alpha-activities and the isotopic compositions of the plutonium fractions of such samples.

The plutonium fractions of several samples subjected to different neutron fluxes were separated and carefully purified to spectrochemical freedom from foreign cations, to the absence of uranium (detected by a sensitive fluorescence test), and to radioactive purity. Duplicate portions of each plutonium fraction were converted to PuF_3 and reduced to high purity metal by microscale methods.[1]

Milligram globules of plutonium metal were massed against calibrated weights and dissolved in weighed quantities of solution. Aliquots were plated on platinum by a very precise gravimetric technique,[2] and counted on a parallel plate nitrogen counter (N-4) by methods previously described.[3] The isotopic compositions of the samples were available from the mass spectrometric examinations of Bartlett and Swinehart.[4] A minor change in the isotopic composition of sample C indicated by a recent determination has been incorporated into the present calculation after correcting for the accumulated radioactive disintegration.[5]

Appropriate corrections for Pu^{239} and the small amounts of Pu^{238} and Pu^{241} present were made in calculating the half-life of Pu^{240} from the observed[3] specific activity of the samples relative to that of Pu^{239}.

The Pu^{240} half-life calculated from three such plutonium fractions in order of increasing Pu^{240} content were sample A, 6180±360 years; sample B, 6100±200 years; and sample C, 6310±130 years; with a best value of 6240±120 years. The indicated probable errors in these measurments includes consideration of the uncertainties in the mass spectrometry and weighing, limitation of spectrochemical sensitivity, observed standard deviations in the counting, and the probable error in the half-life of Pu^{239}.

It is noted that this half-life value is in accord with an estimate of about 6000 years by James *et al.*[6]

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‡ Based on Manhattan Project Document CC-3894 (1946).
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Half-Life of Plutonium-240 by Determination of Its Uranium-236 Daughter

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A NEW measurement of the Pu^{240} half-life has been made using a technique which depends on the growth of the uranium daughters from a plutonium sample of known isotopic composition. The decays involved in this experiment are

$$Pu^{239} \xrightarrow[\alpha]{24{,}410\ \text{yr}^1} U^{235} \xrightarrow[\alpha]{7\times10^8\ \text{yr}}, \quad (1)$$

$$Pu^{240} \xrightarrow[\alpha]{\sim6000\ \text{yr}^2} U^{236} \xrightarrow[\alpha]{\sim2\times10^7\ \text{yr}^3}. \quad (2)$$

Since the time necessary to complete the experiment was short in comparison to the half-lives involved, the following simplified analytical expression can be obtained for the Pu^{240} half-life:

$$T_{\frac{1}{2}}(Pu^{240}) = \frac{\text{moles of } U^{235}}{\text{moles of } U^{236}} \times \frac{\text{moles of } Pu^{240}}{\text{moles of } Pu^{239}} \times T_{\frac{1}{2}}(Pu^{239}).$$

The half-life thus obtained depends on the isotopic ratios of the uranium daughters and of the plutonium parents as determined by the mass spectrometer, and on the known half-life of Pu^{239}. Previous measurements of the Pu^{240} half-life have been dependent on the Pu^{239} half-life and on the ratio of the plutonium isotopes, but have also been subject to the errors inherent in specific activity measurements.

The plutonium used for this experiment was chosen because it contained a relatively large amount of Pu^{240} and because it had been purified several years earlier with respect to the other heavy elements. After a chemical separation of the uranium daughters and subsequent purifications, an analysis on the alpha-differential pulse analyzer indicated that the final uranium fraction was sufficiently free of plutonium for mass spectrometric determinations.

The calculation of the half-life of Pu^{240} involved two experimental errors: (1) The error in the half-life of Pu^{239}, which is given by Westrum as ±0.3 percent;[1] (2) the error in the mass spectrometric measurements of the isotopic ratios, which is about ±0.3 percent. It should be noted that the usual mass discriminations inherent in a mass spectrometer cancel in the present case. Substituting in the analytical expression, the values obtained on the mass spectrometer for the isotopic ratios of Pu^{240}/Pu^{239} and U^{235}/U^{236} and the value $T_{\frac{1}{2}}^{239}=24{,}410$ years,[1] gives the half-life of Pu^{240} as 6580±40 years. This value and its limits of error is to be compared with those of 6240±120 yr,[4] 6850±150 yr,[5] and 6650±150 yr,[5] as determined by specific activity measurements.

The authors wish to express their appreciation to Dr. W. M. Manning for his helpful discussions of this problem.

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Low Excited States of Nuclei and the Quasi-Atomic Model*

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THE independent particle, or quasi-atomic model of the nucleus, has been used to discuss the ground states of nuclei[1,2] and the doublet splitting in light nuclei.[3] Recent experiments[4] on the elastic scattering of protons by He^4, C^{12}, O^{16}, and of neutrons by He^4 have been analyzed,[4,5] and assignments of angular momentum and parity have been made to the excited states observed. These quantum numbers have also been determined for some of the low states of Al^{25} by an analysis of the scattering[6] of protons by Mg^{24}. Although these assignments are not all quite conclusive, we shall assume them to be correct for the purpose of discussion. The resulting series of energy levels, which are about 4 Mev in extent and lie near the ground states, show an interesting correlation with the predictions of an independent particle model with strong spin-orbit coupling.

One assumes that the nucleons of the target nucleus form a core of zero resultant angular momentum and that the influence of this core on the extra nucleon can be represented by an average potential. As a first approximation, this potential might be considered similar to that of a three-dimensional harmonic oscillator.

Since the coulomb repulsion is small in light nuclei, the density of nucleons is greatest near the origin. This[2] suggests a potential more singular at the origin than that of the harmonic oscillator. The result is a splitting of degenerate states with the same oscillator number, such that the energy of the state of lower orbital angular momentum is decreased. Finally, if we assume (LS) spin-orbit coupling, a state for which $J=L+\frac{1}{2}$ is depressed by an amount proportional to L, and one for which $J=L-\frac{1}{2}$ is raised by an amount proportional to $L+1$.

In Figs. 1c and 2c, we have plotted the levels of He^5, Li^5, and F^{17} relative to their ground states. The rest of Figs. 1 and 2 show how these levels can be fitted qualitatively into the above scheme. In Fig. 3 we have worked the levels of N^{13} and Al^{25} into the same type of scheme, but it is noticeable that the "closed shell plus one" nuclei, He^5, Li^5, and F^{17}, show the better correlation.

The degree of validity of the single particle approximation for a state is given roughly by the ratio of its reduced width[7] to the single particle limit $\hbar^2/\mu a$, where a is the interaction radius and μ the reduced mass of the system. On this basis, the dotted $S_{1/2}$ and the $F_{7/2}$ resonances in F^{17} can be excluded from the discussion because their reduced widths are very small. The other levels in F^{17} all have reduced widths comparable with the limit, and the reduced widths of the He^5, Li^5 levels are about equal to the limit. The large spin-orbit splitting is obvious in these three nuclei.

In N^{13} the $P_{3/2}$ resonance is the only one whose reduced width is small enough to indicate considerable multiple particle excitation. The mixing of a large number of wave functions to form this state may account for its abnormally large depression below the corresponding oscillator level.

Since the lowest excited states of He^4, C^{12}, and O^{16} lie well above the highest energy considered here, we expect a relatively small amount of core excitation in these low states of Li^5, He^5, N^{13}, and F^{17}. In Mg^{24}, however, there is a well known excited state at 1.38 Mev, which enhances the probability of core excitation. The Al^{25} excited states shown are the lowest three observed in the elastic scattering of protons by Mg^{24}, and their reduced widths are of the order of 15–20 percent of the single particle limit. Higher levels in this nucleus are narrower and of less definite assignment.

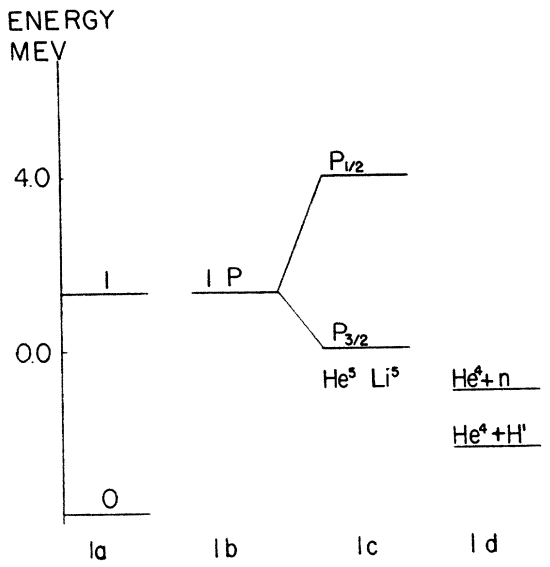

FIG. 1. Energy levels of the Li^5 and He^5 nuclei. (a) The ground state and first excited level of a simple harmonic oscillator. The ground state of Li^5 or He^5 is taken as the energy zero. (b) The corresponding level of the nuclear potential. (c) The observed levels of Li^5 and He^5, showing the large splitting and inversion of the $P_{3/2}$ and $P_{1/2}$ doublet. (d) Dissociation energies of He^4+n and He^4+H^1.

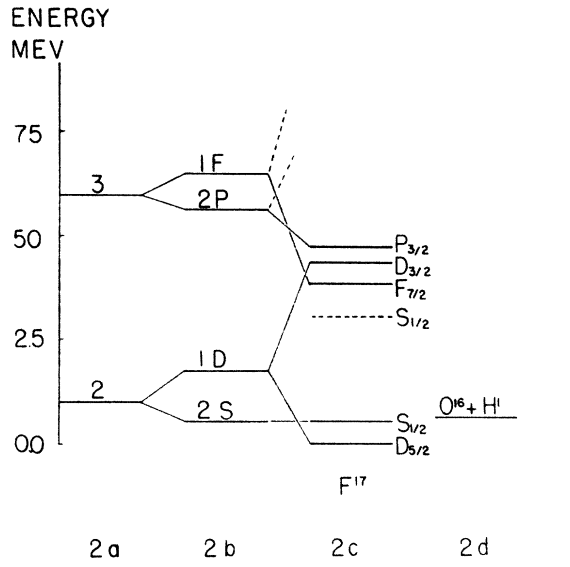

FIG. 2. Energy levels of the F^{17} nucleus. (a) The second and third excited levels of a harmonic potential. (b) The corresponding levels of the nuclear potential showing removal of degeneracy in L. (c) The ground state and known excited levels in F^{17}. The second $S_{1/2}$ level is probably not a single particle level. The splitting and inversion of the $D_{5/2}D_{3/2}$ doublet is clearly shown and that of the $P_{3/2}P_{1/2}$ and $F_{7/2}F_{5/2}$ doublets is suggested. (d) The dissociation energy of $O^{16}+H^1$. The ground state of F^{17} is taken as the energy zero.

Resonance energies are determined by the behavior of the wave function at infinity. In order to relate the resonance energies to the specifically nuclear characteristic energies, one must make a correction for the effect of the part of the wave function which lies outside of the range of nuclear forces. These corrections are calculable[8] and are proportional to the reduced widths, but since we do not know the reduced widths of the ground states, we have presented the observed energy in every case. The magnitude of the

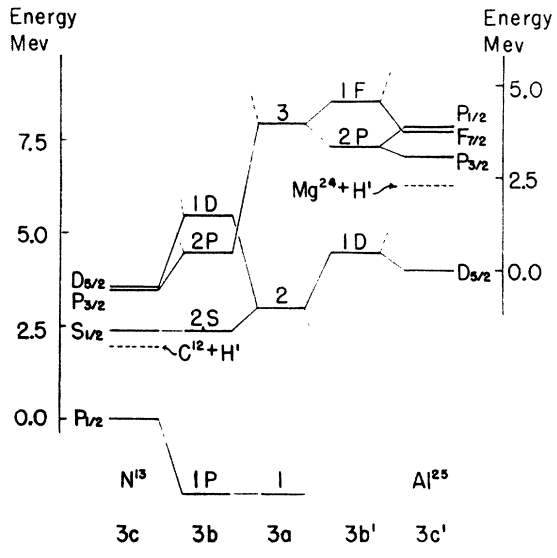

FIG. 3. Energy levels of the N^{13} and Al^{25} nuclei. (a) The first three excited levels of a harmonic potential. (b) and (b′) Splitting of oscillator levels in N^{13} and Al^{25}, respectively, as a result of the departure of the nuclear potential from that of the harmonic oscillator. (c) Ground state and observed levels in N^{13}. (c′) Ground state and observed excited levels of Al^{25}. The left ordinate measures energy from the ground state of N^{13} and the right ordinate measures energy from the ground state of Al^{25}.

correction may be of the order of 1 Mev for very broad levels. It is therefore evident that the energy levels listed in the diagrams are only qualitatively related to the characteristic energies of the nuclei.

These sequences of low excited states of simple nuclei exhibit two striking features: (1) large spin-orbit splitting; (2) good correlation with an independent particle model. It appears that the single particle approximation is a good starting point for more exact study. To explain the large spin-orbit splitting, however, it may be necessary to consider specific nucleon-nucleon spin-orbit interactions.[9]

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Proton-Proton Scattering Near 30 Mev*

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THE work reported in an earlier paper[1] has been continued with a few improvements in technique. The entire apparatus was completely overhauled, and mechanical tolerances in the plate holder were carefully checked. The beam collimator was lengthened to a total of 21 inches, and the three graphite diaphragms shown in Fig. 7 of reference 1 were spaced so that the photographic plates were completely shielded from the $\frac{1}{16}$-inch and $\frac{3}{32}$-inch diaphragms. The lengthening of the collimator reduced the background of slit scattered tracks, making the observation of low angle tracks in the photographic emulsion more reliable. By using swaths which were less than one inch from the axis of the plate holder it was possible to observe tracks whose scattering angles ranged from 5° to 82° in the laboratory system. Plates from the same photographic emulsion batch were used as in the earlier work.

A set of three runs was made and results of these are reported below. Run 46 was the scattering run. Run 44 was a background run in which the scattering chamber was evacuated, while run 47 was a background run which was in all respects like a scattering run except that a molybdenum tube of $\frac{3}{4}$ inch diameter and 0.030-inch wall thickness was inserted axially in the scattering chamber so as to completely surround the beam and thus prevent scattered protons from reaching the plates. Tracks observed in the photographic plates for this run must be due to knock-on protons produced by neutrons in the hydrogen or in the material of the plate holder. The conditions prevailing during each run are summarized in Table I.

The criteria for reading tracks were the same as described in Sec. III-B of reference 1. Each swath was 2.300 inches long and 127±0.5 microns wide. The tracks were counted by Mr. R. C. Terzian, to whom the author is greatly indebted, and over half of the counts were checked by the author to determine the reliability of the counting. In order to speed the gathering of data in the region of small scattering angles, it was decided to try counting only tracks whose scattering angles were in the intervals 5° to 26° and 64° to 82° in the laboratory system. However, after twelve swaths had been counted in this manner, it was decided that the increase in speed was too small to justify the decrease in the reliability of counting tracks, so the method was abandoned. This accounts for the low number of tracks shown in Table I for the angular interval from 26° to 64°. All 1129 of the tracks counted in this manner were checked by the author, as were half of the swaths in which all of the tracks were counted. Since the number of tracks missed by Mr. Terzian amounted to only 1.5 percent, it was assumed in the cross section calculation that no tracks were missed on swaths which were counted by both observers. The number of tracks missed by Mr. Terzian on twelve swaths is given in column 3 of Table II. Column 4 is included to show that the two observers disagreed on only 0.56 percent of the tracks checked.

TABLE I. Summary of runs.

Run No.	Type of run	Time for pressure to reach 10^{-4} mm (sec)	Temp. (°C)	Pressure (mm of Hg)	Charge collected (coulombs ×10⁸)	Number of swaths scanned
44	background	0.6	···	10^{-4}	1.095	8
46	scattering	0.5	19.1	764.1	1.083	36
47	background	0.4	19.1	764.1	1.065	8

In order to enable the reader to visualize the types of all tracks on the plates a random swath $\frac{1}{2}$ inch long was scanned on each of the six plates of run 46. Of a total of 689 tracks of all kinds observed, 360 were judged to represent bona fide scattered protons, 320 were obviously no good, and 9 were spurious tracks which although appearing good failed to conform to all four of the criteria for good tracks.

As was shown in reference 1, the number of scattered protons should be symmetric about 45° in the laboratory system. Data in column 2 of Table II show that this is so, particularly at low scat-

TABLE II. Summary of data.

Angular interval (θ_{lab})	Total number of tracks counted	Number of tracks missed in 12 swaths by R.C.T.	Number of tracks on 12 swaths on which F.L.F. and R.C.T. disagreed	Number of tracks in both background runs
5° to 6°	60	2	0	2
6° to 10°	204	7	0	0
10° to 14°	246	4	2	0
14° to 18°	343	5	0	0
18° to 22°	463	5	0	0
22° to 26°	576	2	2	0
26° to 30°	436	2	1	1
30° to 34°	455	0	0	0
34° to 38°	527	2	0	0
38° to 42°	523	1	0	0
42° to 48°	761	0	0	0
48° to 52°	506	2	1	0
52° to 56°	483	1	1	0
56° to 60°	430	0	1	0
60° to 64°	398	0	1	0
64° to 68°	525	1	2	0
68° to 72°	464	0	4	0
72° to 76°	338	1	3	1
76° to 80°	267	2	0	3
80° to 82°	82	14	1	0
Total	8087	51	19	7

Of the 8087 tracks counted, 1129 were on swaths where tracks with scattering angles from 26° to 64° were omitted, 3432 of the remaining were checked by F.L.F., and 3526 were unchecked.