing of energy between ionizing and other processes is almost independent of particle type and energy (as shown by roughly the same value for the energy absorbed per hole-electron pair), it seems reasonable to assume a maximum Fano factor of 0.15 for our energy region too.

Converted into energy, the FWHM spread due to this source is given by $E_{STAT} = 2.35\sqrt{F E \epsilon}$

Since $\epsilon = 3.70$ for silicon at -75°C, we have:

$E_{STAT} = 1.75\sqrt{E}$ keV, where E is the particle energy in MeV.

The values given in Tables 1 and 2 are calculated from this relationship.

F. Nuclear Collisions

When heavy particles pass through an absorbing medium, part of their energy is lost by collisions with the nuclei of the absorbing medium. This energy appears in the form of recoiling atoms of the absorber which knock out further atoms, producing virtually no ionization. As far as the detector output signal is concerned, the loss of energy in these nuclear collisions causes a small loss of signal--which is not normally large enough to be of any consequence*. However, only a small number of nuclear collisions occur in the track of particle and the energy exchanges at these collisions are rather high. This causes rather a large statistical fluctuation in the output signal.

This effect has been analyzed by Lindhard and Nielsen[5] who show that the dominant result is due to the very low energy portion of the particle's track. Using Lindhard and Nielsen's results we have:

Low energy nuclear contribution $E_{NUCL} = 0.7 Z^{1/2} A^{4/3}$ keV FWHM

where Z and A are the atomic number and atomic weight of the particle.

For alpha particles: $E_{NUCL} = 6.4$ keV FWHM

For protons: $E_{NUCL} = 0.7$ keV FWHM

*Except for heavy ions such as fission fragments where this is believed to account for the so-called ionization defect.

Lindhard and Nielsen also give a formula for evaluting the high-energy contribution and calculation shows this to be quite negligible at energies up to 100 MeV*.

G. Trapping Effects in Detector

Many silicon detectors exhibit severe trapping effects at low temperatures. We have demonstrated that these problems are very significant in determining resolution but mainly at high energies as the charge trapped is proportional to the energy of the incoming particle. Although insufficient data exists on this problem it seems reasonable to assume that the spread in signal resulting from trapping is proportional to $\sqrt{E}$. The effect varies a great deal with the quality of silicon used in the detector, but we have established that it is very small for 1 MeV electrons at -150°C if high quality silicon is used. This indicates that the use of good quality silicon at -75°C should result in no serious trapping problems for particles up to 100 MeV (i.e. the spread introduced should be << 5 keV).

H. Pile-up of Fast Electrons from Target

Secondary electrons from the target can constitute a noise source in a detector. We now employ an electrostatic electron suppressor to remove these electrons and a substantial improvement in resolution has resulted.

*Lindhard and Nielsen also point out that this effect can result in a tail on peaks. However, calculations show this to be negligible for our purposes.

I. Background γ Pile-up

Recent work indicates that slight tailing on peaks observed in nuclear reaction experiments in this energy range may be due to γ-rays from the target producing signals at a high rate in the detector. These superimpose on the signals and can cause loss of resolution and tailing. No simple method of eliminating this effect has been found but use of a bending magnet combined with shielding is an obvious (though fairly complex and expensive) solution if it is necessary. The use of a short amplifier time constant is also desirable to reduce these pile-up effects.

J. Detector Temperature Variations

The energy required to produce a hole-electron pair is a function of temperature. Measurements indicate a change of between .01 and .02%°C. We note that this could easily be a major limitation, and to make its effect negligible, the detector temperature should be controlled to ±0.25°C.

III. Summary of Results

Although this method can be questioned, these various factors will be added together in quadrature since they are almost uncorrelated. (Note: Lindhard suggests that some correlation may exist between nuclear collisions and ionization statistics but we are only concerned here with a maximum estimate and will neglect correlation.) The results are summarized in Tables 1 and 2. The final two columms of these tables show the predicted experimental energy resolution allowing .075% and .02% respectively for beam spread (FWHM).

IV. Discussion

In making a comparision between the observed experimental energy resolutions and those predicted here, we must recognize that very few experimental setups are optimized as required for validity of our predictions. For example, the detector temperature is rarely optimized (this should probably be adjusted for best results), noise from stages other than the first one in the amplifier is not negligible, and time constants are not always ideal. Moreover, inadequate knowledge of beam spread leads to difficulties in assignment of specific numbers to the various contributions.

Experimental results which are worthy of consideration are some obtained in experiments with a range of detectors by B. G. Harvey and his associates at the 88" Cyclotron at Berkeley. For 50 MeV α-particles they obtain a FWHM resolution of about 45 keV. A typical spectrum is shown in Fig. 1. We can account for most of this spread as follows:

(1) Electronic Resolution (Detector, Preamp and Amplifier): 20 keV

(2) Beam Resolution: Probably About 37.5 keV

(3) Nuclear Collisions: 6.5 keV

(4) Detector Statistics: 12.4 keV

Total: 44.7 keV.

Recently the same group has measured scattering of 15 MeV deuterons from a ^{178}Hf target (see Figs. 2 and 3) and obtained an energy resolution of about 18 keV.

Calculations similar to those given here for α's and protons predict 16 keV. We see that the experimental results are in fair agreement with the summation of the known and predicted components. However, it is possible that several factors, such as detector window and target thickness, charge-trapping and γpile-up in the detector, etc., which may be of major importance later, are being hidden by the large factors listed above.

Very recently, D. Hendrie and W. Parkinson have carried out measurements in a well resolved (∿.02%) 58 MeV alpha-particle beam at the University of Michigan. Their final energy resolution (FWHM) was 35 keV (or about .06%). Allowing for their measured electronic resolution (12 keV) and detector temperature variations, the theoretical considerations given earlier would predict nearly 30 keV resolution for their situation.

While it is clearly desirable to carry out more exacting tests, the indications are that the results given in Tables 1 and 2 will probably eventually be realized.

V. Acknowledgements

Several of the experimental observations given here are due to B. G. Harvey and D. Hendrie who also gave much encouragement to this work. Our conclusions are in a large part based on results obtained using detectors made by H. Smith working with R. Lothrop.

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Figures

1) Inelastic Scattering of 50 MeV Alpha from ^{154}Sm

2) Scattering of 15 MeV Deutrons from ^{178}Hf (Linear Scale)

3) Scattering of 15 MeV Deutrons from ^{178}Hf (Logarithmic Scale)

Tables

1 - Anticipated Energy Resolution for Protons

2 - Anticipated Energy Resolution for Alphas

TABLE 1 : ANTICIPATED ENERGY RESOLUTION FOR PROTONS

ENERGY MeV	ELECTRONIC keV	DETECTOR STATISTICS keV	NUCLEAR COLLISIONS keV	BEAM .075% keV	BEAM .02% keV	TOTAL FOR .075% BEAM	TOTAL FOR .02% BEAM
10	5	5.5	0.7	7.5		10.5	
					2		7.7
20	5	7.8	0.7	15		17.6	
					4		10
30	5	9.6	0.7	22.5		25.0	
					6		12.4
40	5	11.1	0.7	30		32.3	
					8		14.6
50	5	12.4	0.7	37.5		39.8	
					10		16.7
60	5	13.6	0.7	45		47.0	
					12		18.7
70	5	14.7	0.7	52.5		54.8	
					14		20.9
80	5	15.7	0.7	60		60.2	
					16		23.0
90	5	16.6	0.7	67.5		67.5	
					18		25.0
100	5	17.5	0.7	75		75.0	
					20		27.0

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TABLE 2 : ANTICIPATED ENERGY RESOLUTION FOR ALPHAS

ENERGY MeV	ELECTRONIC keV	DETECTOR STATISTICS keV	NUCLEAR COLLISIONS keV	BEAM .075% keV	BEAM .02% keV	TOTAL FOR .075% BEAM	TOTAL FOR .02% BEAM
10	5	5.5	6.4	7.5		12.3	
					2		10.0
20	5	7.8	6.4	15		18.8	
					4		11.9
30	5	9.6	6.4	22.5		25.8	
					6		14.0
40	5	11.7	6.4	30		33.2	
					8		15.9
50	5	12.4	6.4	37.5		40.3	
					10		17.8
60	5	13.6	6.4	45		47.3	
					12		19.8
70	5	14.7	6.4	52.5		55.0	
					14		21.8
80	5	15.7	6.4	60		60.2	
					16		23.9
90	5	16.6	6.4	67.5		67.5	
					18		25.8
100	5	17.5	6.4	75		75	
					20		28.3

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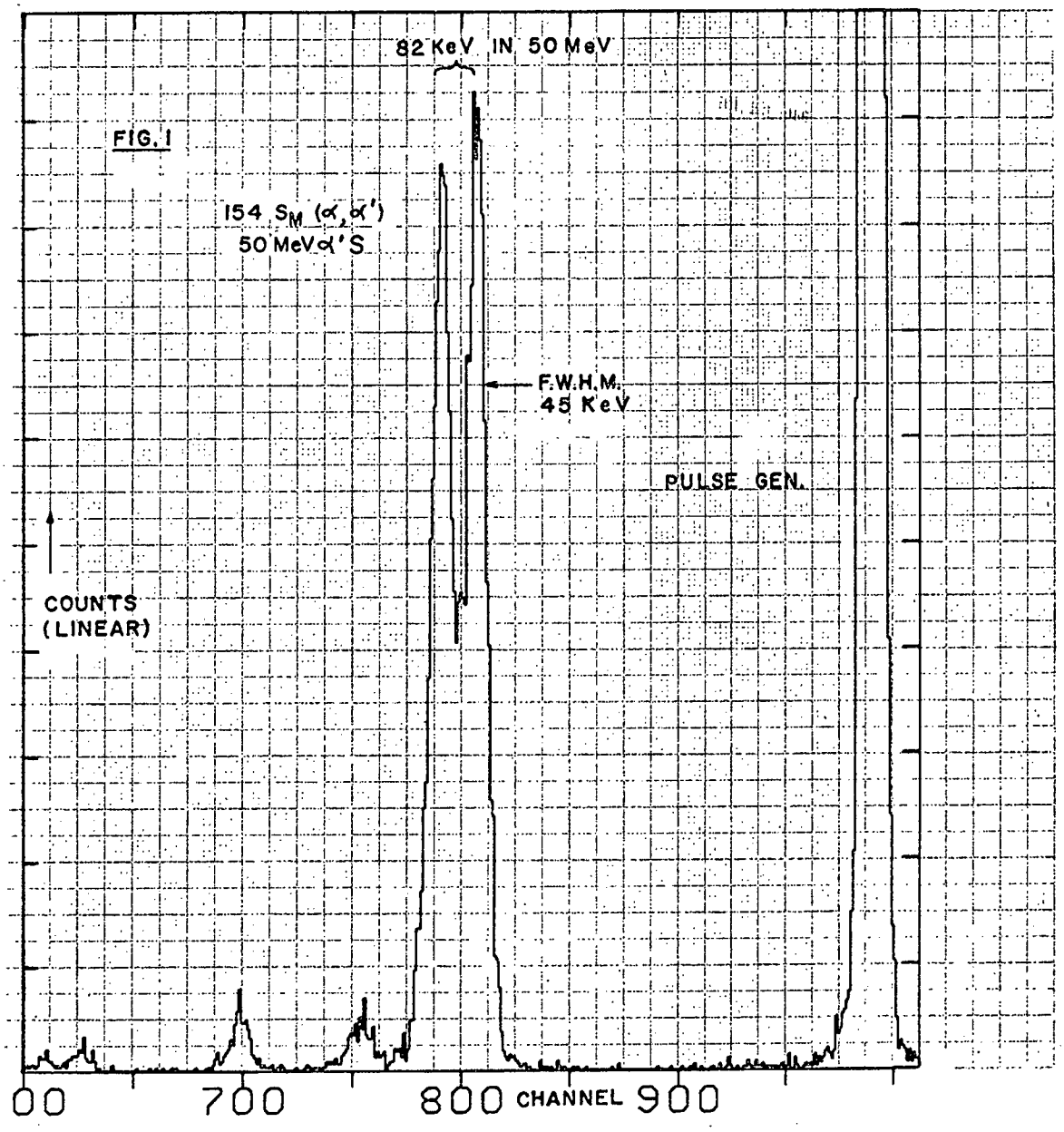
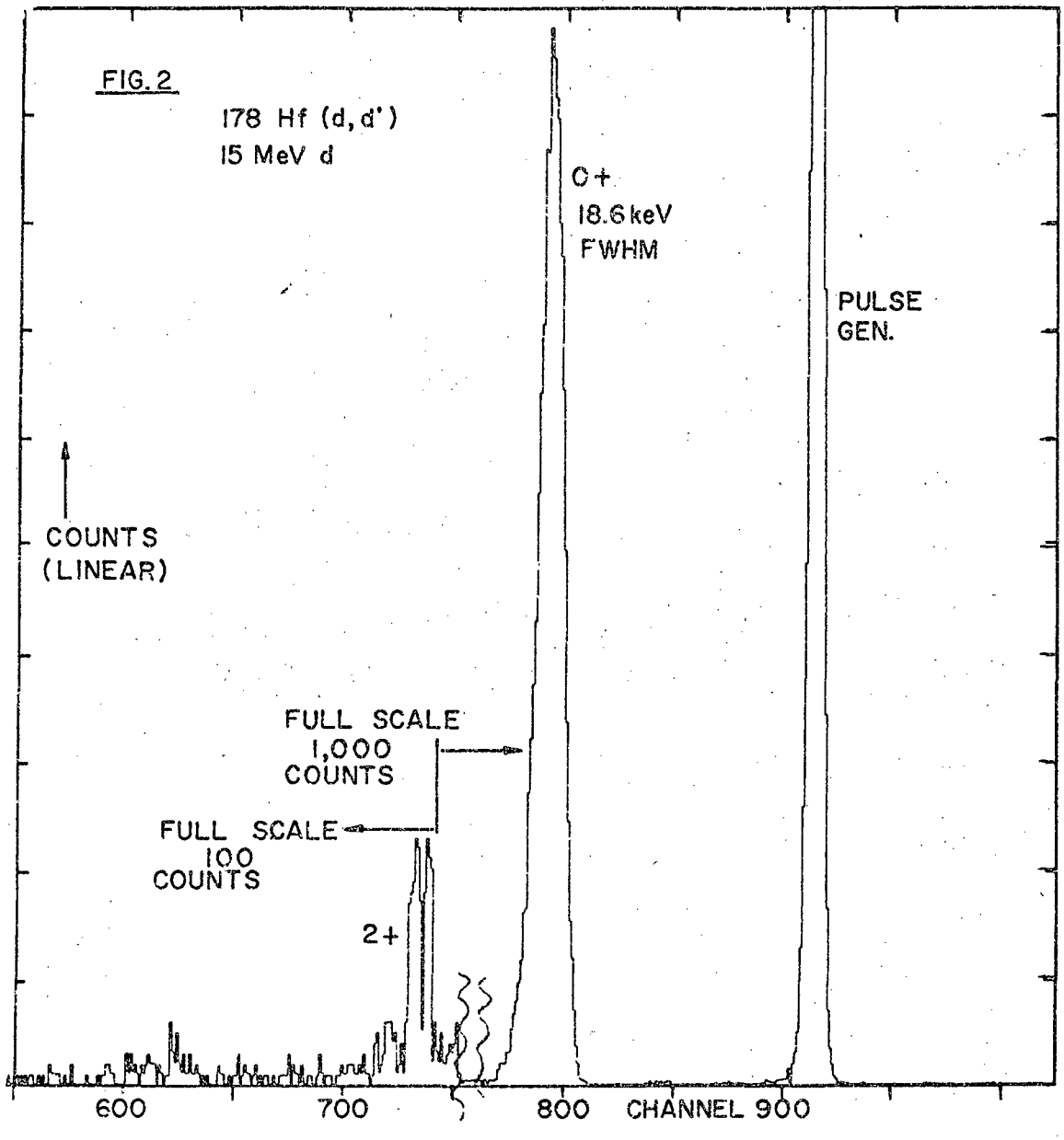


XBL 675-1465

Fig. 1.



XBL 675-1466

Fig. 2.

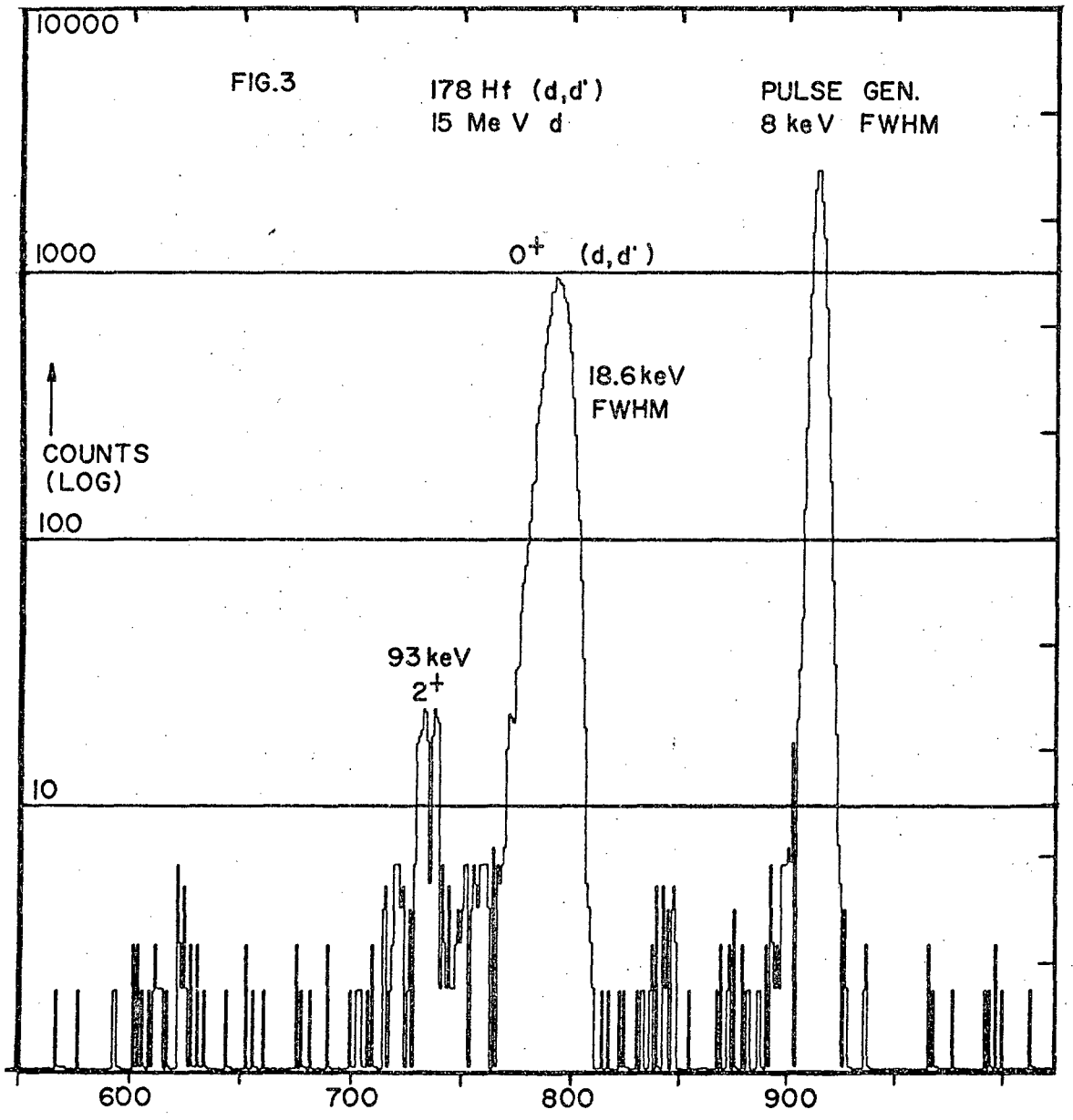


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Fig. 3.

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