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THE BETA DECAY OF B^{13}

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ABSTRACT: B^{13} has been made in the reaction $B^{11}(t,p)B^{13}$ and its radiations have been studied with plastic and NaI(Tl) scintillation spectrometers both singly and in coincidence. The half-life was determined as 18.6 ± 0.5 milliseconds. Decay takes place by beta-ray emission to the C^{13} ground state (93%, log ft = 4.01) and to the 3.68 Mev excited state (7%, log ft = 4.53). Limits are set on the decay to other levels in C^{13}. It is concluded that the ground state has spin and parity 3/2 - as expected. No evidence was found for a beta branch to a possible 5/2 - level in C^{13} which is predicted by the independent particle model.

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Introduction.

Observation of the beta decay process is a very useful tool in the spectroscopy of nuclei. Very few of the beta active light elements, whose ground states are stable against particle emission, remain to be investigated. One of these is B^{13} and we have carried out an investigation of its beta decay to C^{13} in the hope of learning more about both of these nuclei.

B^{13} was first observed by Norbeck[1] via the $Li^7(Li^7,p)$ reaction and subsequently by Muto et al[2] via the $B^{11}(t,p)$ reaction. From the Q values for these reactions the mass excess of B^{13} is 20.40 Mev. It is then stable by 4.88 Mev to decay into B^{12} plus a neutron, and the difference in energy between the B^{13} ground state and the C^{13} ground state is 13.44 Mev.

B^{13} will thus beta decay to available levels in C^{13} and the nature of the decay should inform us on the properties of the states involved. If B^{13} is $3/2^-$ as predicted by the simple shell model and suggested by ref.[2] then it may decay to a $5/2^-$ level in C^{13} whose existence has not yet been demonstrated and whose absence is a continued problem for shell model theorists.[3,4]

Experiments

The study of the decay of B^{13} is rendered difficult by the fact that it is usually accompanied by decaying B^{12}, whose lifetime and betas may be very similar to those for B^{13}. The reaction $B^{11}(t,p)$ was the one used to make the B^{13} activity, the tritium being accelerated in the electrostatic generator of the University of Manchester. The Q value of the $B^{11}(t,p)\,B^{12}$ reaction is -2.9 Mev, so we expect no B^{12} from this reaction at the bombarding energy used throughout our experiments which was 3.3 Mev. B^{12} will arise from the reaction $B^{10}(t,p)B^{12}$ occuring in B^{10} in the target. The target used was one of thickness about 2 mgms/cm^2 of B^{11} made in the electromagnetic separator at Harwell. By comparing the yield of γ-rays from the $B^{10}(\alpha,p,\gamma)C^{13}$ reaction at an alpha particle bombarding energy of 1.5 Mev from this target and from a thick target of natural boron, the percentage of B^{10} in our B^{11} target was found to be less than 0.2%. There are five bound states in B^{12} that could produce B^{12} activity via the $B^{10}(t,p)$ reaction. There is only one known bound state in B^{13}. At 5.5 Mev bombarding energy the cross-section for the $B^{11}(t,p)B^{13}$ ground state reaction is about ten times greater than that for the reaction $B^{10}(t,p)$ to any bound state in B^{12} [2,5]. We may resonably expect this situation not to change too drastically as the bombarding energy is lowered to 3.3 Mev. So the 0.2% or less of B^{10} in the target is not expected to produce much B^{12} compared with B^{13} when the target is bombarded with tritium. This conclusion is borne out by the results. A further possibility for a mechnism of production of B^{12} in the experiment is its formation via the $B^{11}(d,p)$ reaction, the deuterium coming from an HD^+ beam which would be present with tritium in a momentum analysed mass three beam. The thick target yield of B^{12} from the (d,p) reaction was found to be about two or three orders of magnitude greater than the thick target yield of B^{13} from the (t,p) reaction. Small amounts of HD^+ beam in early experiments confused the issue considerably. To overcome this problem the beam was passed through carbon foil "strippers" before entering the bending magnet of the electrostatic generator. The emergent beam was then only tritium when the magnet was set for mass three.

The lifetime of B^{13} was expected to be of the order of tens of milliseconds. To observe such activity a beam pulsing apparatus was built which enabled the beam to be pulsed on and off the target at variable frequencies and with the ratio of "beam on" time to "beam off" time variable. Electronic gates were synchronised with the beam pulsing so that data was only taken for chosen intervals during the "beam off" period. Figure 1 shows a block diagram of the electronics used to observe $\beta - \gamma$ coincidences in the activity. The electronics is conventional except for the beam pulsing and gating circuits. The lifetime of B^{13} in the sequel was about 18 msec and during the experiments equal "beam on", "beam off" periods of 100 msec were used, and the gates arranged so that data were taken in an interval of 65 msec which commenced 5 msec after the beam was removed from the target.

The beta particles were detected in a plastic phosphor, 5.0 cms. diameter, 5.0 cms. thick. This was not quite thick enough to stop the high energy betas and an absorber of 8 mm of graphite and 2 mm of perspex was placed between the source and the phosphor. The beta counter assembly was in the target chamber and the counter subtended a solid angle at the target of about .03 of a sphere. The

γ-ray detector was a NaI crystal, 4.4 cm diameters, 5.0 cm thick. This was placed as near the target as possible with absorbers of 2.5 cm of graphite and 1 cm, of perspex interposed to absorb beta particles and to minimise the bremmstrahlung. The γ-counter subtended a solid angle at the target of about .016 of a sphere.

No attempt was made to shield the counters from the neutrons produced by the tritium beam whilst it hit a stop further down the beam tube during the "beam off" target period. This background was not too important for the beta and gamma ray work. However it was a severe handicap in the attempt to look for delayed neutrons. With our experimental area and arrangement any attempt to shield would probably not have resulted in much improvement.

No trouble was experienced from activities produced from contaminants in the target. The only one likely was C^{15} produced via the $C^{13}(t,p)$ reaction. This 2.3 second activity produces a beta spectrum with a 9.8 Mev end point, and a 5.3 Mev γ-ray[6]. No evidence for either was observed.

The tritium beams used were of the order of 5 mμA in size. This beam was sufficient to give the largest usable counting rates and was produced from an RF ion source using a gas mixture of 0.5% tritium, 99.5% He^4.

Results.

I. Beta particle measurements.

Figure 3 shows the pulse height distribution of the beta rays detected in the plastic phosphor due to B^{13} activity. Also shown is the spectrum due to B^{12}. Taking the end point of this latter spectrum as 13.38 Mev[6] and using two further calibration points, the Compton edges of the pulse height distribution due to 2.62 Mev and 4.43 Mev γ-rays, we obtain for the end point energy of the B^{13} beta rays the value 13.4 ± 0.2 Mev. The B^{12} and B^{13} spectra look very similar. This shows that the decay of B^{13} is mainly to the ground state of C^{13}, since the B^{12} decay is almost 100% to the ground state of C^{12}. Small percentages of betas to excited states of C^{13} would not be noticeable on spectra like those of fig. 2 and a more sensitive way of looking for such branches is to look for de-excitation γ-rays.

II. Half-life measurements.

The lifetime of the B^{13} activity was measured by a time to pulse height conversion technique. The pulses in the beta counter above a certain energy bias were converted into standard size pulses and compared with a linear sweep triggered by the 'beam off target' signal. The difference pulses were then fed into a kicksorter. Figure 3 shows measurements of the lifetime of the activity producing counts above 6 Mev energy dissipation in the beta counter. Shown are two typical runs on B^{13} and B^{12}. From these and several other measurements we determined the half-life of B^{13} to be 18.6 ± 0.5 msec. and that of B^{12} to be 21.6 ± 0.5 msec.. The error quoted is mainly due to uncertainty in relating the time during which the electronic gates are open (which is known accurately) to the number of channels on the kicksorter in which pulses from the time to pulse height converter arrive. This is because the ends of the time to pulse height conversion spectrum are not very sharply defined. The statistical errors are smaller. Thus the relative values of the B^{13} - B^{12} lifetimes are given accurately. The ratio of the B^{13} lifetime to that of B^{12} is equal to 0.86 ± 0.02. The third part of fig. 3 shows the 'lifetime' of random pulses as a check on the time to pulse height converter. There is a slight non-linearity over the width of the gate and the data was corrected for this. Previous measurements of the B^{12} lifetime[6] have a weighted mean of 20.65 ± 0.15 msec.. The most accurate measurement is that of Vedder who quotes $\tau\, 1/2 = 20.6 \pm 0.2$ msec.[7].

III. Gamma-ray measurements.

To determine beta branches to bound states of C^{13} other than that to the ground state, γ-ray spectra were recorded using the

NaI(ℓ) crystal. Fig. 4 shows the pulse height distribution due to B^{13} and B^{12} decays. From this B^{13} spectrum and others we find one observable γ-ray. The mean energy is 3.67 ± .02 Mev. This we interpret as due to a beta branch to the known 3.68 Mev level in C^{13}. The B^{12} spectrum shows the expected 4.43 Mev C^{12} γ-ray. The smooth background in both is due to bramstrahlung and neutrons. The problem of determining upper limits on beta branches to the other bound states in C^{13} at 3.09 Mev and 3.85 Mev is best tackled by looking at the spectrum of γ-rays in coincidence with betas, where clearer distributions should be obtained.

IV. Gamma-beta coincidence measurements.

Fig. 5 shows pulse height distributions of pulses in the γ counter in coincidence with pulses in the beta counter corresponding to dissipation of more than 1.5 Mev electron energy. These spectra can be fitted with a single γ-ray of energy 3.65 ± .05 Mev plus a background which has the same as the singles γ spectrum. This background is due to random coincidences which comprise some 35% of all the coincidence counts. The number of random coincidences was estimated from the counting rates and the coincidence resolving time, which was one microsecond. The randoms account for all pulses above the final peak due to the 3.65 Mev γ-ray. From the spectra of fig. 5 we place upper limits of 10% on any beta branches from B^{13} to the

3.85 Mev and 3.09 Mev states.

V. Relative intensity measurements

We must now determine the relative number of B^{13} decay that proceed to the ground and 3.68 Mev state in C^{13}. This was done in two ways. The most direct was to take spectra like those of figs. 2 and 4 at the same time. From such spectra the number of γ and beta rays observed together was extracted. Then using calculated values of the detection efficiencies of the plastic phosphor for the betas and the NaI(Tℓ) crystal for the γ's, the number of decays from the γ emitting state relative to the number of ground state beta particles was found. From this type of measurement we obtained the answer that 8.2 ± 2.5% of the decays proceed to the 3.68 Mev level, assuming no branch to higher unbound states. Any such branch will be very small and so will not affect the answer to any significant degree.

The second method which gave the relative intensity used the information contained in fig. 5. From these spectra the number of γ-rays in coincidence with a known number of beta rays was estimated. Knowing the γ-counter efficiency we again obtained the number of betas to the 3.68 Mev state relative to the total number of decays. From these measurements we obtained the value 6.5 ± 1.5%.

The value we take for the magnitude of the beta branch to the

3.68 Mev level in C^{13} is 7 ± 1.5%.

VI. Delayed neutron measurements

A search was made for beta branches to any of the higher unbound states in C^{13}. These will decay by neutron emission to the C^{12} ground state. The energy range in which one might observe neutrons is thus from 2 Mev to about 3 Mev, since the next state in C^{13} above the 3.85 Mev level is at 3.86 Mev. If delayed neutrons are present there will not be many of them, since the phase space factor will severely inhibit beta transitions to higher states relative to the higher beta energy transitions. It was decided to use a long counter in the search due to its insensitivity to bremmstrahlung. The use of say a plastic phospher to look for neutron-beta coincidences would remove this problem, since almost all of the bremmstrahlung goes in the same direction as the associated beta, but then counting rates would be so low as to make the experiment impractical. The method of search chosen was to put the long counter counts into the time to pulse height converter and to look for a decaying component in the resulting spectrum. From such a spectrum obtained at the same time as a beta spectrum, we could place un upper limit on the number of neutrons from the B^{13} relative to the total number of betas*. This gave the answer that less than 1.5% of the B^{13} decays

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* A detection efficiency of 5×10^{-4} was taken for the long counter in this calculation. The front face of the long counter was 3" from the source. This we think is a reasonable extrapolation of data on long counter efficiencies obtained by Nobles et al.[8]

proceed to neutron emitting states.

Summary of results

For convenience we gather together in Table 1 the results of this investigation. The energies of the C^{13} states are those quoted in Ref. [6]. The entry "% betas" gives the percentage of all B^{13} disintegrations that lead to the level in question. The log ft. values were computed from the measured lifetime for B^{13}, the end point beta energies were taken from Ref. [6] and the values for log f taken from the tables of Feenberg and Trigg [9]. The situation is summarised in fig. 6 which shows the decay scheme obtained in this experiment together with the known positions and properties of the levels of C^{13} up to 9 Mev excitation energy.

Discussion

The transitions to the $1/2^-$ ground state and $3/2^-$ 3.68 Mev state in C^{13} are allowed. The parity of the B^{13} ground state is thus negative and its spin is limited to 1/2 or 3/2. In independent particle terms B^{13} can be looked upon as three holes in the p shell. In pure j-j coupling the ground state is expected to be $3/2^-$. In pure L - S coupling states of $1/2^-$ and $3/2^-$ are degenerate. A calculation by J. W. Murphy of this laboratory shows that in the intermediate region the state of spin 3/2 is always lower. We thus conclude that the ground state of B^{13} is $3/2^-$.

Since the ground state of B^{13} is $3/2^-$ the transitions to the $1/2^+$ and $5/2^+$ states in C^{13} are forbidden, in agreement with our results. The transitions to the $1/2^-$ and $3/2^-$ levels are quite strong. The log ft value of 4.01 for the ground state transition indicates that B^{13} is well described by a single particle wave function, since we know that the ground state of C^{13} has the ground state of C^{12} as its predominant parent [10]. The larger log ft of 4.53 for the transition to the $3/2^-$ level in C^{13} is not surprising since this state arises from the more complex configuration$(p\ 3/2)^7(p\ 1/2)^2$, i.e. $(p\ 3/2)^{-1}\ (p\ 1/2)^2$.

From this j-j configuration also arises a $5/2^-$ state which is predicted by intermediate coupling calculations to lie around 5 - - 6 MeV excitation in C^{13} [4]. Such a level probably does not exist in C^{13} below about 7.0 Mev *. It could be one of the triplet around 7.5 Mev observed in the $C^{12}(d,p)C^{13}$ reaction [12]. The corresponding levels in N^{13} have now all been observed in the elastic [16] and inelastic scattering [17] of protons by C^{12}. The only one whose spin and parity are not firmly established is that at 7.21 Mev in N^{13}.

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* The levels shown at 5.51 and 6.10 MeV in C^{13} in ref.[6] and also in the latest energy level compilation,[11] are believed not to exist. More work on the $B^{11}(He^3,p)C^{13}$ reaction by groups at Aldermaston[13], on the total neutron cross section for C^{12} at the Argonne Laboratory in the U.S.A.[14], and on the reaction $N^{14}(He^3,\alpha)$ at Harwell[15] shows that it is impossible that there is a level in C^{13} between the 3.85 MeV and 6.86 MeV levels.

The fact that it is observed in the elastic scattering process argues against it being the $5/2^-$ since this latter level should have a very small width for emission of a proton with three units of angular momentum to the C^{12} ground state.

Let us assume that the $5/2^-$ level is around 7.5 Mev in C^{13}. We might then expect a beta branch to it from B^{13} with roughly the same intrinsic strength as the branch to the $3/2^-$ level. This leads to an estimate of the actual beta branch as about 1% of the decays. Having been formed, the 7.5 Mev level will decay by neutron emission to the C^{12} ground state. (Again the width of this level for emission of a neutron to the C^{12} ground state will be small, since it arises from nucleons in the p shell. However, even if the ratio of the reduced neutron width to the single particle estimate were as low as 10^{-5}, the neutron width Γ_n would be greater than a sensible estimate of the competing γ-ray width Γ_γ, assuming this to be due to a strong E1 transition from the $5/2^-$ to the $5/2^+$ level at 3.85 Mev. If Γ_γ were greater than Γ_n or if the $5/2^-$ level were lower in energy than 7.5 Mev, which would tend to make Γ_γ greater than Γ_n, the level should manifest itself by producing 3.85 Mev γ-rays. Our upper limit on decays producing these is lower than that for decays producing delayed neutrons). Hence we may hope to observe the $5/2^-$ level via the delayed neutrons which may occur durinf the B^{13} decay. Our result in this experiment is inconclusive. The upper limit on the branching to levels in C^{13} higher than 6 Mev is not low. Reduction of the neutron background in a further experiment might make observation of delayed neutrons feasible. Our upper limit on 3.85 Mev γ-rays has a bearing on the existence or non-existence of the $5/2^-$ level around 5 - 6 Mev.

If it were there it would mean that the matrix element for the beta decay to it from B^{13} was a factor of three smaller than that for the decay to the $3/2^-$ state; log ft $\gtrsim$ 5.0 compared with log ft = 4.53.

It would be instructive to use the intermediate coupling model wave functions of Kurath[4] to predict ft values of the various B^{13} decays. If the model continued to give a good description of many features of the negative parity levels in the mass 13 nuclei it would be puzzling indeed why it did not do so for the $5/2^-$ level.

* * *

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* * *

TABLE I

C^{13} state (MeV)	E (MeV)	% betas	log ft	E (MeV)	Half-life (m sec.)
0	13.40±0.2	93	4.01		18.6±0.5
3.09		≤ 0.7	≥5.7		
3.68		7	4.53	3.67±0.02	
3.85		≤ 0.7	≥5.5		
6.86					
7.47		≤ 1.5	≥4.2		
7.53					
7.64					

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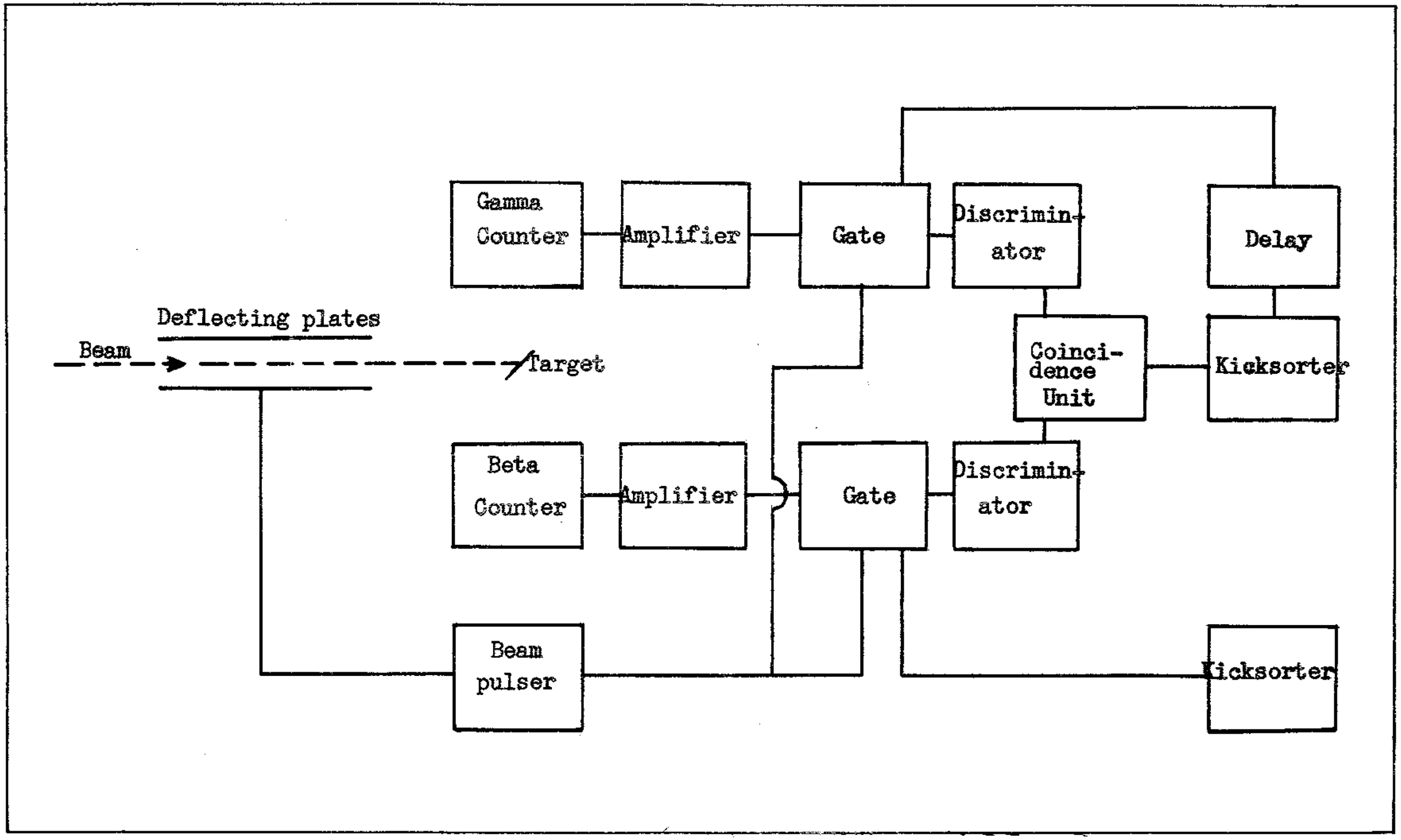
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Target
Gamma Counter
Amplifier
Gate
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Coinci-dence Unit
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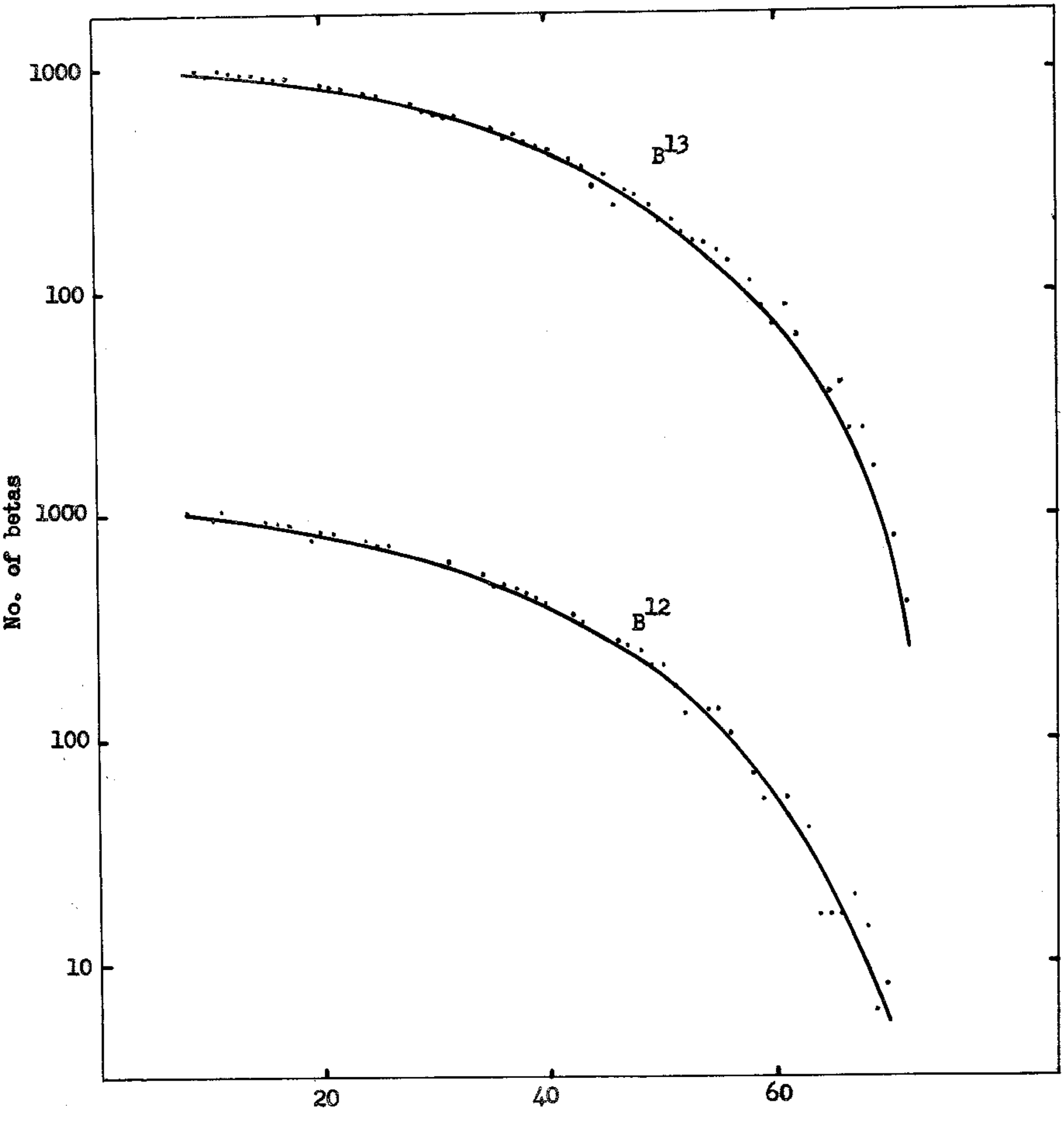
Beta Counter
Amplifier
Gate
Discrimin-ator
Beam pulser
Kicksorter

Fig. 1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1000
100
10
No. of betas
B^{13}
B^{12}
20
40
60
KICKSORTER CHANNEL

Fig. 2

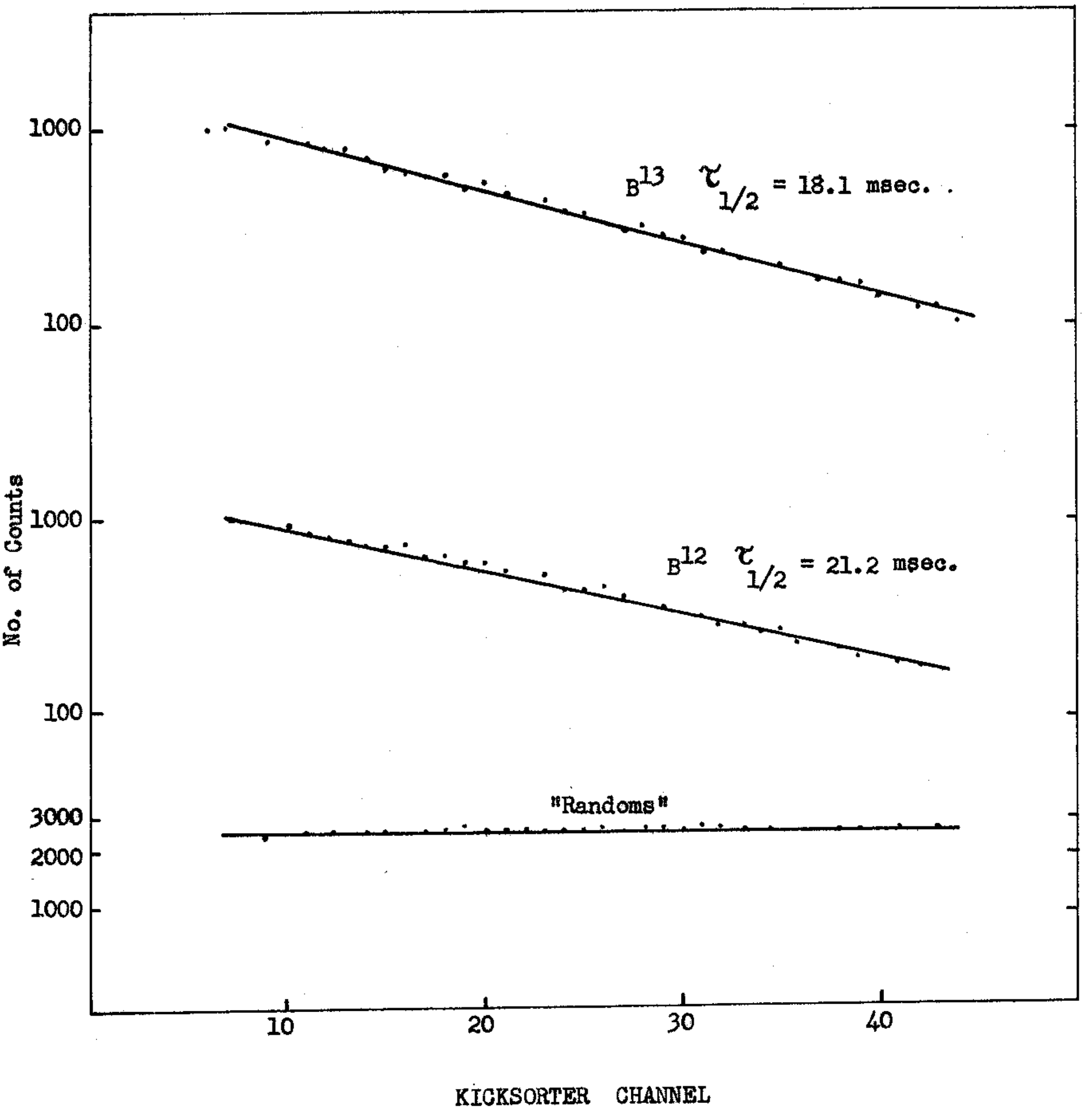
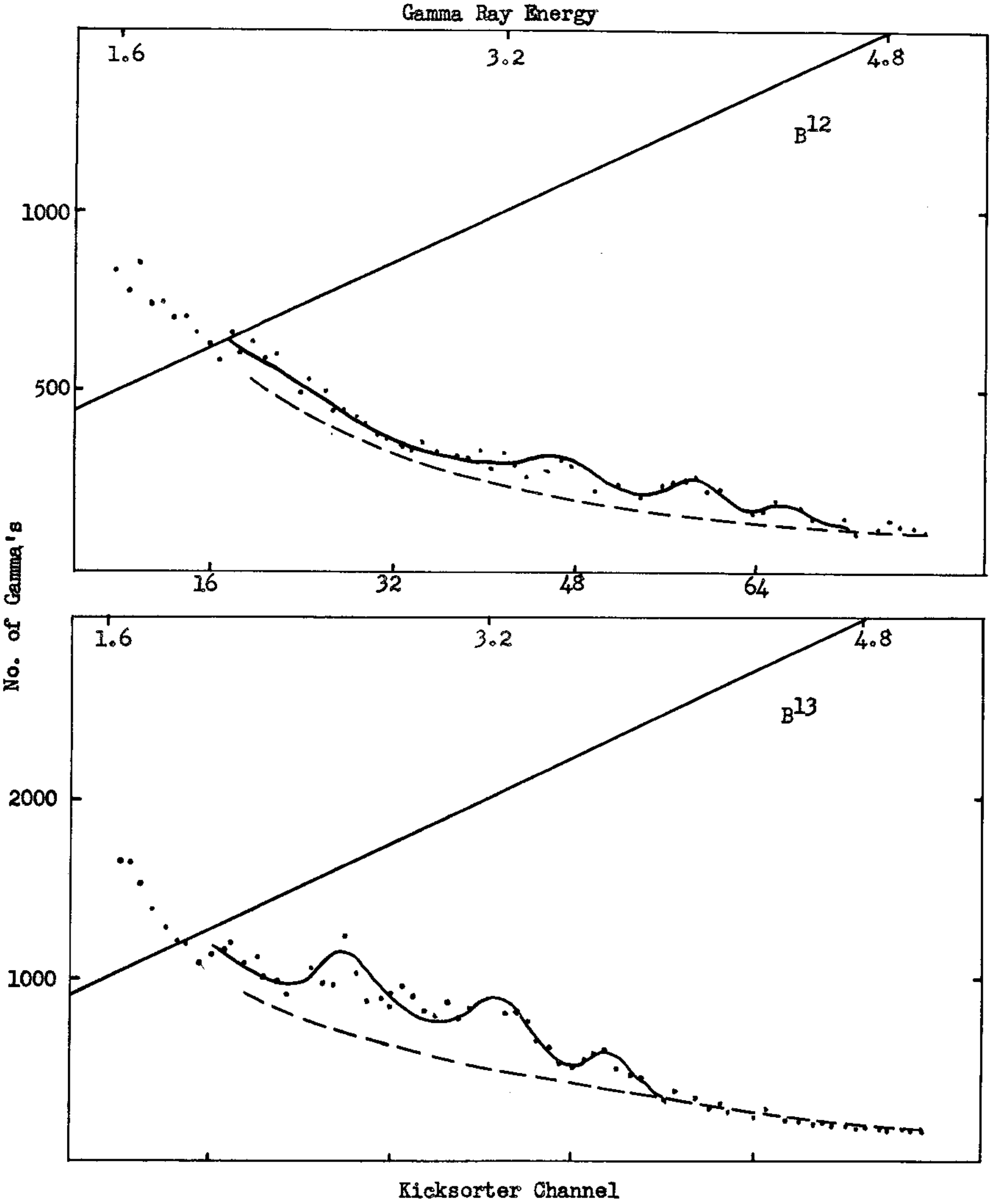

No. of Counts
1000
100
1000
100
3000
2000
1000
B^{13} $\tau_{1/2}$ = 18.1 msec.
B^{12} $\tau_{1/2}$ = 21.2 msec.
"Randoms"
10
20
30
40
KICKSORTER CHANNEL

Fig. 3


Gamma Ray Energy
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3.2
4.8
B12
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48
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No. of Gamma's
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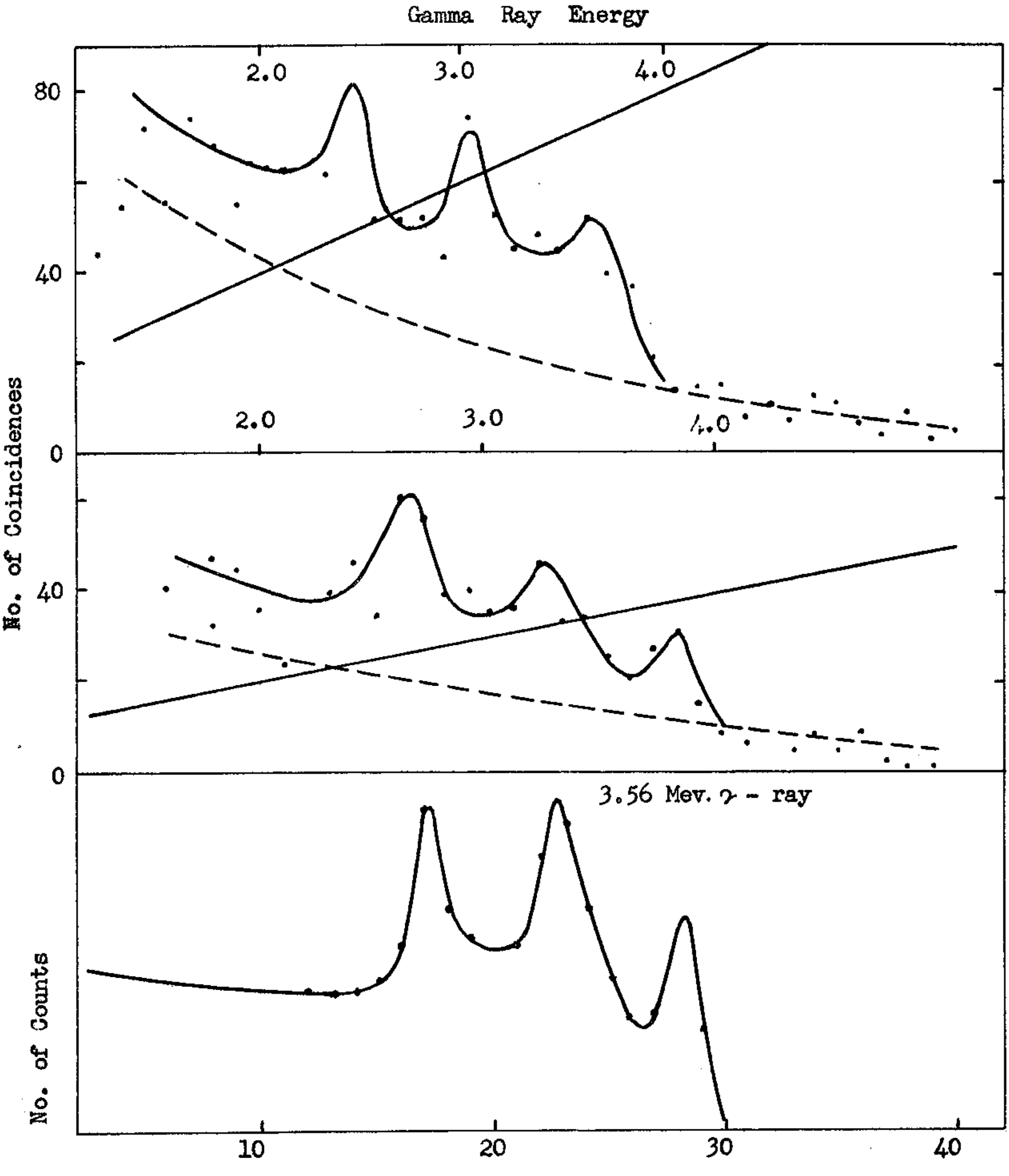
3.2
4.8
B13
2000
1000
Kicksorter Channel

Fig. 4


Gamma Ray Energy
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3.0
4.0
80
40
0
2.0
3.0
4.0
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0
3.56 Mev. γ - ray
No. of Counts
10
20
30
40
Kicksorter Channels

Fig. 5

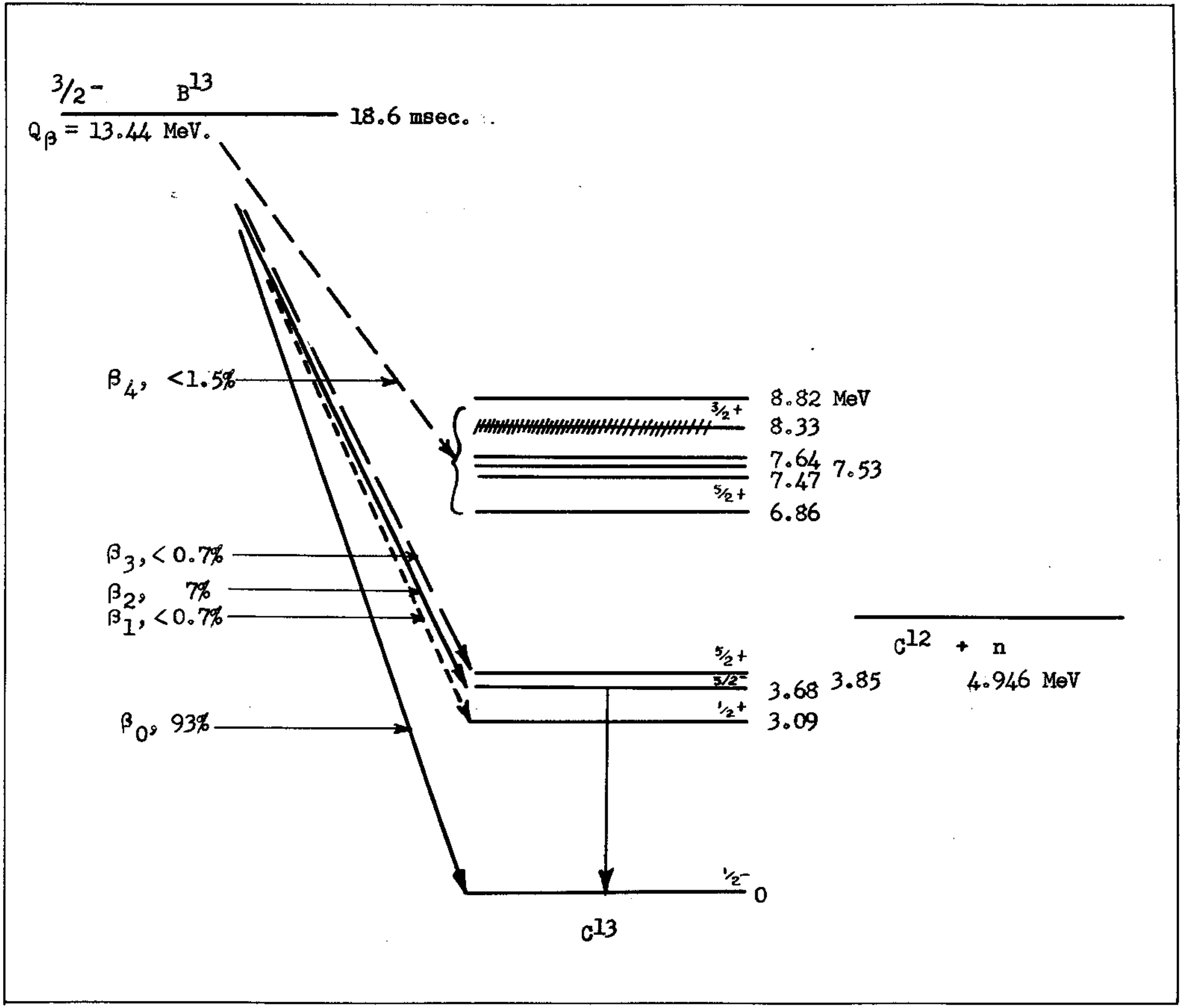
3/2−
B13
Qβ = 13.44 MeV.
18.6 msec.
β4, <1.5%
β3, < 0.7%
β2, 7%
β1, < 0.7%
β0, 93%
8.82 MeV
3/2+
8.33
7.64
7.53
7.47
5/2+
6.86
C12 + n
4.946 MeV
5/2+
5/2−
3.68
3.85
1/2+
3.09
1/2−
0
C13

Fig. 6