# Disintegration of $I^{126}$†

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The radiations from $I^{126}$ have been investigated with a scintillation coincidence spectrometer; $\beta$-$\gamma$, $\gamma$-$\gamma$, and $x$-$\gamma$ events were studied. In a fraction of the electron-capture disintegrations, a gamma ray of energy 0.74 Mev was found to occur in cascade with the previously known 0.65-Mev gamma ray. The crossover transition also was observed. In a fraction of the negative beta-decay processes, a gamma ray of energy 0.48 Mev occurs in cascade with the previously known 0.38-Mev gamma ray; in addition, the crossover transition was observed. The maximum energy of the positron spectrum and the relative intensities of all gamma transitions and of the annihilation radiation were measured. The intensity information, combined with the previously measured ratio of electron-capture probability to beta-decay probability and with the ratio of the intensities of the 0.85-Mev and 1.24-Mev beta rays, is sufficient to give the abundances of all observed transitions in the decay scheme. Both the $ft$ values and the measured ratio of electron-capture probability to positron-emission probability for the ground-state transitions indicate that $I^{126}$ has spin 2 and negative parity. The shell structure assignments, neutron $h_{11/2}$ and proton $g_{7/2}$, are the only ones which can couple to give the resultant spin 2 and negative parity.

IT has been known that $I^{126}$ decays to stable $Xe^{126}$ by negative beta emission and to stable $Te^{126}$ by both electron capture and positron emission.[1–3] Recently, Marty, Langevin, and Hubert,[3] by a method based on a knowledge of the conversion coefficient of the $Cs^{137}$ gamma ray, measured the ratio of the electron-capture probability to the beta-decay probability; their result, 1.1±0.15, is in agreement with the value, 1.26±0.13,[4] obtained earlier by absolute counting techniques.[2] The negative beta spectrum has been investigated several times;[1–3] the measurements, which are all in agreement, show the existence of two beta groups with energies 1.24±0.02 Mev and 0.85±0.03 Mev. The results of coincidence experiments[2,3] prove that the 1.24-Mev beta group, which is 1/2.6 times as abundant as the lower energy group, represents the transition to the ground state of $Xe^{126}$; moreover, the 0.85-Mev beta group was found to be in coincidence with the difference gamma ray of energy 0.382±0.004 Mev. The 0.65-Mev gamma ray has been proved[2,3] to be in the electron-capture branch. A small fraction of the decay of $I^{126}$ takes place by emission of positrons[2,3] with maximum energy 1.21±0.05 Mev.[3]

The gamma-gamma coincidences observed by Perlman and Friedlander,[2] not accounted for in the decay scheme of Marty *et al.*,[3] indicate the existence of gamma rays other than the 0.65-Mev and 0.38-Mev radiations. The results presented in this paper make clear the origin of these coincidences and reveal previously unknown electron-capture and negative beta transitions.

## EXPERIMENTAL METHODS AND RESULTS

### Source Preparation and Purity

The $I^{126}$ used in these experiments was made by the reaction $I^{127}(n,2n)I^{126}$. Small amounts of $I^{125}$ were simultaneously produced by the reaction $I^{127}(n,3n)I^{125}$. Solid potassium iodate was irradiated with fast neutrons produced by $(d,n)$ reaction on beryllium. Two irradiations were carried out, one with a maximum neutron energy of 26 Mev and the other with 19-Mev neutrons, in order to vary the yield of $I^{126}$ relative to that of $I^{125}$. After the addition of a few milligrams of iodide carrier, the $I^{126}$ activity was concentrated by means of a Szilard-Chalmers separation. Several extraction cycles served to purify the activity, which was finally deposited onto thin copper foils in the form of cuprous iodide.[5]

The decay of a fraction of the material produced with 26-Mev neutrons was followed for approximately 90 days. Counting measurements were made with a proportional counter, the window of which was approximately 1.2 mg/cm² thick. Rates were observed with and without a beta-stopping beryllium absorber. The usual semi-log plot of the data taken without absorber is a straight line showing a half-life of 13.3±0.1 days. With absorber the count rate was only a few percent of the rate without absorber; and the plot begins to deviate from a straight line after approximately 45 days, because of the presence of a small amount of 60-day $I^{125}$. The experiments described in this paper were completed before the contribution of $I^{125}$ to the radiation intensity of the samples became appreciable. Moreover, the well-established decay scheme of $I^{125}$, electron capture followed by the emission of a single highly converted gamma ray, is such as

† Research performed under the auspices of the U. S. Atomic Energy Commission.
[1] Mitchell, Mei, Maienschein, and Peacock, Phys. Rev. **76**, 1450 (1949).
[2] M. L. Perlman and G. Friedlander, Phys. Rev. **82**, 449 (1951).
[3] Marty, Langevin, and Hubert, J. phys. et radium **14**, 663 (1953).
[4] In calculating their published value, 1.44±0.15, Perlman and Friedlander used a $K$-fluorescence yield value for Te of 0.75. The value 1.26±0.13 is obtained by use of the better fluorescence yield figure of 0.86 as given by Broyles, Thomas, and Haynes, Phys. Rev. **89**, 715 (1953) and by E. H. S. Burhop in his book *The Auger Effect* (Cambridge University Press, Cambridge, 1952).
[5] G. Friedlander and W. C. Orr, Phys. Rev. **84**, 484 (1951).

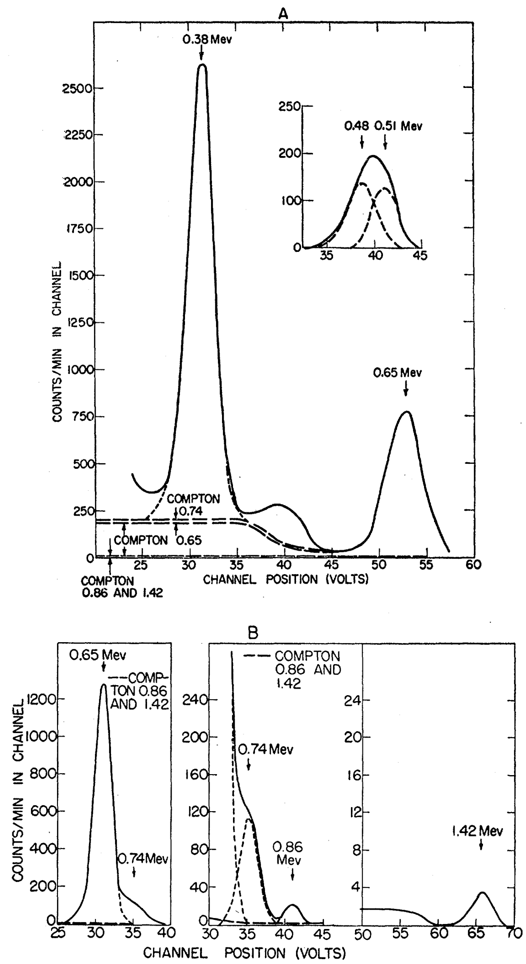


FIG. 1. Gamma rays emitted in the decay of $I^{126}$. Pulse-height distribution measured with a scintillation spectrometer. A (high gain); B (low gain).

not to make the interpretation of the results for $I^{126}$ ambiguous.

## Energies and Intensities of Gamma Rays

A scintillation spectrometer with a DuMont K1186 photomultiplier tube and a NaI(Tl) detector, 1.5 inches in diameter and 1 inch long, was used to measure the energies and intensities of the gamma rays emitted in the decay of $I^{126}$. An examination with a gray-wedge pulse-height analyzer[6] of the radiations which were transmitted through a beryllium absorber (600 mg/cm$^2$) showed the existence of photopeaks at energies 0.74, 0.86, and 1.42 Mev in addition to the expected lines at 0.027 ($K$ x-ray), 0.38, 0.51, and 0.65 Mev. Observation of the relative photopeak intensities at various source-to-detector distances demonstrated that the peaks at 0.74, 0.86, and 1.42 Mev represent nuclear gamma transitions and not the summation in the detector of two coincident gammas of lower energies. The pulse-height spectrum shown in Fig. 1 was obtained with the detector described above and a single-channel analyzer; the $I^{126}$ source was that produced by irradiation with 19-Mev neutrons. A source-to-detector distance of 2 inches was chosen after it had been established that at this distance the contribution of summation pulses was negligibly small. Beta-stopping absorbers were placed in contact with both sides of the source; the annihilation quanta and the nuclear gamma rays were thus detected in the same geometry.

The energy scale in Fig. 1 was calibrated by the use of gamma-ray standards:[7] $Na^{22}$(1.28, 0.51 Mev), $Mn^{54}$(0.84 Mev), $Cs^{137}$(0.662 Mev), and $Be^7$(0.48 Mev). Each photopeak area in the curves of Fig. 1 was evaluated after a subtraction had been made from the observed pulse-height spectrum of the contributions due to Compton processes. A method of curve analysis similar to that of McGowan[8] was used. The evaluation of the Compton contributions was based on the observed pulse-height spectra of the gamma-ray standards. The analysis of the maximum in the region of 0.5 Mev (Insert, Fig. 1A) involved coincidence experiments discussed in the next section. In Table I are listed the energies and relative intensities of the gamma rays emitted in the decay of $I^{126}$.

## Coincidence Studies

The coincidence investigations were carried out with pairs of scintillation detectors appropriate for the various radiations and a gray-wedge coincidence spectrometer.[9] With this spectrometer it is possible to display and photograph pulses representing events in one detector which occur in time coincidence with events of selected amplitude in a second detector.

TABLE I. Energies and relative intensities of the gamma rays emitted in the decay of $I^{126}$.

| (1) Energy (Mev) | (2) Photopeak efficiency[a] (arbitrary units) | (3) Photopeak area (count-volts/min) | (4) Intensity [col. (3)/col. (2)] |
|---|---|---|---|
| 0.382±0.004[b] | 309 | 8700 | 28 ±3 |
| 0.482±0.015 | 202 | 550 | 2.7 ±0.4 |
| 0.510[c] | 185 | 445 | 2.4 ±0.4 |
| 0.651±0.010 | 135 | 3680 | 27 ±3 |
| 0.740±0.020 | 111 | 358 | 3.2 ±0.4 |
| 0.862±0.020 | 91 | 47.0 | 0.52±0.07 |
| 1.420±0.030 | 40 | 12.1 | 0.30±0.04 |

[a] The relative photopeak efficiencies are taken from the data of B. Kahn and W. S. Lyon, reference 11. A small correction has been applied to take into account the fact that measurements were made at a source-to-detector distance of 2 inches rather than 1 inch. This correction, amounting to ~4 percent maximum, was evaluated from unpublished curves of P. R. Bell.
[b] See reference 2.
[c] Annihilation radiation.

[6] Bernstein, Chase, and Schardt, Rev. Sci. Instr. **24**, 437 (1953).

[7] *Nuclear Data*, National Bureau of Standards Circular 499 and Supplements (U. S. Government Printing Office, Washington, D. C., 1950).

[8] F. K. McGowan, Phys. Rev. **93**, 167 (1954).

[9] Chase, Bernstein, and Schardt, Phys. Rev. **90**, 353 (1953); R. L. Chase, Brookhaven National Laboratory, Report BNL 263 (T-42) (unpublished).

A coincidence resolution time of 0.1 microsecond was used. The geometrical arrangement of the detectors and source and the nature of the absorbers used were varied to suit the individual experiments. In Table II are summarized the results of these experiments.

The number of x-x coincidences per $K$ x-ray observed from the $I^{126}$ sources was considerably in excess of the number expected from conversion of any of the gammas associated with the electron-capture decay. A careful search of the events in coincidence with x-rays failed to reveal the existence of any highly converted gamma transitions in the energy range 70–190 kev. The results of two experiments made it evident, however, that the x-x coincidences originated mostly from a few percent $I^{125}$ impurity in the sources. In the first, the ratio of the x-x coincidence rate to the x-ray emission rate for the source produced by irradiation with 26-Mev neutrons was found to be approximately 3.5 times as great as that for the source made with 19-Mev neutrons. This observation is in agreement with the expectation that the yield of the reaction $I^{127}(n,3n)I^{125}$, relative to that of the reaction $I^{127}(n,2n)I^{126}$, rises with increasing neutron energy. Secondly, the x-x coincidence rate from the source made with 19-Mev neutrons was found to decay with the half-life characteristic of $I^{125}$.

As previously noted, the photopeaks at 0.48 and 0.51 Mev were not resolvable from each other in the gamma-ray spectrum (see Fig. 1A); however, the existence of the 0.48-Mev gamma ray was established from the coincidence observations in 135° geometry. The intensity of the 0.48-Mev transition relative to that at 0.38 Mev was determined by an experiment with 135° geometry in which the 0.38-, 0.48-Mev coincidence rate per 0.38-Mev gamma was compared with the beta, 0.411-Mev gamma coincidence rate per beta from a $Au^{198}$ source.[10] In this comparison, one of the detectors was either an anthracene scintillator for the betas of $Au^{198}$ or a NaI(Tl) crystal and pulse-height selector, channeled at 0.38 Mev, for $I^{126}$. The second detector, a standard 1.5 inch by 1 inch cylindrical NaI(Tl) crystal kept in a fixed position relative to the sources, was used in conjunction with a pulse-height selector to detect, in turn, the coincident 0.411-Mev $Au^{198}$ or 0.48-Mev $I^{126}$ radiations. The areas under the coincident 0.411- and 0.48-Mev photopeaks were evaluated, and a correction for the ratio of the photopeak efficiencies at the two energies was applied.[11] It was calculated that the intensity of the 0.48-Mev transition is 9.6 percent of that of the 0.38-Mev transition. This result was used to evaluate the contribution of the 0.48-Mev photopeak to the maximum observed in the gamma-ray spectrum in the vicinity of 0.5 Mev. After this contribution had been subtracted from the composite area at 0.5 Mev, the difference curve was found to peak at 0.51 Mev, as shown in the Insert of Fig. 1A. The energy, 0.482 $\pm$0.015 Mev, quoted in Table II, was determined by comparison of the position of the coincident photopeak with that from a gamma-ray standard.

TABLE II. Results of coincidence experiments with $I^{126}$.

| Selected event | Events observed in coincidence with selected event | Remarks |
|---|---|---|
| $K$ x-ray | $K$ x-ray;[a] 0.85-Mev $\beta$ spectrum; conv. $e^-$ of 0.38-Mev $\gamma$; 0.65-, 0.74-, 1.42-Mev $\gamma$'s | no conv. electrons of energy 40–160 kev in coinc.; neither 0.38- nor 0.84-Mev $\gamma$ in coinc. |
| all $\beta$'s | 0.39-, 0.51- (0.48-)[b] Mev $\gamma$'s | |
| $\beta$'s of energy >0.96 Mev | 0.51-Mev $\gamma$ | no other $\gamma$ in coinc. |
| 0.38-Mev $\gamma$ | 0.85-Mev $\beta$ spectrum; 0.48-Mev $\gamma$ | 135° geometry[c] |
| 0.48-Mev $\gamma$ | 0.38-Mev $\gamma$ | 135° geometry[c] |
| 0.51-Mev $\gamma$ | 1.19[d] $\pm$0.05-Mev $\beta^+$ spectrum; 0.51-Mev $\gamma$ | |
| 0.65-Mev $\gamma$ | $K$ x-ray; 0.74-Mev $\gamma$ | little or no $\beta^+$ in coinc. |
| 0.74-Mev $\gamma$ | $K$ x-ray; 0.65-Mev $\gamma$ | little or no $\beta^+$ in coinc. |
| 0.86-Mev $\gamma$ | 0.38-Mev $\beta$ spectrum | no x-ray in coinc; no $\gamma$ in coinc. |
| 1.42-Mev $\gamma$ | $K$ x-ray | no $\gamma$ in coinc. |

[a] See discussion of x-x coincidences in text.
[b] The photopeaks of the 0.51-Mev and 0.48-Mev gamma rays are not resolved from each other.
[c] A detector-source-detector angle of approximately 135° was chosen in order to eliminate 0.51-, 0.51-Mev annihilation coincidences.
[d] The end-point energy of the positron spectrum was determined directly from the photographic record of this coincidence experiment; the $Au^{198}$ beta spectrum (0.963 Mev, see reference 7) was used to calibrate the energy scale. The result obtained is in good agreement with that of Marty *et al.*, reference 3, who reported 1.21$\pm$0.05 Mev. Throughout this paper the value 1.21 Mev, the result of a spectrographic measurement, will be used.

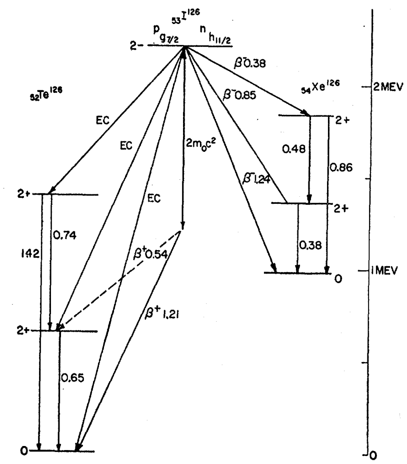


FIG. 2. Decay scheme of $I^{126}$.

## DISCUSSION

The results of the coincidence studies show that the 0.65-, 0.74-, and 1.42-Mev gamma rays are associated with electron-capture decay and that the 0.38-, 0.48-, and 0.84-Mev radiations follow negative beta decay. On the bases of the relative gamma-ray intensities, the coincidence results, and the beta- and gamma-ray energy measurements, the level arrangements shown in Fig. 2 are firmly established. The abundances of the various transitions (Table III) were calculated from the relative intensities of the gamma rays and the

[10] The fact that only 96 percent of the beta transitions from $Au^{198}$ are followed by unconverted 0.411-Mev gamma rays was taken into account. See reference 7.
[11] B. Kahn and W. S. Lyon, Nucleonics **11**, No. 11, 61 (1953).

TABLE III. Abundances and comparative half-lives of the radiations from $I^{126}$.

| Radiation | Abundance (percent) | log*ft* |
|---|---|---|
| 0.38-Mev $\beta^-$ | 3.7 ±0.5 | 7.6 |
| 0.85-Mev $\beta^-$ | 29 ±3 | 7.9[a] |
| 1.24-Mev $\beta^-$ | 11 ±2 | 8.9[a] |
| 0.54-Mev $\beta^+$ | 0.33±0.03[b] | |
| 1.21-Mev $\beta^+$ | 1.04±0.25 | 8.5 |
| EC to ground state | 24 ±7 | 7.8 |
| EC to 0.65-Mev level | 27 ±3 | 7.5 |
| EC to 1.42-Mev level | 4.0 ±0.5 | 7.8 |
| | 100 | |
| 0.38-Mev $\gamma$ | 32 ±3 | |
| 0.48-Mev $\gamma$ | 3.1 ±0.5 | |
| 0.65-Mev $\gamma$ | 31 ±3 | |
| 0.74-Mev $\gamma$ | 3.7 ±0.5 | |
| 0.86-Mev $\gamma$ | 0.59±0.08 | |
| 1.42-Mev $\gamma$ | 0.35±0.05 | |

[a] The comparative half-lives given by Marty *et al.*, reference 3, for these transitions are in error due to an interchange of $f$ values in their Table II, p. 669.
[b] Calculated from the abundance of the EC transition to the 0.65-Mev level and from the ratio, $K$-capture/$\beta^+=75$, expected for an allowed transition. See reference 13. The $L$-capture rate is estimated to be 12 percent of the $K$-capture rate. See M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 437 (1949).

annihilation radiation, from the ratio (1.26) of electron-capture probability to negative beta-decay probability, and from the intensity of the 0.85-Mev beta relative to that of the 1.24-Mev beta (2.64).[3] The comparative half-lives given in Table III were calculated from the graphs of Moszkowski[12] and the tabulated abundances.

From the results in Table III, several comparisons (Table IV) may be made with the data of Marty *et al.*[3] Although these authors were unaware of the existence of the 0.48-, 0.74-, 0.84-, and 1.42-Mev gamma rays and of other associated transitions, their experimental results are in agreement with the results presented in this paper in so far as comparisons may be made.

For the ground-state transition, $I^{126}\longrightarrow Te^{126}$, the experimentally determined $K$-capture/$\beta^+$ probability ratio is 21±8. The value expected from theory,[13] if the transition were allowed, would be 4.6; and this value would not be changed significantly if the transition were first forbidden of the type $\Delta I=0$ or 1, yes.[3,14] However, when $\Delta I=2$, yes, the theoretical value is increased by a factor approximately 4 to 6.[14] In the case of this $I^{126}$ ground-state transition, Marty *et al.*[3] have calculated from the theory of Nataf and Bouchez[15] that the value of the ratio, $K$ capture/$\beta^+$, would be 18 for the condition $\Delta I=2$, yes. These arguments indicate that a spin change of 2 with parity change is involved; and since $Te^{126}$, an even-even nucleus, must have the ground-state assignment 0+, the designation for $I^{126}$ should be 2−.

The designation 2− for $I^{126}$ is in accord with several other experimental results. Stevenson and Deutsch,[16] from measurements of $\beta$-$\gamma$ angular correlation, concluded that $I^{126}$ has spin 2 and negative parity. The log*ft* values (Table III) for the $\beta^+$ and $\beta^-$ ground-state transitions, 8.5 and 8.9, respectively, fall about midway in the range of observed comparative half-lives[17,18] for transitions of the class $\Delta I=2$, yes; they are out of the range for $\Delta I=0$ or 1, yes, and seem too high for $\Delta I=1$, no, $\Delta l=2$, the choice of Marty and co-workers[3] and of Nordheim.[17]

Because the first excited states of $Xe^{126}$ and $Te^{126}$ are expected to have spin 2 and even parity,[19,20] the beta transitions to these states should involve a spin change of zero and parity change. The log*ft* values, 7.9($Xe^{126}$) and 7.5($Te^{126}$), are about one unit higher than the midpoint value,[18] 6.5, for transitions of this type; however, as pointed out by King and Peaslee,[18] when the single particle spin change $\Delta j$ exceeds the nuclear spin change $\Delta I$, log*ft* is increased by approximately one unit. It is plausible that such a condition is operative in the case of these transitions to the first excited states, for which $\Delta I=0$.

The designations 2+ for the second excited states of $Xe^{126}$ and $Te^{126}$ may be deduced from consideration of the intensity of the 0.48-Mev gamma relative to that of the 0.86-Mev crossover and of the intensity of the 0.74-Mev gamma relative to that of the 1.42-Mev crossover. With any assignments other than 2+ or 2−, the expected intensity ratios[21] would be greatly different from those observed; and 2− appears improbable because the log*ft* values for the transitions to the second excited states, 7.6($Xe^{126}$) and 7.8($Te^{126}$), are larger than those found for allowed transitions. Moreover, no second excited states of even-even nuclei are definitely known to have spin 2 and negative

TABLE IV. Comparisons of some intensity ratios.

| Intensity ratio | This work | Marty, Langevin and Hubert |
|---|---|---|
| $\dfrac{\text{Total } K \text{ capture}}{(0.65\text{-Mev } \gamma+0.74\text{-Mev } \gamma)}$ | 1.4 ±0.2 | 1.35 ±0.1[a] |
| $\beta^+/\beta^-$ | 0.031±0.006 | 0.027±0.002 |
| $\left(\dfrac{K \text{ capture}}{\beta^+}\right)_{\text{ground state}}$ | 21 ±8 | 12 $^{+7}_{-3}$ |

[a] The instrument used by these authors did not resolve the 0.65- and 0.74-Mev gammas from each other.

[12] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[13] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).
[14] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
[15] R. Nataf and R. Bouchez, J. phys. et radium **13**, 190 (1952).
[16] D. T. Stevenson and M. Deutsch, Phys. Rev. **84**, 1071 (1951).
[17] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951); G. P. Nordheim, Revs. Modern Phys. **23**, 322 (1951). It may be noted that Nordheim, in his classification of the $I^{126}$ ground-state beta transition, has made use of an erroneous log*ft* value, 7.6, given by Mitchell *et al.*, reference 1.
[18] R. W. King and D. C. Peaslee, Phys. Rev. **94**, 1284 (1954).
[19] In the case of the $Xe^{126}$, the value of the conversion coefficient of the 0.38-Mev gamma ray shows that the transition from the first excited state to ground involves a spin change of 2 and no parity change. See reference 3.
[20] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).
[21] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

parity.[20] The magnitude of these values for log $ft$, very little different from those for the transitions to the first excited states, may be explained by the same arguments[18] which apply to the transitions to the first excited states.

The assignment 2− for the ground state of $I^{126}$ is readily interpretable in terms of the nuclear shell model. The only reasonable single-particle configurations[22] which can couple to give the resultant spin-parity value 2− are neutron $h_{11/2}$ and proton $g_{7/2}$.

From the spin and parity assignments for the levels in $Xe^{126}$ and $Te^{126}$ and from the energies of the gamma rays, it is concluded that approximately 1 percent of the total $K$ x-ray intensity from $I^{126}$ arises from internal conversion.[23]

A value, 0.99±0.05 Mev, for the mass difference, $Xe^{126}$ minus $Te^{126}$, may be calculated from the energies of the ground-state transitions. This figure is believed to be more accurate than that now available from mass measurements.[24]

#### ACKNOWLEDGMENT

We would like to thank Dr. Rolfe Herber for arranging an irradiation at the MIT cyclotron, and Drs. A. W. Schardt and G. Friedlander for helpful suggestions.

[22] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

[23] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).

[24] R. E. Halsted, Phys. Rev. **88**, 666 (1952).

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# Angular Distribution of Charge-Exchange Scattering of 40-Mev $\pi^-$ Mesons by Hydrogen*

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The angular distribution of the reaction $\pi^- + p \rightarrow \pi^0 + n$ has been measured at a mean $\pi^-$ energy of 40 Mev by detecting coincident photons corresponding to $\pi^0$ emission at approximately 0°, 90°, and 180°. The result is

$$d\sigma^0/d\Omega = (0.45\pm0.07) - (0.98\pm0.13)\cos\theta + (0.54\pm0.21)\cos^2\theta \text{ mb/sterad.}$$

The corresponding total cross section is $\sigma_t^0 = 7.9\pm1.8$ mb. An analysis of this result and of previous measurements on $\pi^+$ and $\pi^-$ scattering at 37 Mev has been made, following the hypothesis of charge independence. It is possible to find two distinct types of solution. One type has positive $T=\frac{1}{2}$ $s$-wave and $T=\frac{3}{2}$ $p$-wave phase shifts, and negative $T=\frac{3}{2}$ $s$-wave and $T=\frac{1}{2}$ $p$-wave phase shifts. For the other type, the signs of the phase shifts are almost all reversed. Each type consists of a pair of solutions which are intrinsically indistinguishable at low energies because of the impossibility of determining the sign of the spin-flip scattering amplitude. A choice between the two types of solution is in principle possible with improved data. Predictions of the angular distributions of $\pi^-$ elastic scattering are made.

## I. INTRODUCTION

THE study of the scattering of pi mesons from nucleons is one of the more direct means of investigating the meson-nucleon interaction. In this connection, the simplification introduced into the interpretation of meson-nucleon scattering by the hypothesis of charge independence is of current interest. This hypothesis allows one to describe all meson-nucleon scattering processes by specifying only $2(2l+1)$ phase shifts, where $l$ is the largest relevant orbital quantum number of the incident meson. In the energy range in which the meson wavelength is more than its Compton wavelength, it is reasonable to limit consideration to low angular momentum states, $l=0$ and 1; one therefore seeks a measure of six phase shifts.

Angell, Perry, and Barnes *et al.*[1–3] have reported on the elastic-scattering processes at an incident energy of 37 Mev, and we have previously reported[4] a measurement of the total cross section for charge-exchange scattering at a mean energy of 34 Mev. In the present paper, we present the results[5] of a measurement of the angular distribution of charge-exchange scattering at a mean energy of 40 Mev. Within the experimental errors, all of these observations can be explained in terms of the same phase shifts.

## II. METHOD

In previous observations[6–8] of the angular distribution of pion-proton charge-exchange scattering, only

* This work was supported in part by the U. S. Atomic Energy Commission.

[1] C. E. Angell and J. P. Perry, Phys. Rev. **92**, 835 (1953).

[2] J. P. Perry and C. E. Angell, Phys. Rev. **91**, 1289 (1953). J. P. Perry, thesis, University of Rochester, 1953 (unpublished).

[3] Barnes, Angell, Perry, Miller, and Nelson, Phys. Rev. **92**, 1327 (1953).

[4] A. Roberts and J. Tinlot, Phys. Rev. **90**, 951 (1953).

[5] A brief report of these results was presented at the 1954 New York meeting of the American Physical Society [Phys. Rev. **94**, 766 (1954)].

[6] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 155 (1953).

[7] Fermi, Glicksman, Martin, and Nagle, Phys. Rev. **92**, 161 (1953).