The Dual Decay of Re^{186}

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The decay of Re^{186} (91 hr) has been investigated using spectrometer and coincidence methods. Two beta-groups with maximum energies of 1.070±0.005 Mev and 0.942±0.008 Mev have been observed. The lower energy beta-spectrum leads to an excited state in Os^{186} of 0 136-Mev energy. Nine percent of all disintegrations are by K-capture; two-thirds of which lead directly to the ground state of W^{186} and one-third to an excited state of 0.122-Mev energy. Evidence is given for a spin 1 and odd parity of the ground state of Re^{186}. These assignments agree with the predictions of the one-particle spin-orbit coupling model extended to odd-odd nuclei.

I. INTRODUCTION

THE nuclear radiations of Re^{186} were studied by Beach, Peacock, and Wilkinson.[1] The beta-ray spectrum was found to be simple, and each beta-ray to be followed by a 0.212-Mev and a 0.138-Mev gamma-ray in cascade. Grant and Richmond,[2] however, observed a complex beta-spectrum and three gamma-lines of 0.132 Mev, 0.275 Mev, and 0.7 Mev. In order to obtain more information on the excited levels of Os^{186}, it was attempted to measure the angular correlation of the gamma-rays supposedly emitted in cascade. No gamma-gamma-coincidences could be observed in contradiction to the results reported by Beach *et al.* A reinvestigation of the disintegration of Re^{186} was therefore undertaken. During the progress of our work, measurements on the decay of Re^{186}, independent from ours, have been reported by Metzger and Hill.[3] Their results are in very good agreement with the disintegration scheme reported here.

The neutron-activated Re-powder was obtained from the Isotopes Division of the U. S. Atomic Energy Commission, Oak Ridge. In order to prepare sources free from other radioactive material, a chemical separation was performed. The metallic rhenium was dissolved in hot nitric acid and was separated from elements other than molybdenum by addition of $SnCl_2$ and KCNS and extraction of the rhenium complex with successive portions of ether. The rhenium recovered from this extraction was purified of molybdenum by precipitation of the latter as the 8-hydroxyquinoline complex. The very thin source used in the spectrometer measurements was prepared by evaporating a water solution of perrhenic acid on a 12 $\mu g/cm^2$ zapon film and had a surface density of 40 $\mu g/cm^2$. A thicker source (50 mg/cm^2) was used for the gamma-ray measurements and consisted of black Re_2S_7 precipitated from hot acid solution and collected on a small filter paper.

In order to reduce the 18-hr Re^{188} to a negligible amount, the measurements were commenced 10 days after the end of the neutron irradiation in the pile.

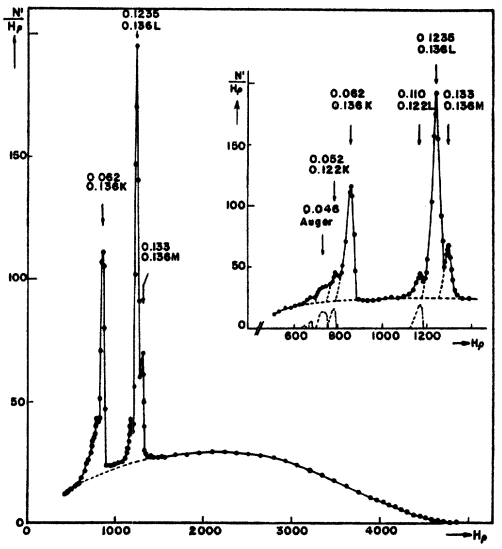

FIG. 1. The electron spectrum of Re^{186}. Arrows mark internal conversion lines. The energy values of the conversion lines and of the associated gamma-rays are given in Mev.

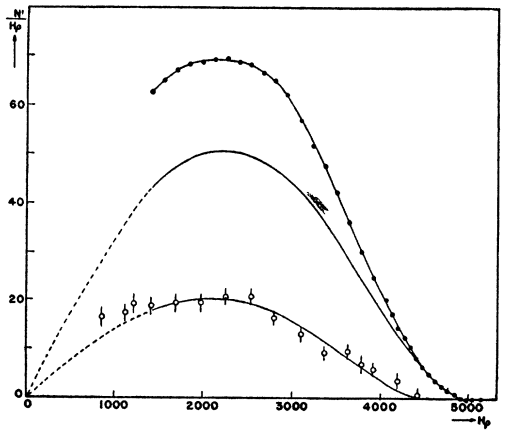

FIG. 2. Beta-spectra of Re^{186}. The two partial spectra are determined from the Fermi plot analysis. The shape of the lower energy spectrum has also been determined directly by measurements of beta-gamma-coincidences in the spectrometer (open circles).

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[1] Beach, Peacock, and Wilkinson, Phys. Rev. **76**, 1585 (1949).

[2] P. J. Grant and R. Richmond, Proc. Phys. Soc. (London) **62**, 573 (1949).

[3] F. R. Metzger and P. D. Hill, Phys. Rev. **81**, 300 (1951).

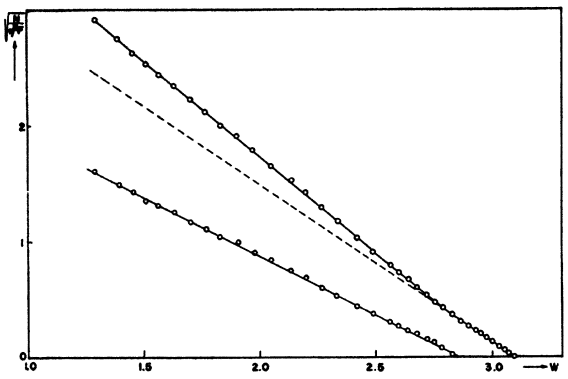

FIG. 3. Fermi plot of the Re^{186} spectra. It is assumed that the two spectra are of the allowed form.

II. THE ELECTRON SPECTRUM OF Re^{186}

The momentum distribution of the electrons from Re^{186}, obtained with a double-lens spectrometer,[4] using a zapon counter window of 0.2 mg/cm² thickness, is shown in Fig. 1. The continuous beta-spectrum (Fig. 2) can be resolved into two groups on the basis of a Fermi analysis of the data. Figure 3 shows the Fermi plot and the result of the subtraction of the higher energy beta-ray group, assuming that the spectra are of the allowed form. This analysis yields two beta-ray groups of 1.070±0.005-Mev and 0.942±0.008-Mev maximum energy, with intensities 73±5 and 27±5 percent, respectively. The resulting momentum distributions are shown in Fig. 2. Direct measurements of the shape of the lower energy beta-ray group using coincidence techniques (see Sec. IV) are in good agreement with the results obtained by the Fermi analysis.

The energies of the three strongest conversion lines correspond to a gamma-ray of 0.136-Mev energy converted in the K, L, and M shell of osmium. The energy of this gamma-ray is, within the experimental error, equal to the energy difference of the partial beta-spectra, indicating that this gamma-ray is emitted following the 0.942-Mev beta-decay. The energy difference between the electron lines of 0.0525 Mev and 0.110 Mev corresponds exactly to the difference between the K- and L-binding energies of wolfram ($E_K^W=69.2$ kev; $E_L^W=11.8$ kev). One is therefore tempted to interpret these two lines as the K- and L-components associated with a single gamma-ray of 0.122 Mev emitted from an excited state of W^{186}. This implies that the Re^{186} nuclide decays not only by electron emission to Os^{186}, but also by electron capture to W^{186}. The occurrence of K-capture is further indicated by the presence of a rather broad electron line of medium energy, 0.046 Mev, which probably must be considered as due to Auger-electrons resulting from K-capture and K-conversion. The latter alone could not account for the relatively large number of observed Auger-electrons. The broadening of the 0.046-Mev line can be explained by the presence of Auger-electrons from both the wolfram atoms ($E_K^W-2E_L^W=45.0$ kev) and the osmium atoms ($E_K-2E_L=47.8$ kev). More experimental evidence for the occurrence of K-capture in Re^{186} will be given in connection with x-ray-electron coincidences.

The two extremely weak electron lines of 0.0315 Mev and 0.0375 Mev found in the Re^{186} spectrum are not explained and will be neglected in the following dis-

TABLE I. Interpretation of the conversion lines of Re^{186}.

Energy of electron line Mev	Origin of electrons	Energy of associated gamma-line (Mev)	Relative intensity. (Intensity of whole continuous beta-spectrum = 1.0)
0.1330	M-shell of Os	0.1360	0.0154
0.1235	L-shell of Os	0.1362	0.0800
0.0620	K-shell of Os	0.1357	0.0485
0.1103	L-shell of W	0.1223	0.010
0.0525	K-shell of W	0.1217	0.0059
0.046	{KLL-Auger-electrons from osmium KLL-Auger-electrons from wolfram}		0.005
0.0373	?	?	0.0001
0.0315	?	?	0.00002

[4] Bleuler, Blue, and Johnson, to be published.

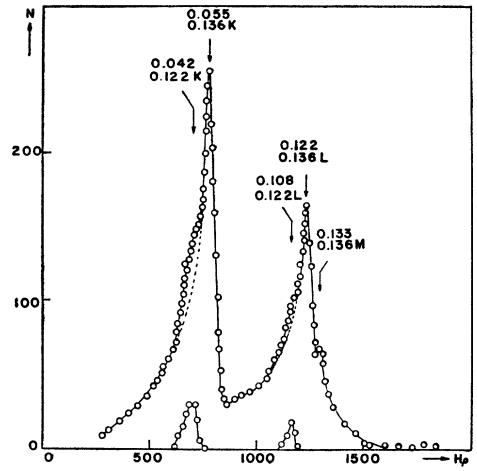

FIG. 4. Photoelectrons ejected from a 5 mg/cm² gold radiator by the gamma-rays following the decay of Re^{186}.

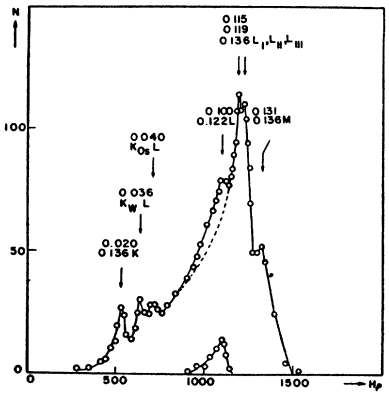

FIG. 5. Photoelectrons ejected from a 0.3 mg/cm² uranium radiator by the gamma- and x-rays emitted during the decay of Re^{186}.

cussion. The interpretation of the conversion lines given in Table I is confirmed by the following measurements of gamma- and x-rays emitted during the decay of Re^{186}.

III. THE GAMMA-RAY SPECTRUM OF Re^{186}

The gamma- and x-ray spectrum of Re^{186} has been measured by observing the photoelectrons ejected from Pb, Au, and U radiators of 19 mg/cm², 5 mg/cm², and 0.3 mg/cm² thickness, respectively. The results are shown in Figs. 4 and 5. The source was contained in a copper capsule thick enough to stop all beta-rays. Only two gamma-lines of 0.136±0.001-Mev and 0.122±0.002-Mev energy could be associated with the observed photo peaks from the three different radiators. The relative intensities of the two gamma-rays have been calculated from the heights of the photoelectron lines, taking into account the effect of finite radiator thickness and the variation of the photoelectric cross section with energy.

TABLE II. The gamma- and x-rays emitted by Re^{186}.

Radiator	Energy of photo-electron peak (corrected for finite thickness of radiator) Mev	Shell	Corresponding gamma-energy or x-ray-energy Mev	Relative intensities of the associated gamma-rays
Pb (19 mg/cm²)	0.048	K	0.136	1.0
	0.120	L	0.136	
	0.132	M	0.136	
	0.035	K	0.123	0.10±0.02
	0.106	L	0.122	
Au (5 mg/cm²)	0.055	K	0.135	1.0
	0.122	L	0.136	
	0.133	M	0.136	
	0.042	K	0.1225	0.10±0.02
	0.108	L	0.122	
U (0.3 mg/cm²)	0.020	K	0.136	
	0.115	$L_I L_{II}$	0.136	1.0
	0.119	L_{III}	0.136	
	0.100	L	0.122	0.11±0.03
	0.036	L	0.057 (W K-radiation)	
	0.040	L	0.061 (Os K-radiation)	

The results are given in Table II. The photoelectron peak at 0.036 Mev, observed with the U-radiator and interpreted as due to the L-photoline of wolfram K-radiation, gives further evidence of the occurrence of K-capture. A search for gamma-rays of energies greater than 0.136 Mev gave negative results, in contradiction to the measurements reported by Beach, Peacock, and Wilkinson.[1]

IV. COINCIDENCE MEASUREMENTS WITH SPECTROMETER

From the results of the above measurements, it must be concluded that the 0.136-Mev gamma-ray is emitted from an excited state of Os^{186} which is reached by the 27 percent partial electron spectrum of 0.942-Mev maximum energy and that the 0.122-Mev gamma-ray is emitted following K-capture into W^{186}.

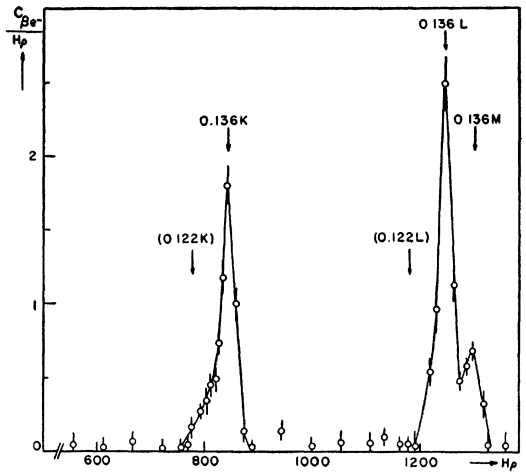

FIG. 6. Momentum distribution of the conversion electrons coincident with the beta-spectrum. The two peaks due to the K- and L-conversion of the 0.122-Mev gamma-ray measured in the single-count spectrum (Fig. 1) have disappeared by detecting $\beta^- - e^-$ coincidences.

To verify this mode of decay, coincidence measurements have been performed between conversion electrons focused in the spectrometer and beta-rays detected by an end-window counter placed near the source in the spectrometer. A 24 mg/cm² Al absorber between the counter and source was thick enough to stop all conversion electrons from reaching the end-window counter. The momentum distribution of the electrons coincident with the beta-rays emitted by Re^{186} is shown in Fig. 6. Only $\beta^- - e^-$ coincidences involving

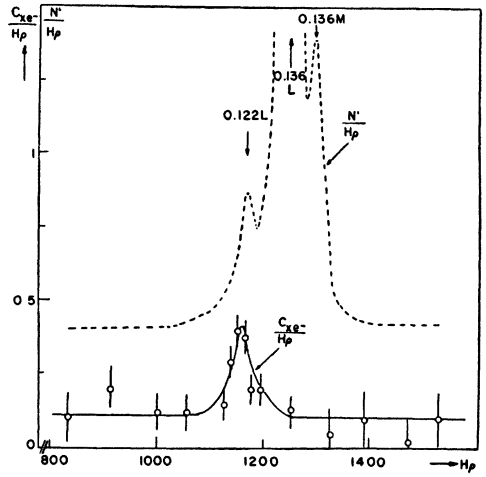

FIG. 7. Momentum distribution of the L-conversion electrons coincident with K-x-rays. For comparison, the single count spectrum (see also Fig. 1) of the same energy region has been included. The two peaks due to the L- and M-conversion of the 0.136-Mev gamma-ray have disappeared in the x-e^- coincidence measurements.

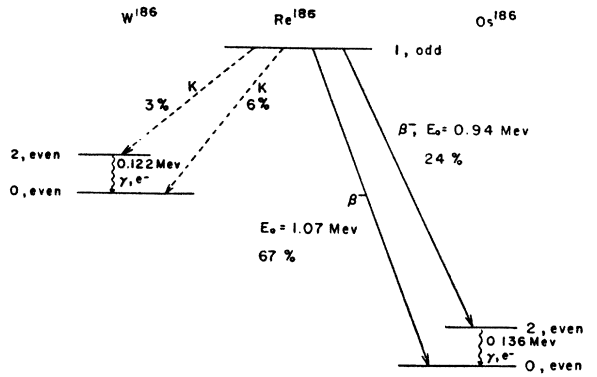

FIG. 8. Disintegration scheme of Re^{186}.

the conversion electrons of the 0.136-Mev gamma-ray have been observed, demonstrating that the 0.122-Mev gamma-ray is not emitted following the beta-decay into osmium. In order to give positive evidence that the 0.122-Mev gamma-ray is emitted following K-capture, coincidences have been measured between the wolfram K-x-rays detected by a krypton filled x-ray counter and the L-conversion electrons of the 0.122-Mev gamma-line (Fig. 7). The electrons were prevented from entering the x-ray counter by a 0.2 g/cm² paraffin absorber and a 0.3 g/cm² aluminum foil. The latter also absorbed all L-x-ray quanta from osmium or wolfram. The measurements show conclusively that the 0.122-Mev gamma-transition is preceded by K-capture.

The shape of the low energy beta-ray spectrum has been determined directly by observing beta-gamma-coincidences in the spectrometer. A 0.9 g/cm² Sn-absorber placed between source and gamma-counter prevented recording of any electron x-ray coincidences. The result of these measurements is consistent with the momentum distribution as derived from the analysis of the Fermi plot (Fig. 2).

V. THE DISINTEGRATION SCHEME OF Re^{186}

The two beta-ray groups of 1.070 Mev and 0.942 Mev, together with the observed gamma-ray of 0.136 Mev, the β^-–γ and β^-–e^- coincidence measurements, suggest that 73 percent of all β^- transitions lead directly to the ground state of Os^{186} and that the remaining 27 percent are succeeded by one gamma-ray of 0.136 Mev, which is converted in the K-, L-, and M-shell of osmium. From the relative intensities of the conversion lines and the two partial spectra, the conversion coefficients are determined as $\alpha_K=0.37\pm0.08$, $\alpha_L=0.61\pm0.13$, $\alpha_M=0.12\pm0.03$. Comparison of α_K with extrapolated values from the tables of Rose *et al.*[5] shows that the gamma-ray must be interpreted as an electric quadrupole transition. Since, at the present, no reliable theory of the L- or M-conversion for the energy and the atomic number involved here is available, no attempt is made to compare these conversion data with theoretical calculations.

The discussion of the K-capture of Re^{186} in connection with our data is somewhat more complex. From the relative number of observed Auger-electrons, it is possible to determine the relative number of K-capture processes,[6] taking into account that Auger-electrons are also emitted following K-conversion. The Auger-electrons due to the latter process can easily be calculated by using the relative intensities of the K-conversion lines (Table I). The result is that, in 9 ± 2.5 percent of all disintegrations, the Re^{186} decays by K-capture into W^{186}; in 6 ± 2 percent, the K-capture leads directly to the ground state, it is followed by a gamma-ray of 0.122-Mev energy in the remaining 3.0 ± 0.5 percent. The latter can be determined from the relative number of 0.136-Mev and 0.122-Mev gamma-quanta and from a comparison of the number of the conversion electrons associated with these two transitions. This comparison also leads to the following conversion coefficients of the 0.122-Mev gamma-transition: $\alpha_K=0.45\pm0.1$ and $\alpha_L=0.73\pm0.15$. The 0.122-Mev gamma-transition in W^{186} must thus also be considered as an electric quadrupole transition.

Figure 8 summarizes the results and suggests our decay scheme. A further verification of this disintegration scheme was made in performing x–gamma and x–x-coincidences using two scintillation counters and also using thin-walled Bi-counters of known efficiency.[7] Our failure to detect any gamma-gamma-coincidences with the sensitive scintillation counters indicates that there are less than 10^{-5} percent positrons emitted in all disintegrations. The number of coincidences observed showed good agreement between the coincidence rates calculated, assuming the decay scheme of Fig. 8. The absorption curve of the electromagnetic radiation in Sn showed an intensity ratio of

$$(I_{0.136}+I_{0.122})/I_K=1.0\pm0.2.$$

The ratio expected from the mode of decay, as represented by Fig. 8, is 0.9 ± 0.1.

VI. DISCUSSION

The ft-values for the two beta-ray groups of 1.07-Mev and 0.94-Mev maximum energy are $\log(ft)_{1.07}=7.68$ and $\log(ft)_{0.94}=7.93$, respectively. This suggests, for both spectra, a first-forbidden transition with $\Delta I=\pm1$.[8] This result is consistent with the allowed shape of the spectra, since first-forbidden spectra of heavy elements are nearly identical with allowed spectra for $\Delta I=0, \pm1$.[9]

Since the product nucleus Os^{186} is *even-even* and hence presumably has even parity and spin 0, odd parity and a spin 1 may be assigned to the ground state of Re^{186}. The same result also follows from a consideration of the

[5] Rose, Goertzel, Spinrad, Harr, and Strong, *Tables of K-Shell Internal Conversion Coefficients* (privately distributed).

[6] Steffen, Huber, and Humbel, Helv. Phys. Acta 22, 167 (1949).

[7] Hart, Russel, and Steffen, Phys. Rev. 81, 460 (1951).

[8] L. W. Nordheim, Phys. Rev. 78, 294 (1950); L. W. Nordheim, Tables for beta-decay systematics (tables privately circulated).

[9] E. Konopinsky, Revs. Modern Phys. 15, 209 (1943).

angular momentum and the parity of the 0.136-Mev excited level of Os^{186}. The comparative half-lives for the two beta-transitions to the ground and excited states of Os^{186} are of the same order of magnitude and hence must be of the same order of forbiddeness, involving probably the same spin change. This again suggests that the ground state of Re^{186} must have a spin 1. The same applies to the K-capture decay to the excited and ground states of W^{186}, which is also an *even-even* nucleus.

The extension of the one-particle spin-orbit coupling model to odd-odd nuclei,[10] also suggests a spin 1 and an odd parity for the ground state of Re^{186}, since the odd proton is presumably in a $d_{\frac{3}{2}}$ and the odd neutron in a $f_{\frac{7}{2}}$ state.[8]

The author wishes to express his thanks to Miss Phyllis Allen for performing the chemical separations and to Mr. Raymond R. McLeod for preparing the krypton-counter. He is also indebted to Dr. E. Bleuler for many discussions.

[10] M. G. Mayer, Phys. Rev. 78, 16 (1950).

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Neutron Energy Distributions in Proton Bombardment of Be and C at 100 Mev*

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The energy distributions of neutrons emitted in the forward direction when beryllium and carbon targets are bombarded by 100-Mev protons were investigated. The neutron energy distribution was found from the range distribution of recoil protons from a polyethylene target, measured with a scintillation counter telescope. The distribution for beryllium was found to be peaked at about 93 Mev, while the distribution for carbon fell off rapidly above 70 Mev. The influence on the observed distribution of energy resolution effects, particularly those involving energy spread of the cyclotron proton beam, is discussed.

I. INTRODUCTION

AN investigation has been made of the energy distributions of the neutrons emitted in the forward direction when beryllium and carbon targets were bombarded by 100-Mev protons from the internal proton beam of the Harvard cyclotron. A collimated beam of the neutrons was allowed to fall upon two polyethylene scatterers. The recoil protons from one of these scatterers served as a monitor of the beam intensity while the range distribution of the recoil protons from the other scatterer was studied. From these results the energy distribution of the neutron beam was inferred.

II. DESCRIPTION OF EXPERIMENT

A diagram of the experimental arrangement is given in Fig. 1. The target was placed within the cyclotron tank at a location such that neutrons emitted in the forward direction with respect to the incident protons passed through a $\frac{1}{2}$-inch thick Lucite window in the cyclotron vacuum tank and through a collimating hole in the 6-foot shielding surrounding the cyclotron.

The targets were rectangular bars $1\frac{3}{4}$ inches high, and, as held in the cyclotron, with a radial dimension of $\frac{1}{4}$ inch. The target was held by two light phosphor bronze clips which gripped the target at its top and bottom with small caps and which extended radially back from the target to a supporting probe. With this arrangement the entire direct beam struck the target, and the contribution of scattered protons striking the holder was small. The beryllium target was 0.125 inch thick for all runs. Different carbon targets were used for runs A and B, 0.125 and 0.196 inch thick, respectively.

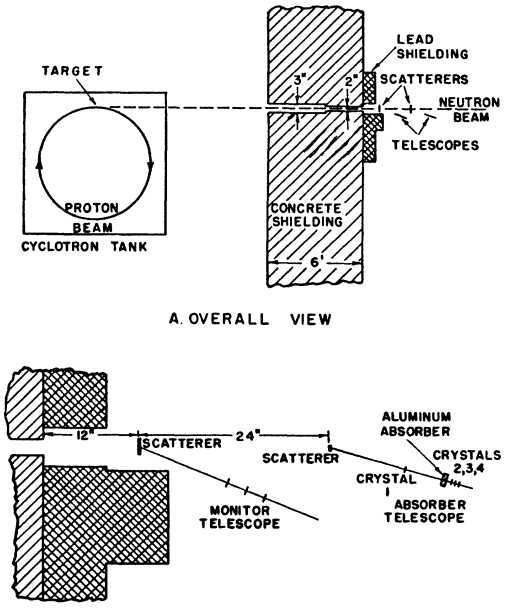

FIG. 1. Experimental arrangement.

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