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June 1985

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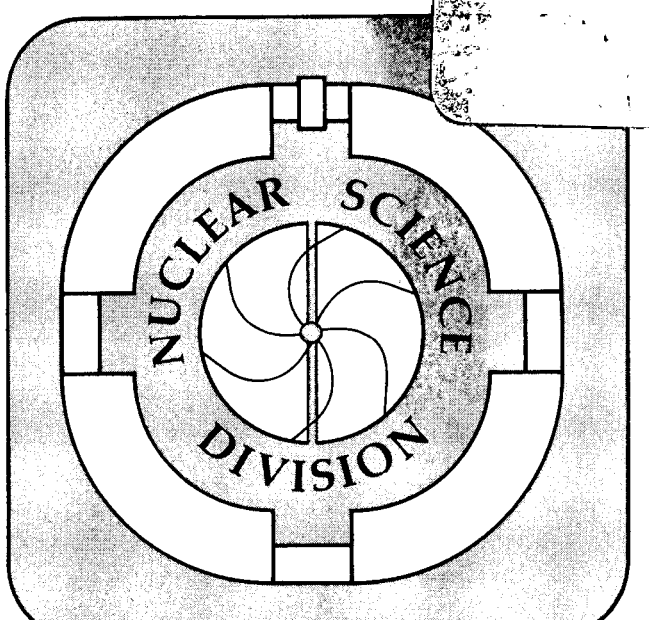

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BETA-DELAYED PROTON DECAYS OF ^{27}P and ^{31}Cl: A STUDY OF GAMOW-TELLER DECAYS WITH LARGE Q-VALUES*

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ABSTRACT:

The beta-delayed proton emissions of the odd-Z, $T_z = -3/2$ nuclei ^{27}P and ^{31}Cl have been studied. This work represents the first observation of the decay of ^{27}P, yielding a half-life of 260 ± 80 ms, and completes the series of beta-delayed proton emitters with $T_z = -3/2$ in the sd-shell. Several new proton groups were attributed to the decay of ^{31}Cl; their half-lives are consistent with a previous observation. The estimated log ft values of the observed transitions for both ^{27}P and ^{31}Cl are consistent with clustering of the beta strength above the isobaric analog states in the daughter nuclei as predicted by a complete (1s,0d)-space shell-model calculation. The observed half-lives are in good agreement with the shell-model predictions. The present results suggests a quenching of the Gamow-Teller strength by a factor of 0.6, in accordance with earlier observations.

RADIOACTIVITY: $^{28}Si(p,2n)^{27}P$ and $^{32}S(p,2n)^{31}Cl$ at $E_p = 45$ MeV; $T_z = -3/2$ nuclei; measured $T_{1/2}$ and beta-delayed proton activity; deduced beta branching and log ft values; analysis with full-space $d_{5/2}$-$s_{1/2}$-$d_{3/2}$ shell-model wave functions.

INTRODUCTION

Intense beta-delayed proton emission associated with superallowed beta decay to the isobaric analog state has offered a unique way of establishing the existence and decays of several $T_z = -3/2$ and -2 nuclei[1,2]. The latest observations have been the discoveries of the β-delayed single-proton and two-proton decays from ^{22}Al and ^{26}P nuclei[3]. Even with the observation of ^{26}P, the decay of the heavier isotope ^{27}P remained undiscovered. Difficulties encountered in earlier searches for ^{27}P decay resulted from a very low predicted total branching ratio ($\sim 10^{-4}$) for the beta-delayed protons and from severe background problems which hindered investigation of its beta/gamma spectroscopy. Fast on-line mass separation techniques would be required for any beta/gamma measurements on phosphorus and these have yet to be developed. The ^{27}P system belongs to the group of odd-Z, $T_z = -3/2$ nuclides which are quite weak delayed proton precursors because the isobaric analog states in the daughter nuclei are practically bound against particle emission. These nuclides, ^{23}Al (Ref. 4), ^{31}Cl (Refs. 5 and 6) and ^{35}K (Ref. 7) belonging to the same series, have been discovered previously via their beta-delayed proton emission and, in the case of ^{35}K, via its beta-delayed gamma-decay as well.

Although phase space factors favor beta decay to lower lying states in these nuclei, the predicted existence of a cluster of states which lie above the isobaric analog state and which incorporate a major part of the total beta strength from the parent suggests that the beta-delayed proton measurements present an attractive opportunity to

detect these decays. Specifically, predictions of the Gamow-Teller beta decay for sd-shell nuclei[8,9], based on full space $d_{5/2}$-$s_{1/2}$-$d_{3/2}$ shell-model wave functions[10], indicate that more than half of the predicted Gamow-Teller strength in the decays of both ^{27}P and ^{31}Cl lies above the isobaric analog state (IAS). In this work we have exploited this feature to measure the hitherto unknown beta-delayed proton decay of ^{27}P and additional features of the decay of ^{31}Cl.

EXPERIMENTAL

Proton beams with energies from 28 to 50 MeV and intensities of 4 μA from the Lawrence Berkeley Laboratory 88-Inch Cyclotron were used to produce beta-delayed proton emitters of interest from natural Si targets (50 mg/cm^2) and from ZnS targets (2 mg/cm^2). Reaction products from five adjacent target foils were thermalized in 1.5 atm of helium and were subsequently swept through a capillary system that consisted of five short (3 cm) capillaries connected to the main 1.27 mm diameter and 70 cm long capillary tube. To minimize losses of the short-lived activities of interest, they were collected on a rotating wheel directly in front of the detector telescope system as shown in Fig. 1. The detector system consisted of an 8.3 μm, 50 mm^2 ΔE, a 68 μm, 100 mm^2 E and a 200 μm, 300 mm^2 E_{rej} detectors. The third detector served both as a means to detect protons with energies above 2.7 MeV and as a reject counter for positron associated events. The latter operating feature was especially useful in discriminating against the beta-^{16}O events resulting from the beta decay of ^{20}Na. The overall resolution of the telescope for protons was 75 keV.

Half-lives for the beta-delayed particle activities were measured by varying the speed of the rotating catcher wheel. The observed yield thus varies with the half-life and the effective counting time as determined by the wheel speed. Simultaneously produced activities such as ^{8}B, ^{20}Na, ^{28}P or ^{32}Cl, which have known half-lives, were used as references.

RESULTS

The p + Si Reaction and the Decay of ^{27}P

Beta-delayed proton spectra obtained in proton bombardments of silicon targets at 28 and 45 MeV are shown in Fig. 2. The bombardment energy in Fig. 2(b) was chosen to be below the 30.7 MeV production threshold for ^{27}P while still providing an energy and efficiency calibration for the telescope system using the ^{28}P activity[11] and later also the ^{32}Cl activity[11]. The lower spectrum represents a pure beta-delayed proton spectrum of ^{28}P consistent with the results of Ref. 11. As can be seen in Fig. 2(a), the 45 MeV bombardment resulted in two additional proton groups labeled 1 and 2: an intense group at 730 keV and a weaker group at 1325 keV. No contribution from the ^{24}Al-activity produced in (p,αn) reactions is seen because ^{24}Al is only a weak β-delayed alpha emitter.

The new groups were found to decay with a half-life of 260 ± 80 ms. This value was obtained by comparing the intensities of the proton groups with the intensity of the 4438 keV beta-delayed alpha group of ^{20}Na (Ref. 12) with catcher wheel speeds of 7, 10, 15 and 31 cm/s.

This activity was produced simultaneously via the $^{28}Si(p,2\alpha n)$ reaction; its production threshold is 35.2 MeV. A similar analysis yielded a half-life of 250 ± 50 ms for the 956 keV group (p_4) of ^{28}P, consistent with the adopted value of 268 ms [12]. The assignment of the observed proton groups to ^{27}P was based primarily on yield measurements performed at 28 and 45 MeV bombardment energies, and on the observed half-life, which is consistent with the upper value of 330 ms obtained from simple calculations assuming a log ft of 3.30 for the superallowed decay of ^{27}P and known log ft values for the first two allowed decays of its mirror nucleus ^{27}Mg (Ref. 12).

Table 1 gives a summary of the observed proton groups of ^{27}P. The derivation of excited state energies in ^{27}Si is based on the assumption that protons decay to the 0^+ isomeric state in ^{26}Al (Refs. 12,13) [see later discussion and Figure 3]. The overall beta branching to proton emitting states in ^{27}Si can be estimated to be 5×10^{-4} from the effective production cross section ratio of ^{27}P and ^{28}P at 45 and 28 MeV, respectively, and as given by the ALICE code[14]. This deduced branching value and the measured 260 ms half-life results in a log ft value of 4.7 for the 730 keV group indicating allowed character for the preceeding beta-transition.

A partial decay scheme for ^{27}P is presented in Fig. 3. Its ground state spin and parity of $1/2^+$ are based on its mirror nucleus ^{27}Mg (Ref. 15). Both of the observed proton groups are assigned to transitions leading to the 0^+ state at 228 keV excitation in ^{26}Al. The deduced beta branchings to the proton unbound states suggest that these decays are allowed. This restricts the spin-parity of these

states to $1/2^+$ or $3/2^+$. Barrier penetrability calculations alone favor an $l = 0$ or 2 transition to the 0^+ state by a factor of more than 10^3 relative to an $l = 4$ transition to the 5^+ ground state. Additional support for decay to the 0^+ final state is given by a recent proton capture study on the 5^+ ground state of ^{26}Al which revealed several excited states in the energy region studied here[16]. However, from their measured spin-parity values and excitation energies, none of these states correspond to either of the states observed in the β-decay of ^{27}P.

By assuming a log ft of 3.30, the upper value for the T = 3/2 superallowed decay, one obtains a value of about 17 percent for the beta branching to the analog state. Calculations with the shell-model wave functions of Ref. 10 indicate the Gamow-Teller strength in this superallowed transition is negligible. The same calculations also predict that a sizable fraction of the allowed beta strength lies just above the IAS and is thus missed in the present delayed proton experiment.

The p + S Reaction and the Decay of ^{31}Cl

Beta-delayed proton spectra obtained in the proton bombardments of ZnS targets at 28 and 45 MeV are shown in Fig. 4. Again, the bombarding energy in Fig. 4(b) was chosen just below the production threshold of the next lighter isotope ^{31}Cl. All six known proton groups of ^{32}Cl can be found in this spectrum. The spectrum of Fig. 4(a) shows the appearance of 8 additional proton groups when the bombarding energy

is increased to 45 MeV. The strongest peak at 986 keV consists of a 23 percent contribution from the 991 keV group of ^{32}Cl as deduced from the intensity ratio of the 991 keV (p_2) and the 1324 keV group (p_4) of ^{32}Cl at these two energies. The energies of the groups labeled 2 and 4 in Fig. 4(a) agree well with the observations in Refs. 5 and 6. No evidence of a contribution from the very weak β-delayed proton activity ^{28}P is seen in the spectra. The assignment of the additional new groups 1, 3 and 5-8 to the ^{31}Cl beta-delayed proton decay is based primarily on the yield measurements at the two bombarding energies and on the agreement with the earlier observed half-life of 150 ± 25 ms[5].

Table 2 shows a summary of the observed proton groups associated with the decay of ^{31}Cl. The excitation energies of the proton-emitting states in ^{31}S are based on the assumption that the proton decay proceeds to the 1^+ ground state of ^{30}P [12,15] (see later discussion and Fig. 5). Overall beta-branching to proton-emitting states in ^{31}S can be estimated to be 7×10^{-3} from the effective production cross section ratio of ^{31}Cl and ^{32}Cl at 45 and 28 MeV, respectively, and as given by the ALICE code. As an example, this value corresponds to a log ft value of 4.5 for the most intense group. Similarly, the other observed groups can be shown to have allowed character.

Possible beta-delayed proton emitters produced via 45 MeV proton bombardment on Zn in the targets can be ruled out. The only precursor that can be produced is ^{62}Ga. However, the high Coulomb barrier and

the small energy window available for the proton decay, since Q_{EC} = 9171 keV and S_p = 6480 keV, exclude this possibility[5,13].

A partial decay scheme of ^{31}Cl is shown in Fig. 5. Its assumed spin and parity are again based on its mirror nucleus ^{31}Si. The spectrum of low-lying excited states in ^{30}P and the Q-value together suggest that all the observed proton groups arise from transitions to its 1^+ ground state. The log ft values deduced for these transitions are between 4.5 and 5.9 (compare Table 2) which indicates spin-parity assignments of $1/2^+$, $3/2^+$, or $5/2^+$ for the proton unbound states. The superallowed decay to the isobaric analog state at 6277 ± 25 keV[15] can be estimated to correspond to ~18 percent branching of the total beta decay. Several excited states which lie above the analog state are known in ^{31}S and have energies which are consistent with the energies observed in this work. However, the lack of reliable spin-parity assignments for these states makes comparison with our results difficult.

DISCUSSION

The experimental study of Gamow-Teller beta decay is important to a fundamental understanding of nuclear structure. The mediator of Gamow-Teller transitions, an operator which flips both spin and isospin, is particularly simple and restrictive in its action. Hence the values of its matrix elements can be related to specific properties of wave functions with relative clarity. At the most detailed level, a given partial half-life, or the equivalent reduced strength, provides

information about the degree of overlap between individual initial and final nuclear states. At a more comprehensive level, when Q-values provide access to a significant range of excitation energies, the distribution of matrix element values versus energy, the "Gamow-Teller strength function", provides information about the global response of the parent wave function to spin-isospin excitation. Finally, the integrated beta decay strength, when properly analyzed, can be related to the general properties of nuclear wave functions or even of the constituent nucleons themselves.

In each of these contexts, the full import of the experimental data must be extracted by analysis with theoretical models of the relevant wave functions. Only with such analyses can the observed magnitudes be quantitatively related to the questions at issue. It is critical when making analyses with shell-model wave functions to use model spaces which incorporate both members of all spin-orbit pairs. Aside from recoupling within a given orbit, the only allowed transitions of the Gamow-Teller operator are the spin flips between the $j = l + 1/2$ and $l - 1/2$ states of a given orbit. Without these degrees of freedom in the model transition densities, the predicted strengths will be unrealistic.

The present data are analyzed with wave functions from a unified calculation of all sd-shell states[10]. The model spaces for these calculations always incorporate the full set of $d_{5/2}$-$s_{1/2}$-$d_{3/2}$ configurations and the model Hamiltonians for all nuclei originate from a single formulation. We generated wave functions with this approach for the $T = 3/2$ ground states of the $A = 27$ ($J = 1/2$) and 31 ($J = 3/2$)

nuclei and all of their possible daughter states which fell within the Q-value windows of the decays. From these wave functions we calculated the matrix elements of the $\sigma\tau$-operator for each possible transition. The conventional prescription for the Gamow-Teller strength B(GT) is to multiply the $\sigma\tau$-strength by the factor $(g_a/g_v)^2 = 1.51$, where g_a/g_v is the ratio of the axial-vector to vector coupling constants for the free neutron decay. The ft value is then equal to 6170/[B(F) + B(GT)], where B(F) is the Fermi strength.

Most measured Gamow-Teller decays in the light nuclei occur near the valley of stability and are characterized by small Q-values. The strengths of these transitions have been analyzed with shell-model wave functions from the calculation just described[8,9]. The conclusion which is drawn from these analyses is that there is a systematic difference in scale between the measured values and the values calculated from the matrix elements of the $\sigma\tau$-operator with the normalization specified above. The theoretical strengths are too large by a factor of 1.70 ± 0.03 on the average or, equivalently, the experimental strengths are quenched below the initial theoretical expectations by a factor of 0.60 ± 0.03. This observed quenching is consistent with the results of the recent generation of medium energy (p,n) experiments and is also consistent with the results of detailed theoretical analysis of the effects upon the shell-model strengths of higher-order core polarization, mesonic-exchange currents and nucleon excitation.

The present data provide important information about the theoretical issues of the energy distribution of Gamow-Teller strength and the domain of validity of the quenching of such strength. The key

feature which give these and similar data their importance in these contexts is their large Q-values. Typical allowed beta decays occur with small Q-values and hence only the lowest few levels in the daughter systems are sampled. The dominant spin-flip nature of the Gamow-Teller process implies, however, that most of the transition strength is to be found at an excitation energy characteristic of the spin-orbit splitting, about 7 to 10 MeV in the sd shell. Presumably as a consequence of this fact, the typical matrix elements for the decays to low-lying states account for only a small fraction of the total allowed strength. The model predictions of these small (highly cancelled) matrix elements are inevitably very sensitive to small defects in the chosen Hamiltonian.

Hence, the postulation of a universal quenching factor based on model predictions for such small matrix elements must be subjected to further tests, ideally ones in which the dominant portion of the strength is sampled. The importance of the medium-energy (p,n) simulations of Gamow-Teller processes stems from their capability to sample this dominant strength. However, the (p,n) simulations are subject to other uncertainties in the region of dominant strength, and at best offer only an approximation to the rigorousness of our understanding of the actual weak decays. Gamow-Teller decays with large Q-values, such as we have with the present ^{27}P and ^{31}Cl decays, offer the chance to determine whether the energy distribution of the dominant portion of the strength agrees with prediction and whether, in the context of these predictions, the integral of such strength is consistent with the properties of the weaker, low-lying states.

The shell-model predictions of the energy distribution of Gamow-Teller strength for the ^{27}P and ^{31}Cl decays are shown in Figs. 6 and 7. The strength predicted to fall within each 250 keV energy bite is summed and these values plotted as histograms. The values shown are the normal GT strengths multiplied by the factor 0.6 obtained from analysis of the low-lying beta decays in this region, as discussed. In each spectrum we see that the dominant portion of the strength is centered near 8 MeV, with a width of about 3-4 MeV. Some of the difference in appearance in the two spectra is due simply to the fact that the ^{27}P decay can access only 1/2+ and 3/2+ states, while the ^{31}Cl decay can proceed to 1/2+, 3/2+ and 5/2+ states. The relatively low density of 1/2+ states accentuates the difference. The predicted values of the half-lives which correspond to these plots (with the appropriate Fermi strength factored in) are $T_{1/2}$ = 215 ms for ^{27}P and 159 ms for ^{31}Cl.

These predictions can be tested by our present data, but only incompletely, since direct observation of major portions of the spectra is blocked on the low-excitation-energy side by the proton-stability threshold and on the high-excitation-energy side by the Q-value limit and the practical consequences of the dependence of observed decay rates upon the energy release. Hence, the data give us two basic types of information. One, the half-life, is an integral over all decays within the Q-value window. Disagreement between theoretical and experimental half-lives says that the theory has failed, but does not say exactly how. Maybe the assumed overall quenching factor does not

extrapolate to the states at higher excitation energy, maybe the predicted energy distribution of the strengths is incorrect, so that the strong energy dependence in the decay probability formula produces the incorrect half-life, or maybe the model wave functions just do not predict the correct amount of strength overall for these particular cases.

Agreement between prediction and experiment for the half-life could mean that all of these facets of the theory are correct, but could also result from a fortuitous cancellation between compensating errors in the predictions. The presently measured half-lives for these decays, 260 ± 80 ms for ^{27}P and 150 ± 25 ms for ^{31}Cl, are in reasonably good agreement with our predictions of 215 ms and 159 ms, respectively. The dominant sources of the half-life values are the lowest few states, for which the energy release factor outweighs the intrinsic weakness of their matrix elements, and the analog state, with its large Fermi component. The contributions of the large strengths at higher excitation energies yield important corrections to these two dominant sources. With all of these states factored in, the quenching factor of 0.6 clearly produced better agreement with experiment than would be obtained with the conventional normalization.

The second type of information from the present experiment with which theory can be tested comes from the events with which we detected and measured the decay of these nuclei, the beta transitions to the window of proton-decaying states which lie above the isobaric analog states. The plots of the observed GT strength are shown in comparison to the predictions in Figs. 6 and 7. For ^{27}P, relatively little strength is predicted to fall within the window of observability, which

runs from about 8 to 10 MeV. The measured transitions are consistent with the predicted strength in the same range, but the lack of distinct character in the model spectrum in this region and the experimental problems of background and statistics make it impossible to go beyond this qualitative statement. It would be valuable to be able to test directly, rather than through the medium of the half-life, whether the larger amount of strength which is predicted between 6 and 8 MeV is actually there. Nonetheless, the level of agreement which is established with the present data is important in that it confirms the existence of significant Gamow-Teller strength well above the isobaric analog state. If there were appreciably less strength at this energy, the present technique would have failed to detect the decay at all.

More strength is predicted to fall within the window of observability for ^{31}Cl and more transitions are observed experimentally. Again, the data are consistent with prediction, but the level of quantitative certainty is greater than for ^{27}P. It is not to be expected that there will be one-to-one correspondences between model and experimental levels at this excitation energy, which corresponds to energies of the tenth to the twentieth states of a given J for T = 1/2 levels. The successful theory should have, first, the observed amount of strength, second, this strength appearing at the observed energies, and, third, the number of levels (or fewer) than those observed. In this context, the agreement between prediction and experiment is quite good, as was the complementary test via the half-life. Underpinning both comparisons is the assumed quenching factor for the model Gamow-Teller strength.

Further experimental progress in elucidating these decays will provide additional details needed to throughly test our theoretical understanding of these type of phenomena. The present results and their analysis suggest that there will continue to be a fruitful interchange of theoretical and experimental progress in this area.

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Table 1. Proton groups observed in the beta decay of ^{27}P.

Peak Number	E_p(Lab) (keV)	Excitation Energy in ^{27}Si (keV)[a]	Relative Intensity
1	730 ± 10	8451 ± 10[b]	100 ± 5[c]
2	1325 ± 30	9069 ± 30	6 ± 3

[a] Based on S_p = 7464.4 ± 0.4 keV (Ref. 13) and on the 0^+ final state at 228.2 keV in ^{26}Al.

[b] A Transition from the 8.45 MeV state to the 5^+ ground state of ^{26}Al would correspond to a laboratory energy of 950 keV; this transition cannot be completely excluded because of the appearance in our spectra of the strong 956 keV group from ^{28}P, as seen in Fig. 2.

[c] Estimated $I_\beta = 4.6 \cdot 10^{-4}$ and log ft = 4.7; see text.

Table 2. Proton groups observed in the beta decay of ^{31}Cl.

Peak Number	E_p (Lab) in keV This Work	Ref. (6)	Excitation Energy in ^{31}S (keV)[a]	Relative Intensity
1	845 ± 30		7000 ± 30	3 ± 2
2	986 ± 10	989 ± 15	7147 ± 8	100 ± 2[b]
3	1173 ± 30		7339 ± 30	3 ± 2
4	1520 ± 15	1528 ± 20	7701 ± 12	23 ± 6
5	1695 ± 20		7879 ± 20	10 ± 3
6	1827 ± 20		8015 ± 20	13 ± 4
7	2113 ± 30		8311 ± 30	7 ± 3
8	2204 ± 30		8405 ± 30	6 ± 3

a) Based on $S_p(^{31}S)$ = 6126.8 ± 2.3 keV (Ref. 13)

b) Estimated $I_\beta = 4.4 \cdot 10^{-3}$ and log ft = 4.5; see text.

FIGURE CAPTIONS

Fig. 1. Collection and counting set-up for the beta-delayed particle activities. The effective solid angle subtended by the telescope is 4 percent of 4π.

Fig. 2. Proton spectra arising from the bombardments of Si targets with (a) 45 MeV and (b) 28 MeV protons corresponding to integrated beam currents of 330 and 110 mC, respectively. Exact intensities and energies of the labeled peaks in the ^{28}P spectrum can be found in Ref. (11). The lower energy cut-off is slightly below 700 keV. This can be seen from the weak appearance of the 680 keV proton group p_2 in (b), which was the strongest proton group observed in Ref. (11).

Fig. 3. Proposed partial decay scheme of ^{27}P. Decays which have not been directly seen are indicated as dashed lines.

Fig. 4. Delayed proton spectra arising from bombardments of ZnS targets with (a) 45 MeV and (b) 28 MeV protons corresponding to integrated beam currents of 90 mC and 40 mC, respectively. Intensities and energies of the labeled peaks in the ^{32}Cl spectrum can be found in Ref. (11). Energies and intensities of the ^{31}Cl-related groups are given in Table 2.

Fig. 5. Proposed partial decay scheme of ^{31}Cl. Decays without a direct observation are indicated as dashed lines.

Fig. 6. Gamow-Teller strength distribution for the beta decay of ^{27}P. Theoretical distribution (a) is from the shell-model calculation. Experimental distribution (b) displaying only a part of the strength, is from the beta-delayed proton experiment. Symbols IAS, S_p and Q_{EC} denote the energy of the $T = 3/2$ isobaric analog state, the proton separation energy and the total decay energy available in the beta decay, respectively.

Fig. 7. Theoretical (a) and observed (b) Gamow-Teller strength distributions for the beta decay of ^{31}Cl. Only a part of the total strength can be seen in the experiment on the β-delayed protons. See also the caption in Fig. 5.

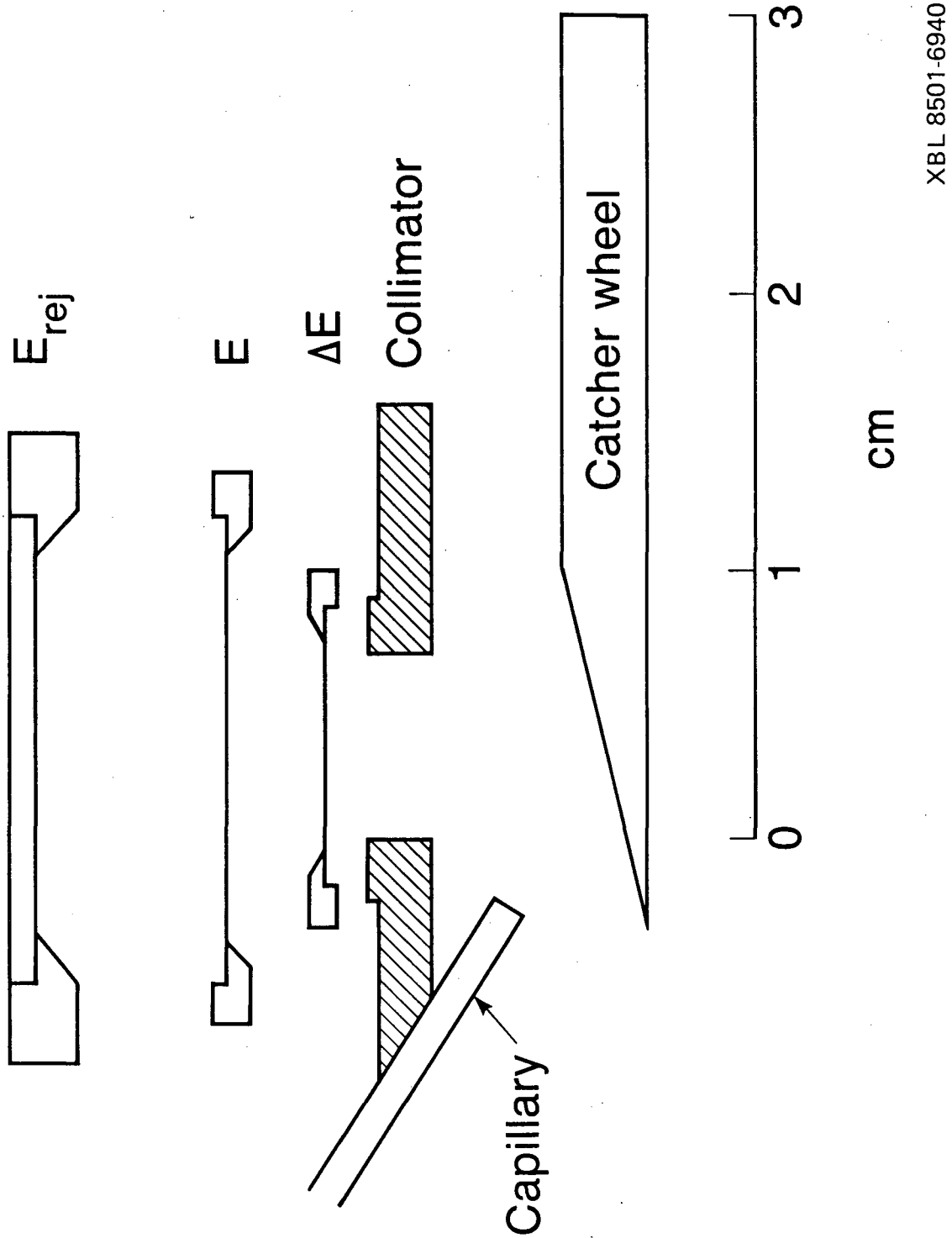

E_{rej}
E
ΔE
Collimator
Catcher wheel
Capillary
0
1
2
3
cm
XBL 8501-6940

Fig. 1

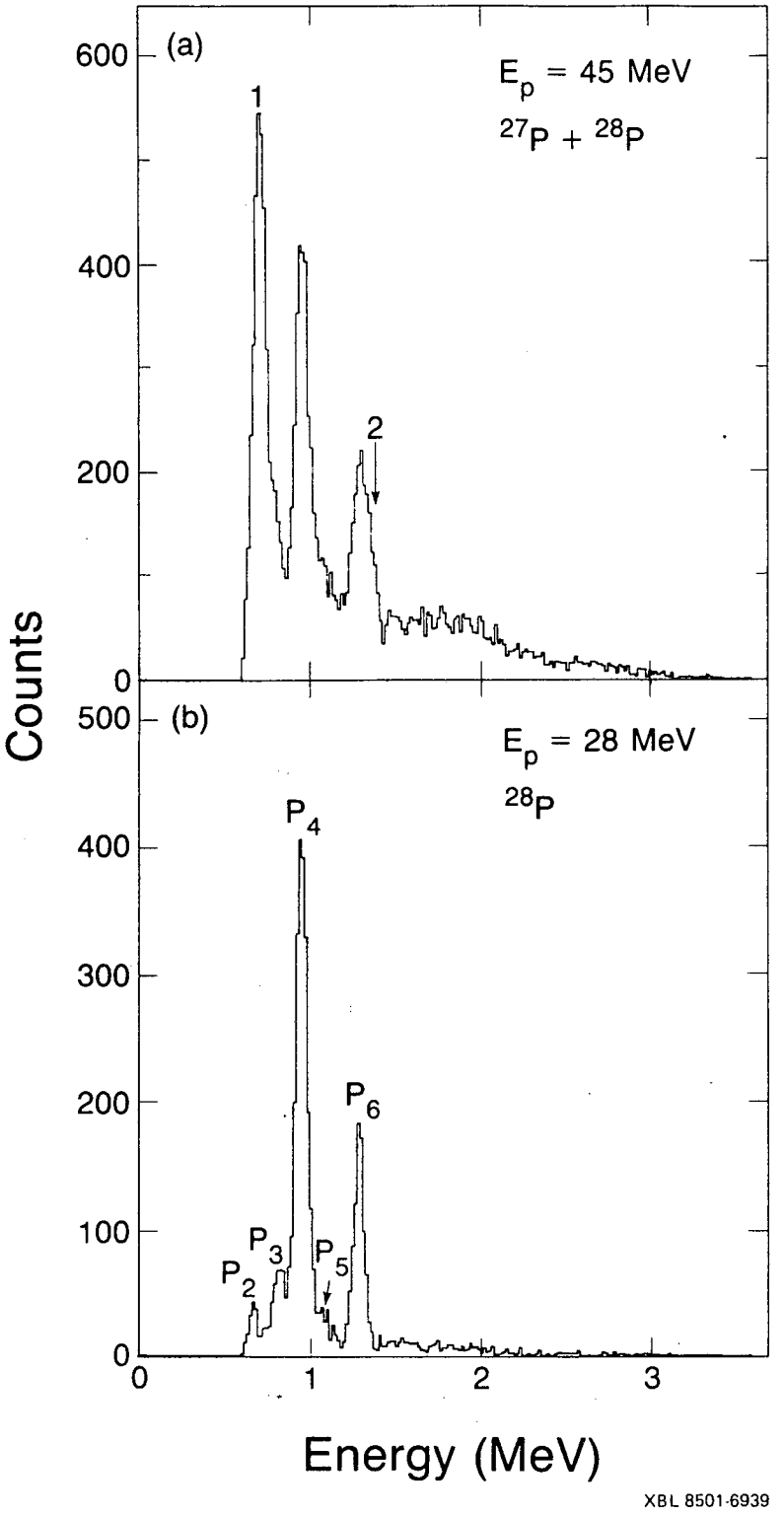
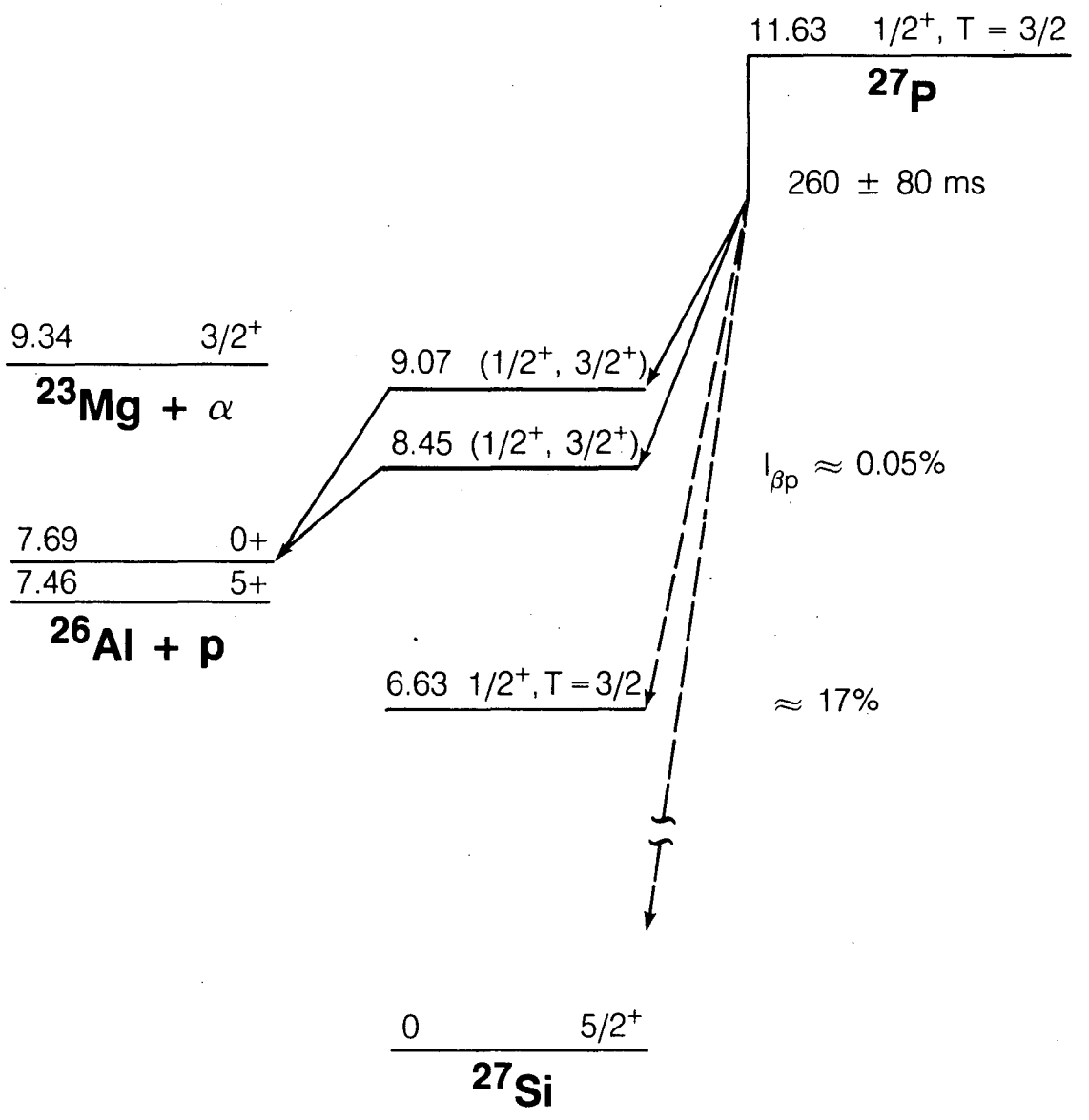

(a)
E_p = 45 MeV
^{27}P + ^{28}P
1
2
600
400
200
0
(b)
E_p = 28 MeV
^{28}P
P_2
P_3
P_4
P_5
P_6
500
400
300
200
100
0
0
1
2
3
Counts
Energy (MeV)
XBL 8501-6939

Fig. 2



XBL 851-6941A

Fig. 3

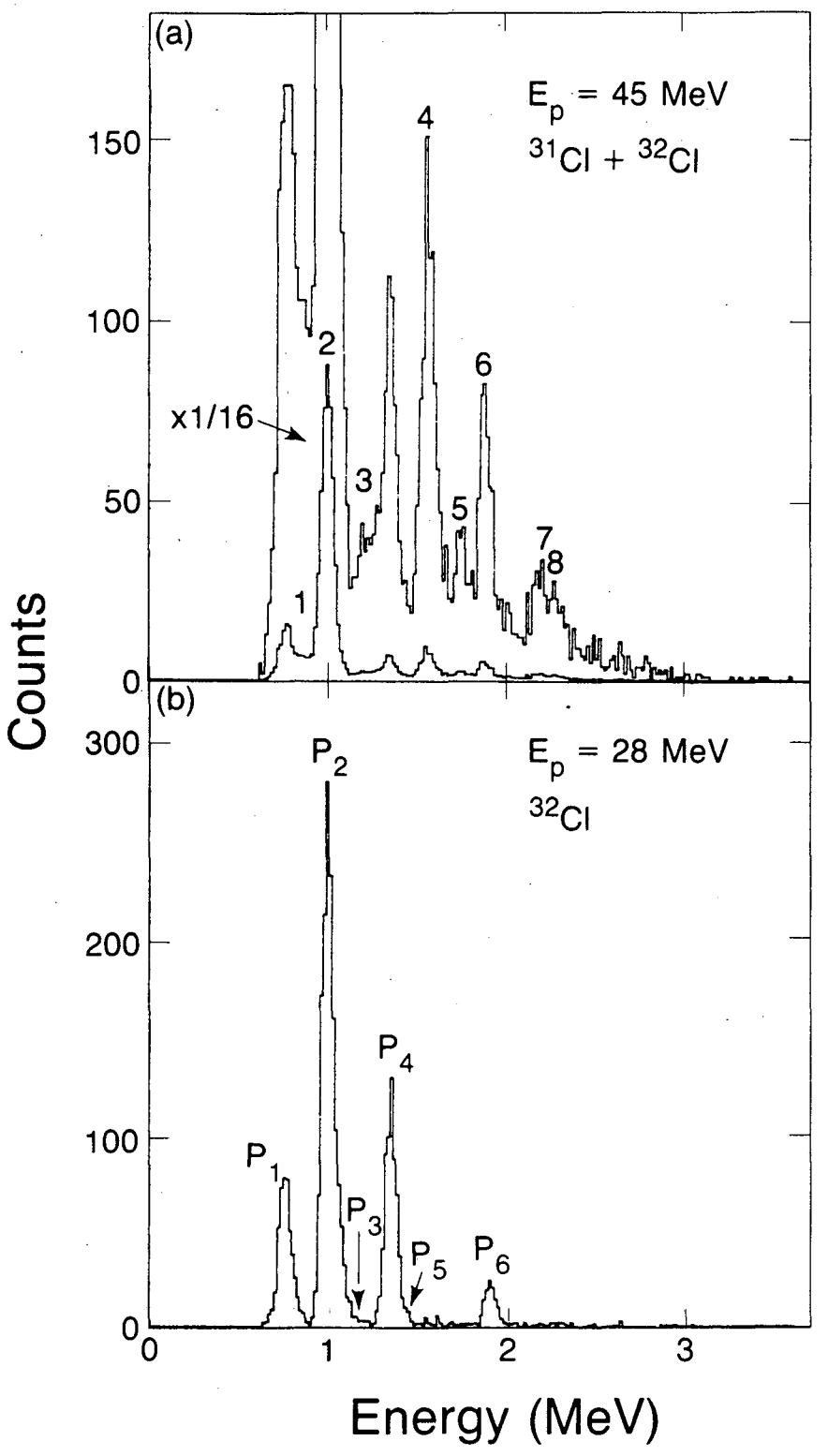
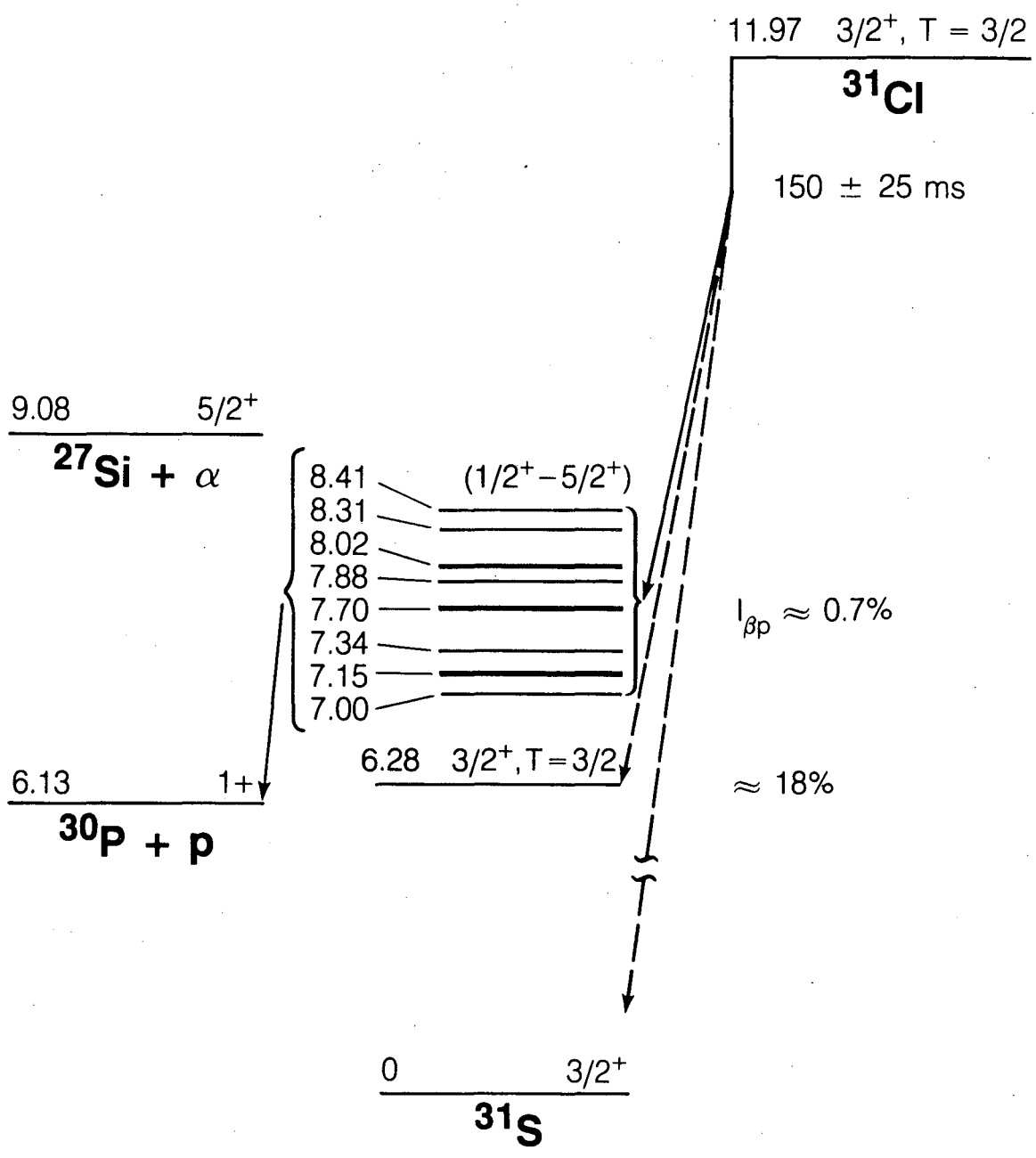
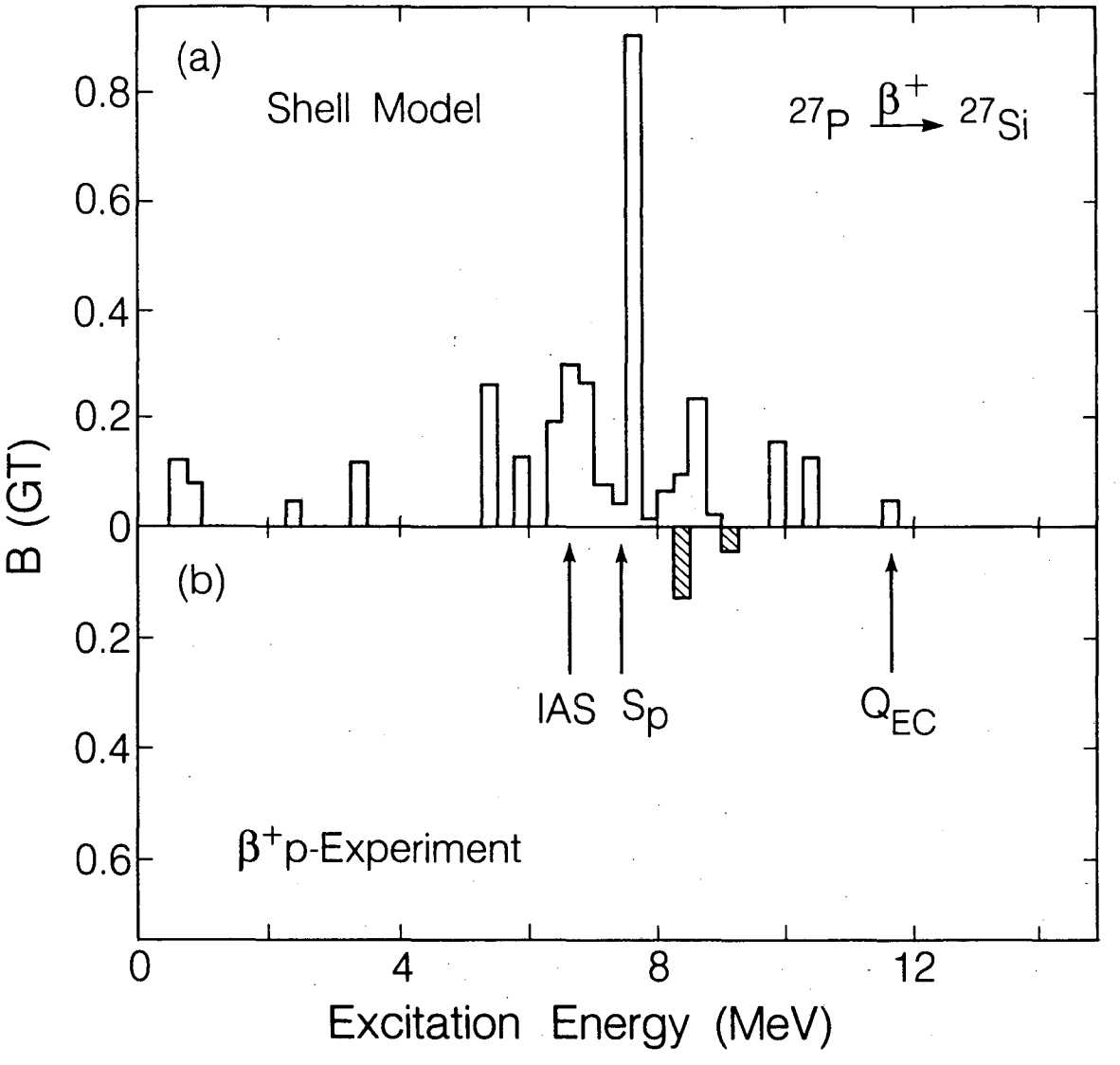

(a)
E_p = 45 MeV
^{31}Cl + ^{32}Cl
x1/16
1
2
3
4
5
6
7
8
150
100
50
0
(b)
E_p = 28 MeV
^{32}Cl
P_1
P_2
P_3
P_4
P_5
P_6
300
200
100
0
0
1
2
3
Counts
Energy (MeV)
XBL 8501-6943

Fig. 4



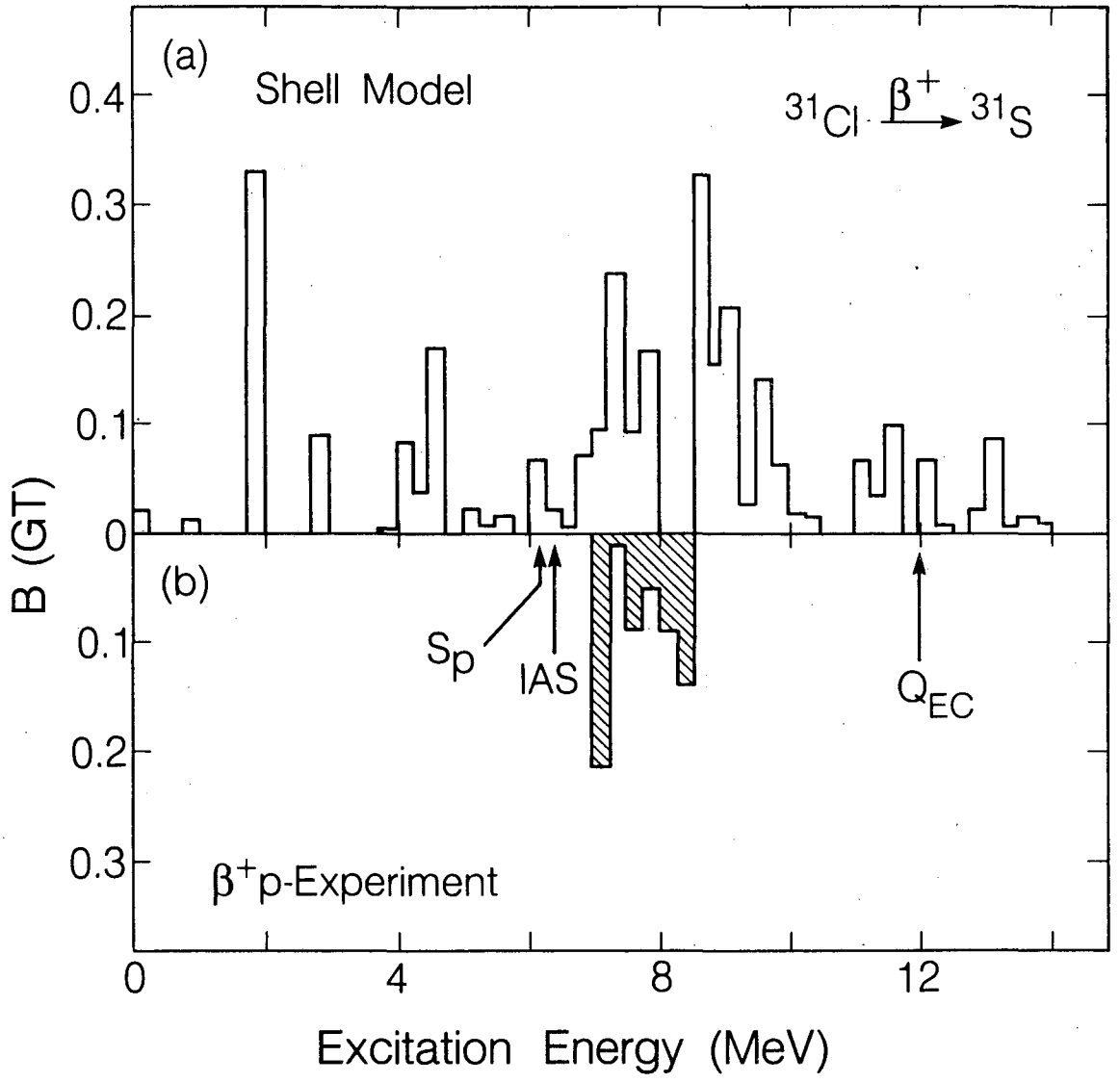
XBL 851-6941

Fig. 5



XBL 855-2590

Fig. 6



XBL 855-2591

Fig. 7

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