# Decay of $Sc^{42m}$ and the Levels of $Ca^{42}$†

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(Received 2 November 1962)

A 62.0±0.4-sec isomer, $Sc^{42m}$, has been observed which decays by emission of a positron group of endpoint energy 2.87±0.10 MeV to an excited state in $Ca^{42}$ at 3.191 MeV, followed by a cascade of three $\gamma$ rays of energies 0.438±0.003, 1.226±0.010, and 1.520±0.010 MeV. The levels of $Ca^{42}$ and their assigned spins are: 1.523 MeV, 2+; 1.836 MeV, 0+; 2.424 MeV, 2+(1+); 2.750 MeV, 4+; and 3.191 MeV, 6+. The spin of $Sc^{42m}$ is 7+. Studies of the reaction $Ca^{40}(He^3,p)$ showed that the first and second excited states of $Sc^{42}$ are at 0.67±0.03 and 1.58±0.05 MeV, respectively, the former being $Sc^{42m}$. The excitation function for the $Ca^{40}(\alpha,pn)Sc^{42m}$ reaction was also measured. The general trends of levels in even $f_{7/2}$ nuclides are rather well explained by two treatments of the $jj$-coupling model, with exceptions for $Ca^{44}$ and $Ca^{42}$.

## I. INTRODUCTION

FOLLOWING the inception of the independent-particle model with the hypothesis of strong spin-orbit coupling,[1] there has been considerable theoretical interest in the level structure of nuclides containing several $f_{7/2}$ nucleons outside the $Ca^{40}$ doubly magic core. Several of the theoretical investigations have been based mainly on the independent-particle model,[2–4] whereas others have included collective-model effects.[5,6] We have obtained further information on coupling of $f_{7/2}$ particles by study of the positron decay of high-spin, 62-sec $Sc^{42m}$ (discovered by us[7] and, independently, by Nelson *et al.*[8,9]) which populates levels of $Ca^{42}$ that are not seen in the beta decay[10,11] of 12.5-h $K^{42}$ ($I=2-$), or in the positron decay[12] of 0.689-sec $Sc^{42}$ ($I=0+$).

## II. EXPERIMENTS

### 1. Mass and Charge Assignments

Bombardment of natural calcium targets with $He^3$ ions of 12 to 24 MeV and $He^4$ ions of 30 MeV produced a positron and $\gamma$-ray activity having a 62-sec half-life. Attempts were made to identify the activity with one of the four elements titanium, scandium, calcium, or potassium. In the time available, titanium and scandium could be collected together, separated from calcium and potassium. The separation was made by extracting the titanium and scandium into an 0.5 $M$ solution of thenoyltrifluoroacetone (TTA) in benzene from an 0.1 to 5 $M$ HCl solution of reaction products. The activity appeared in the extracted phase and was, thus, established as titanium or scandium and not calcium or potassium.

Attempts were also made to separate the titanium alone by extracting the tetraphenylarsonium chloride salt of $TiCl_6^=$ from HCl solution into chloroform. At no time was more than a few parts per thousand of the initial activity separated by this means, specific for titanium. It is, thus, concluded that the species is an isotope of scandium.

The short-lived activity was shown definitely to be an isotope of scandium by bombardments of $K^{39}$ (as natural KCl) with 17- to 30-MeV $He^4$ ions (producing no Ti isotopes) and subsequent separation of the 62-sec activity by the TTA extraction technique. The bombardments also produced considerable amounts of 7.7-min $K^{38}$ by the $K^{39}(\alpha,\alpha n)$ and $Cl^{35}(\alpha,n)$ reactions and 34.2-min $Cl^{34m}$ by the $Cl^{35}(\alpha,\alpha n)$ reaction. The 62-sec activity was barely distinguishable in the $\gamma$-ray spectra of the gross reaction products, but its relative intensity was increased 50 fold and became clearly distinguishable over the $K^{38}$ and $Cl^{34m}$ activities in the benzene fraction from the TTA separation. Thus, the activity is clearly an isotope of scandium.

The assignment to mass 42 was initially based on the three cross bombardments $Ca^{40}(He^3,p)$, $Ca^{40}(\alpha,pn)$, and $K^{39}(\alpha,n)$ and on the good agreement between the observed $\gamma$-ray energies and the energy differences between the levels of $Ca^{42}$ previously determined by other workers (see below). Also, the yield at 30-MeV $He^4$-ion energy was much too large to be produced by any calcium isotope except $Ca^{40}$.

The assignment was further checked by measuring the excitation function for production of the activity via $He^4$-ion bombardment of vacuum evaporated $CaF_2$

† This work was supported by the U. S. Atomic Energy Commission.

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targets. The 30.72±0.06-MeV $He^4$-ion beam from the MIT cyclotron was degraded by insertion of weighed aluminum foils to give a series of bombarding energies which were determined with the use of a semiconductor particle detector. During each 1- to 3-min bombardment the beam current collected by an electrostatically shielded Faraday cup (which also served as target holder) was monitored by use of a current integrator and pulse-height analyzer operating as a multiscaler.

Following each bombardment, the $\gamma$ rays from the target were counted directly with a NaI(Tl) crystal. A decay curve of the $\gamma$ rays of $E_\gamma > 0.7$ MeV was measured using the pulse-height analyzer as a multiscaler. The counting arrangement was calibrated against a 3-in.×3-in. NaI(Tl) crystal (under standard geometrical conditions) from which the absolute disintegration rates were determined. The decay curves obtained were analyzed with the aid of the FRANTIC computer program[13] to obtain the counting rates of the 62-sec activity at the end of bombardments. The thickness of calcium on the targets was determined by an EDTA titration of the material dissolved from the targets.[14]

The excitation function obtained is shown in Fig. 1

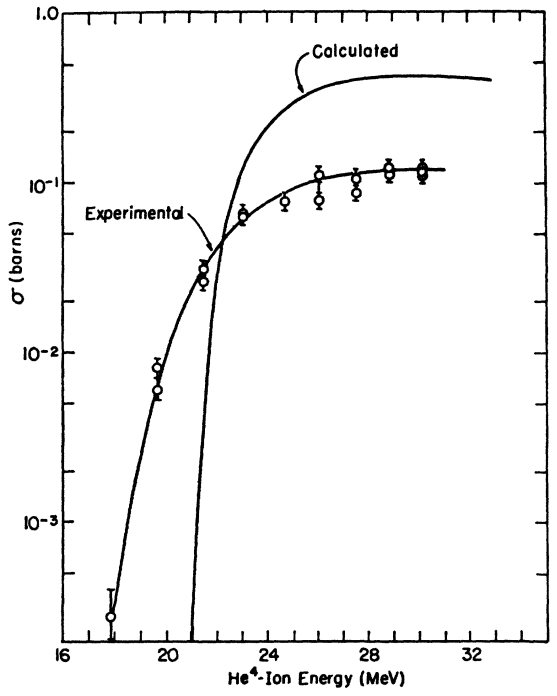


FIG. 1. Experimental and predicted excitation functions for production of $Sc^{42m}$ and $Sc^{42}$ by the $He^4$-ion bombardment of $Ca^{40}$. Experimental curve represents production of only $Sc^{42m}$. Calculated curve is for total production of $Sc^{42}$ isomers assuming mass value of $Sc^{42m}$ (see text).

where the energy at each point is the $He^4$-ion energy at the midpoint of the target. In order to determine if the position and shape were consistent with the assumption of a combination of $Ca^{40}(\alpha,pn)$ and $Ca^{40}(\alpha,d)$ reactions, calculations of the excitation functions predicted by the Monte Carlo method described by Dostrovsky *et al.*[15] were made. In the calculations the masses from König *et al.*[16] were used except for those of $Ti^{42}$, $Ti^{41}$, and $Sc^{42m}$. The $Ti^{42}$ and $Ti^{41}$ masses were predicted for this work from mirror-nuclide systematics. The mass for $Sc^{42}$ was calculated from that of $Ca^{42}$, the $Sc^{42}$–$Ca^{42}$ mass difference,[17] and the $Sc^{42m}$–$Sc^{42}$ mass difference determined in this work (see below). The $\delta$ values (used to correct level densities for even-odd effects) were those which Dostrovsky *et al.*[15] had determined for the nuclides around the $Z$ and $N=28$ closed shells. These values were applied without change to the nuclides around the $Z$ and $N=20$ closed shells. The level-density parameter $a$ was assumed to be $A/20$. Results of the

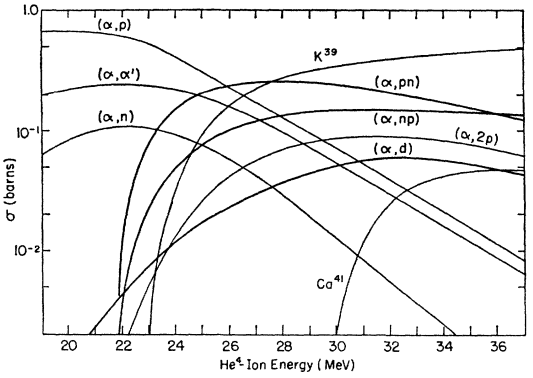


FIG. 2. Excitation functions for products from $He^4$-ion bombardment of $Ca^{40}$ predicted by the Monte Carlo method. In cases where several paths leading to the same final nucleus have been lumped together, the curves are designated by the product nucleus.

calculations are given in Fig. 2. In comparing the magnitude and shape of the calculated and experimental excitation functions, one must recall that the experimental cross sections are those for formation of only the high-spin isomer, whereas, the calculated curves are for total production of $Sc^{42}$ with mass that of $Sc^{42m}$. The major differences in shapes occur at low energies, probably as a result of the very approximate treatment of the proton and deuteron barrier penetration. In any case, it is clear that the excitation function is that for the $(\alpha,pn)$ and $(\alpha,d)$ reactions and not that for the $(\alpha,p)$ or $(\alpha,p2n)$ reaction. For the latter, the cross sections predicted for $He^4$-ion energies up to 35 MeV were less than 1 mb (threshold = 29.33 MeV).[16]

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[14] The authors are indebted to James T. Corless, Massachusetts Institute of Technology for performing this analysis.

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## 2. Gamma-Ray Spectroscopy

In addition to 0.511-MeV annihilation radiation, $\gamma$ rays of energies 0.438±0.003, 1.226±0.010, and 1.520 ±0.010 MeV are observed in the decay of $Sc^{42m}$. A $\gamma$-ray spectrum obtained using a 3-in.×3-in. NaI(Tl) crystal and graphite absorber is shown in Fig. 3. The crystal was mounted in a lead house in a geometrical configuration similar to that used by Heath to measure standard $\gamma$-ray spectra and to determine peak-to-total ratios.[18] The ratio of intensities of the three $\gamma$ rays after correction for absorption, peak-to-total ratios, and total counting efficiencies[18] is 1.00±0.03:1.00±0.01:1.00 for the 0.44-MeV:1.23-MeV:1.52-MeV $\gamma$ rays. The upper limit on the intensity of any other $\gamma$ rays is 1%. Gamma rays corresponding to "crossover" transitions occur in less than 0.3% of the decays.

Gamma-gamma coincidence experiments were performed using two 2-in.×2-in. NaI(Tl) crystals. Pulses from one branch of the system were stored in a 20-channel analyzer, previously described by Crut *et al.*[19] It is possible to obtain pulses from this analyzer when counts are stored in any preselected ranges of channels. Prior to the coincidence experiments, singles spectra were taken using the 20-channel analyzer. The analyzer was then adjusted to give output pulses $A$ or $B$ whenever counts were recorded in the channels corresponding to the photopeaks of one or the other of two of the principal $\gamma$ rays. When pulses from the two branches of the system were in fast (resolving time 20 nsec) and slow coincidence (~4$\mu$sec) and the pulse in the first branch fell in the group $A$ or group $B$ channels, the coincidence gate of a 256-channel pulse-height analyzer was opened for analysis of the signal in the second branch. With a group-$A$ pulse in the first branch, the pulse from the second branch was stored in the first 128 channels of the 256-channel memory. If the count in the first branch fell into the $B$ group, a routing pulse from the slow coincidence unit was fed to a programming unit[20] which caused the analyzer to store the pulse from the second branch in the second 128 channels. Using this setup, it was possible to obtain simultaneously the spectra coincident with two different $\gamma$ rays.

In the investigation of the $Sc^{42m}$ decay scheme, we obtained the spectra in coincidence with the 1.23- and 1.52-MeV $\gamma$ rays. The coincidence spectra indicated that the three $\gamma$ rays are in coincidence with each other and with annihilation radiation. The relative intensities of the $\gamma$ rays in the coincident spectra are, within experimental error, the same as those observed in the singles spectra, with the exception of the annihilation radiation whose intensity was 30 to 50% lower than in the singles spectra. The latter observation was the result

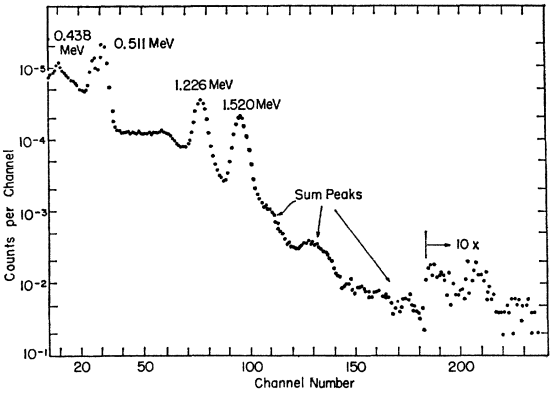


FIG. 3. Spectrum of $\gamma$ rays from decay of $Sc^{42m}$ showing the four major peaks and several sum peaks obtained using a 3-in.×3-in. NaI(Tl) crystal and graphite absorber.

of good collimation in front of the crystals in the coincidence experiments. The fact that, with the exception of annihilation radiation, the relative intensities of all the $\gamma$ rays remained the same in the coincident spectra indicates that the lifetimes of the parent states involved are shorter than the 20-nsec resolving time of the fast coincidence circuit. The spin changes in the transitions are thus limited to $\Delta I \leq 2$ (multipolarities $E2$, $M2$, $E1$, or $M1$, except no $M2$ for the 0.44-MeV $\gamma$ ray).

## 3. Beta-Ray Spectroscopy

Beta-ray spectra were determined using a split plastic scintillator shaped into a 45-deg cone with base diameter of 2.5 in. Analysis of the experimental spectra using the Kurie computer program[20,21] indicated that the main group of particles had an allowed positron shape with end point energy of 2.87±0.10 MeV. In addition, there were smaller contributions at high energies resulting from $\gamma$-plus-$\beta^+$ coincidence summing. The only other activity present in appreciable amounts was a few percent of 3.92-h $Sc^{43}$ from the $Ca^{40}(\alpha,p)$ reaction on the calcium target foil. These spectra exhibited no conversion-electron lines of energies between 0.05 and 4 MeV with as much as 2% of the total number of $\beta^+$ counts in the spectrum.

## 4. Half-Life Determination

Decay curves were obtained by use of a 256-channel pulse-height analyzer operating in the multiscaler mode at a channel-advance rate of 10 per min. The decay curves most nearly free of other activities were obtained from samples produced by $He^4$-ion bombardment of calcium and by counting only $\gamma$ rays of energy greater than 0.55 MeV. The $Sc^{42m}$ decay could be followed for at least seven half-lives before becoming small compared with the activity of long-lived components present.

[18] R. L. Heath, Atomic Energy Commission, Research and Development Report IDO-16408 (unpublished).
[19] M. Crut, D. R. Sweetman, and N. S. Wall, Nucl. Phys. **17**, 665 (1960).
[20] Paul C. Rogers, Ph.D. thesis, Massachusetts Institute of Technology, September, 1962 (unpublished).
[21] The Kurie computer program is designed for analysis of experimental $\beta$-ray spectra by the least-squares techniques. It also includes a means of correcting for the finite response of scintillation detectors of the types used in these experiments.

Decay data were analyzed using the FRANTIC computer program.[13] The main problem in determining the half-life accurately arose because of upward gain shifts in the photomultiplier tube resulting from high initial count rates from each $Sc^{42m}$ sample. This condition had the effect on the decay-curve analyses of yielding better fits to the data when a dead-time factor smaller than the experimentally determined value was used. When the measured dead-time factor was used, the analyses indicated the presence of a component of ~200-sec half-life in quantities far greater than expected on the basis of reasonable cross-section estimates for reactions involving less abundant calcium isotopes or impurities. The final value selected, 62.0±0.4 sec, was that obtained using an effective dead time per pulse of 11.5±2.0 μsec (measured value=18.8 μsec) in analyses of high-activity decay curves. This value of the effective dead time caused the analyses to yield reasonably small amounts of ~200-sec activity with a small variance-of-fit to the data. Approximately the same value for the half-life was obtained from analysis of low activity decay curves regardless of which dead-time factor was used. The uncertainty assigned to the quoted half-life value arises mainly from the gain-shift problem.

### 5. $Sc^{42}$-$Sc^{42m}$ Energy Difference

The $Sc^{42}$–$Sc^{42m}$ energy difference was determined by measurement of the energies of proton groups emitted in the $Ca^{40}(He^3,p)Sc^{42}$ reaction with a bombarding energy of 25 MeV. Protons were identified and their energies measured by use of an $E-\Delta E$ counting arrangement employing the electronics system described by Stokes *et al.*[22] A parallel-plate flowing-gas proportional counter served as the $\Delta E$ detector and a NaI(Tl) crystal detector was used to measure residual energies. Protons emitted in the $Be^9(He^3,p)B^{11}$ reaction were used to calibrate the energy scale.

The $Q$ value for formation of the ground state of $Sc^{42}$ is found to be 4.92±0.05 MeV. Proton groups of lower energies are observed, corresponding to formation of excited states of $Sc^{42}$ at 0.67±0.03 and 1.58±0.05 MeV. Although the spectrum of protons was measured at five angles, the angular distributions of the proton groups were not characterized well enough to obtain information on the spins of the levels formed. It is assumed that the first excited state is the 62-sec isomer. As noted below, support for this assumption is obtained from the energy cycle.

## III. DISCUSSION

The ground-state isomer of $Sc^{42}$ decays to the 0+ ground state of $Ca^{42}$ with a half-life of 0.689 sec[12] and $\beta^+$ end-point energy of 5.389±0.015 MeV.[17] As determined by our analysis using the Kurie program[21] for a 256-point numerical integration, the log $ft$ value for this transition, 3.477±0.010, corresponds to that of a superallowed transition for which $\Delta I=0$, no parity change, indicating that $Sc^{42}$ has spin 0+. Scandium-42, with one $f_{7/2}$ neutron and one $f_{7/2}$ proton outside the $_{20}Ca_{20}^{40}$ core, falls into the class of nuclides covered by the Brennan-Bernstein[23] rule $R2$, which predicts two rather closely spaced isomers of spins $|J_p-J_n|$ and $J_p+J_n$, or 0+ and 7+ for $Sc^{42}$. Thus, $Sc^{42m}$ probably has spin 7+, although our upper limits on the intensities of $\gamma$ rays and conversion electrons resulting from an isomeric transition allow us to say only that $I\geq 5$. We assume that the parity of the level is positive as the result of coupling of two $f_{7/2}$ particles.

TABLE I. Excited states of $Ca^{42}$.

| Braams[a] $Ca^{42}(p,p')$ (MeV) | Buechner and Mazari[b] $Sc^{45}(p,\alpha)$ (MeV) | This work $Sc^{42m}-\beta^+$ (MeV) |
|---|---|---|
| 1.523±0.004 | 1.526±0.006 | 1.520±0.010 |
| 1.836±0.004 | 1.836±0.006 | Not observed |
| 2.422±0.005 | 2.425±0.006 | Not observed |
| 2.750±0.005 | 2.753±0.006 | 2.746±0.014 |
| Not observed | 3.191±0.008 | 3.184±0.015 |
| 3.250±0.006 | | |
| 3.297±0.006 | | |
| 3.389±0.006 | | |
| Others | | |

[a] See reference 25.
[b] See reference 24.

The half-life of $Sc^{42m}$, 62.0±0.4 sec, and positron end point, 2.87±0.10 MeV, give a log $ft$ value of 4.185±0.068 as determined by the Kurie computer program.[21] This value corresponds to an allowed transition with $\Delta I=0, \pm 1$, no parity change. The excited state of $Ca^{42}$ populated in this decay deexcites by emission of a cascade of three $\gamma$ rays. Our data do not alone give the order of emission of the $\gamma$ rays, but by comparison with the energy levels of $Ca^{42}$ determined by Buechner and Mazari,[24] we find the order of $\gamma$ rays to be: 0.44, 1.23, and 1.52 MeV. The corresponding levels are compared with those determined by Braams[25] and Buechner and Mazari[24] in Table I.

In order to test the assignment of the 62-sec activity to the first excited state of $Sc^{42}$, the $Sc^{42}$–$Ca^{42}$ mass difference as determined by three paths is compared. By the first path, the difference is 7.08±0.10 MeV from the sum of the 3.19-MeV level in $Ca^{42}$ and $Q_{EC}$ of the $Sc^{42m}$ $\beta^+$ decay from this work. By the second path the difference is 7.08±0.04 MeV from the sum of $Q_{EC}$ for the $Sc^{42}$ $\beta^+$ decay[17] and $Sc^{42m}$–$Sc^{42}$ difference from our work. For the final path, the value is 7.08±0.05 MeV from the $Q$ value for formation of the first excited state of $Sc^{42}$ via the $Ca^{40}(He^3,p)$ reaction and $Ca^{40}$ and $Ca^{42}$ masses from König *et al.*[16] This assignment is in agreement with

[22] R. H. Stokes, J. A. Northrop, and K. Boyer, Rev. Sci. Instr. **29**, 61 (1958).

[23] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

[24] W. W. Buechner and M. Mazari, Rev. Mex. Fis. **7**, 117 (1958).

[25] C. M. Braams, thesis, Utrecht, 1956 (unpublished). Data given in reference 24.

the measurements by Nelson and co-workers[8,9] which showed directly that the 62-sec isomer lies above the 0.69-sec $Sc^{42}$ isomer. Their measurements of the thresholds for production of the various states by the $K^{39}(\alpha,n)$ reaction indicate the $Sc^{42m}$–$Sc^{42}$ energy difference to be $0.526\pm0.04$ MeV with a second excited state at 1.34 $\pm0.06$ MeV. The difference between these energies and those of the same levels as determined in this work ($0.67\pm0.03$ MeV and $1.58\pm0.05$ MeV, respectively) are not understood.

Our proposed decay scheme for $Sc^{42m}$ and other information on the levels of $Ca^{42}$ from nuclear-reaction studies and decay of $K^{42}$ are given in Fig. 4. Arguments for the assignments of spins and parities to the various levels are given in the following paragraphs.

The first three excited states of $Ca^{42}$ are known to be 2+, 0+, and 2+(1+), respectively, with the 2+ favored from systematics,[10,11] for the third. The fourth excited state, at 2.75 MeV, is concluded by Morinaga *et al.*[10] to be 0+ or 4+ and by McCullen and Kraushaar[11] to be 0+ or $\geq4$. The fifth excited state, at 3.19 MeV, can be limited to $\geq4+$ from the allowed $Sc^{42m}$ $\beta^+$ decay and observed lower limit ($\geq5+$) on the spin of $Sc^{42m}$. Of the possibilities discussed above for the spin of the 2.75-MeV level we can rule out 0+, as the level is fed from the 3.19-MeV state of spin $\geq4+$ and the transition multipolarities are limited to $E2$, $E1$, or $M1$. By the same reasoning, the transition from the 2.75-MeV level to the 2+ level at 1.52 MeV requires the spin of the former to $\leq4$. Thus, we conclude that the 2.75-MeV level has spin 4+.

With the spin of the 2.75-MeV level assigned 4+, only three combinations for the spins of the $Sc^{42m}$ isomer

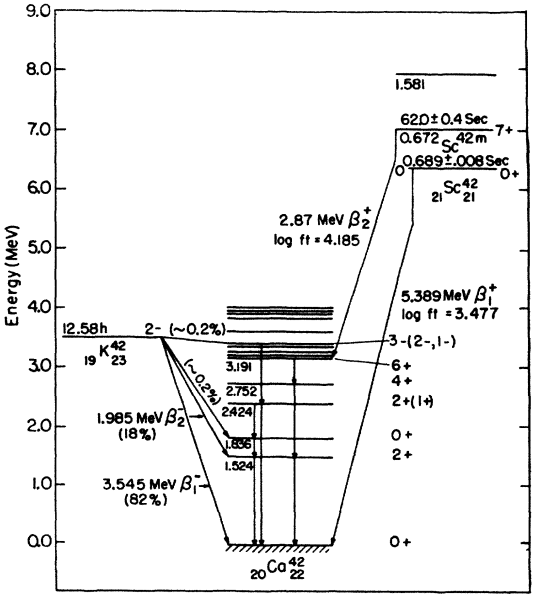


FIG. 4. Level structure of $Ca^{42}$ and proposed decay scheme of $Sc^{42m}$ with data from the $K^{42}$ decay (references 10, 11).

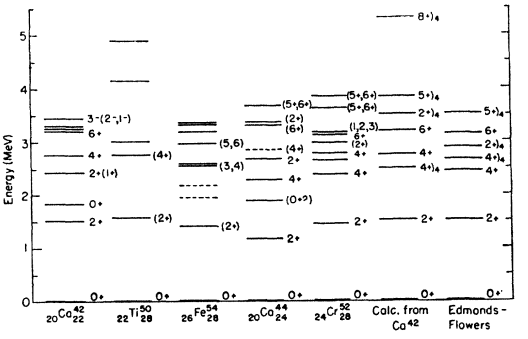


FIG. 5. Experimental and predicted level structures of even-$A$, single-closed-shell nuclides in the $f_{7/2}$ region. $Ca^{42}$, this work; $Ti^{50}$ and $Fe^{54}$, reference 28; $Ca^{44}$, reference 29; $Cr^{52}$, reference 30.

and $Ca^{42}$ level at 3.19 MeV are possible in view of the allowed $\beta$ decay with no branching and the limitation of multipolarities in the $\gamma$ transitions as noted above. The three combinations are: (7+, 6+), (6+, 6+), and (6+, 5+) for the isomer and $Ca^{42}$ state, respectively. From measurements of the $Ca^{40}(\alpha,d)$ reaction, Harvey *et al.*[26] have found that the spin of $Sc^{42m}$ is definitely not 6. Therefore, we conclude that the spins of $Sc^{42m}$ and the 3.19-MeV level of $Ca^{42}$ are 7+ and 6+, respectively.

## IV. INTERPRETATION

The existence of the $Sc^{42m}$ isomer gives further support to the Brennan-Bernstein[23] hypothesis that nuclides falling in class $R2$ (containing two odd "particles" or "holes," as distinguished from "particle-hole" combinations, both having $j=l+1/2$ or $j=l-1/2$) have two close-lying levels of spins $|J_p-J_n|$ and $J_p+J_n$. As Jänecke[27] has pointed out, $Cl^{34}$ and $Sc^{42}$ are exceptions to the general observation that, in self-conjugate nuclides, the level having isotopic spin, $T$, of zero lies below the one having $T=1$.

In Fig. 5, are shown the low-lying levels in the single-closed-shell (s.c.s.) nuclides having even numbers of $f_{7/2}$ nucleons [$Ca^{42}$(this work,) $Ti^{50}$ and $Fe^{54}$,[28] $Ca^{44}$,[29] and $Cr^{52}$ [30]] and the positions of the levels as calculated by the methods of Talmi[4] and Edmonds and Flowers.[3]

According to Talmi's method the states are described by $jj$-coupling wave functions and it is assumed that the only effective interaction (assumed to be the same within a subshell) is a two-body force. The radial wave functions are not specified, but it is assumed that they are not changed by addition of nucleons within the subshell. Using this model, it is, for example, possible to

[26] B. G. Harvey (private communication).
[27] J. Jänecke, Nucl. Phys. **30**, 328 (1962).
[28] See compilation in Landolt-Börnstein, *Numerical Data and Functional Relationships in Science and Technology*, New Series, Group I: Nuclear Physics and Technology, Vol. 1, Energy Levels of Nuclei: $A=5$ to $A=257$, edited by A. M. Hellwege and K. N. Hellwege (Springer-Verlag, Berlin, 1961).
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predict the positions of the $f_{7/2}^n$ levels in various $f_{7/2}$ s.c.s. nuclides from the positions of the $f_{7/2}^2$ levels. Using the prescriptions given by de-Shalit,[31] we have calculated the predicted positions of $f_{7/2}^n$ levels in nuclides of this type based on the levels of $f_{7/2}^2$ in $Ca^{42}$. (The same type of calculation with essentially the same results has been reported in reference 32.) The results for even nuclides are shown in Fig. 5. According to the model, the 2+, 4+, and 6+ seniority $2(v=2)$ levels should occur at the same heights above the 0+ ($v=0$) ground states in all of the even nuclides. Also, the 2+, 4+, 5+, and 8+ ($v=4$) levels in $Ca^{44}$ and $Cr^{52}$ would be expected to lie at the same energies.

It is seen that, where one can clearly identify the levels, there is rather good agreement in the positions of the $v=2$ levels from one nuclide to another, with the exception of those of $Ca^{44}$. Note, however, that with the new spin assignments[29] among the $Ca^{44}$ levels, agreement with the other $f_{7/2}$ nuclides has been considerably improved, although the first excited state still falls at a surprisingly low energy. The $v=4$ levels of $Cr^{52}$ having an $f_{7/2}^4$ proton configuration, appear to agree reasonably well with the predictions based on the $Ca^{42}$ levels. It has been noted[32] that the lower 4+ level in $Cr^{52}$ probably has seniority 4. In $Ca^{44}$, the 4+ level at 2.28 MeV may also have $v=4$, but there is not enough information to determine the seniority with certainty. We have also calculated the predicted positions for levels of $f_{7/2}^3$. There is little experimental information for comparison; however, the level ordering in $V^{51}$ appears to be in good agreement with predictions, but the level spacings are generally smaller in the experimental level structure than in that predicted from the $Ca^{42}$ levels.

Edmonds and Flowers[3] have calculated the relative positions of levels in $f_{7/2}$ nuclides using the $jj$-coupling model, oscillator wave functions of the form $\phi_l \exp[-\frac{1}{2}(r/a_0)^2]$, and a residual two-body interaction of Gaussian shape described by $V(r)=D\exp[-(r/a)^2]$. In Fig. 5, we have shown their calculated level positions for a range parameter $(a/a_0)$ of 1.4, normalized to the $Ca^{42}$ first excited state. Their predictions are in rather good agreement with those based on Talmi's model and with the experimental data, although the positions of the two 4+ levels are inverted in the Edmonds-Flowers predictions. There is an inversion of the 4+ levels upon going to the Edmonds-Flowers range parameter of 2.0; however, the other levels are not well fitted using this value of the parameter. If the level in $Cr^{52}$ at 2.965 MeV is the 2+ ($v=4$) level, its position is reproduced better by the Edmonds-Flowers predictions than by those obtained using Talmi's method and the $Ca^{42}$ levels.

The $jj$-coupling model accounts rather well for the general features of levels in $f_{7/2}$ nuclides. However, in the forms presented by Talmi and Edmonds and Flowers, it does not seem capable of explaining the rather different position of the first excited state in $Ca^{44}$. An additional feature that has not been explained is the origin of the 0+ and 2+ (1+) levels in $Ca^{42}$ at 1.84 and 2.42 MeV, respectively. One might suspect that they are the $(p_{3/2}^2)_{0,2+}$ levels; however, on the assumption that the 3/2− level at 1.95 MeV in $Ca^{41}$ is the $p_{3/2}$ level, one would expect the $(p_{3/2}^2)_0-(f_{7/2}^2)_0$ energy difference to be of the order of 3.9 MeV. If the levels at 1.84 and 2.42 MeV in $Ca^{42}$ are mainly $p_{3/2}^2$, considerable mixing of other configurations would be needed to bring the energy levels down to such low values. It is not clear whether or not corresponding levels are present in the other even $f_{7/2}$ nuclides. There are poorly established levels in $Fe^{54}$ at 1.95 and 2.17 MeV, and a well-established, but unclassified, level at 2.55 MeV. The (0+) level in $Ca^{44}$ at 1.88 MeV is possibly an analog of the 0+ level at 1.84 MeV in $Ca^{42}$. Of the two 2+ levels at 2.66 and 3.35 MeV in $Ca^{44}$, one is probably the $f_{7/2}^4$, $v=4$ level and the other may be analogous to the 2.42-MeV level of $Ca^{42}$. In $Ti^{50}$ and $Cr^{52}$, there are no unexplained levels below 2.5 MeV, although in $Cr^{52}$ there are unexplained levels at 2.65 and 3.16 MeV. (Zaika and Nemets[33] note a possible unresolved level in $Ti^{50}$ "at low energy" from $(d,p)$-reaction data.) Thus, if the $jj$-coupling model is to be able to give a more complete description of the $f_{7/2}$ nuclides, the origin of the $Ca^{42}$ levels at 1.84 and 2.42 MeV must be considered and the absence or shift of the corresponding levels to higher energies in the other even $f_{7/2}$ nuclides explained.

The possible influence of collective effects in this region is not clear. In $Ca^{42}$ one might be tempted to describe the levels as being mainly vibrational, with the 1.84-, 2.42-, and 2.75-MeV levels representing the 2-phonon state, and the 3.19-MeV 6+ level being one member of the 3-phonon state. However, the mean position of the assumed 2-phonon levels, 2.5 MeV, is considerably less than twice the energy of the first excited (1.52-MeV) level. Raz[5] has calculated the positions of levels obtained in $f_{7/2}$ nuclides when a weak or intermediate surface interaction is added to the two-body interaction. The ratios of the energies of upper levels to that of the 2+ first excited state are given as a function of the strength of the two-body force, $D$, and a surface-interaction parameter, $x$. Using the corrected curves[34] for $D=0.2$, excellent fits to the ratios $E_{4+}/E_{2+}$ and $E_{6+}/E_{2+}$ in $Ca^{42}$, $Ca^{44}$, and $Cr^{52}$ are obtained using $x$ values of 0.02, 0.32, and 0.08, respectively, assuming for $Ca^{44}$ and $Cr^{52}$ that the upper 4+ levels have $v=2$. Note that the value of $x$ is determined by the ratio $E_{4+}/E_{2+}$, and the ratio $E_{6+}/E_{2+}$ provides an independent check. Although, in their present formulation, Raz' calculations do not explain the anomolous levels (e.g.,

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the 1.84- and 2.42-MeV levels in $Ca^{42}$), the good fits obtained suggest that the model deserves further attention. Kisslinger and Sorensen[6] have made an extensive study of levels using a model based on strong short-range (pairing) forces and longer range ($P_2$) forces; however, they have not extended their model to include nuclides below the $N=28$ shell.

### ACKNOWLEDGMENTS

We wish to acknowledge the cooperation of Dr. Donald R. F. Cochran of Los Alamos in the early phases of this work and in the other $He^3$ bombardments, and Dr. Jere D. Knight of Los Alamos for his many helpful suggestions. We thank Drs. Allen Blair and Harvey E. Wegner for use of their equipment in the $Ca^{40}(He^3,p)$ experiment. One of us (PCR) expresses his gratitude to Drs. George A. Cowan and J. M. B. Kellogg for the opportunity of performing the $He^3$ experiments at the Los Alamos Scientific Laboratory. We thank Professor Charles D. Coryell for his critical reading of the manuscript. The IBM-7090 computer of the MIT Computation Center was used in the analysis of data in this work.

PHYSICAL REVIEW VOLUME 129, NUMBER 6 15 MARCH 1963

# Kinetic Energy Release in 23-MeV Deuteron Fission of $U^{238}$†

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Average recoil ranges have been measured for six fission products formed by reactions of 23-MeV $H^2$ with $U^{238}$. The ranges of products from near-symmetric fission ($Cd^{115}$ and $Ag^{111}$) are longer than for neutron fission of $U^{235}$, while the ranges of asymmetric products ($I^{131}$, $Ba^{140}$, $Mo^{99}$, and $Sr^{89}$) are shorter. The kinetic-energy deficit for near-symmetry fission is $15\pm6$ MeV smaller for this system than for thermal-neutron fission of $U^{235}$. The magnitude of the kinetic-energy deficit for $U^{236}$ fission is re-examined by comparing range data with recent time-of-flight measurements and neutron emission probabilities. This comparison leads to a kinetic-energy deficit of approximately 23 MeV for $U^{236}$ fission.

## I. INTRODUCTION

MANY different measurements have been made of velocities, energies and ranges of fission products from various kinds of fission.[1,2] One interesting feature of many of these measurements is that the kinetic energies of near-symmetric fission products seem to be significantly smaller than the asymmetric products. We define the term "kinetic-energy deficit" as the difference between maximum kinetic-energy release and that for symmetric fission. This kinetic-energy deficit has been reported for several fissile nuclei at excitation energies near the threshold.[1–3] A few experiments have been reported at very large excitation energies,[4,5] but there is very little information about this effect at excitation energies a few tens of a MeV greater than threshold.[3,4] The quantitative evaluation of this kinetic energy deficit has not, as yet, been established for low-energy fission. Coincidence-counting techniques have been very successful for measurements of the energies of asymmetric products.[1,2] But various difficulties have prevented these techniques from obtaining unambiguous results for the symmetric fission products of much lower yield. Radiochemical recoil range measurements have perfect resolution, but conversion from range to energy requires some assumptions.

Several workers have reported range measurements for thermal-neutron induced fission of $Pu^{239}$ and $U^{235}$ and spontaneous fission of $Cf^{252}$.[6–10] The analysis of these data is based on a comparison with velocity measurements of the fragments of high yield.[8–10] From the velocities and an assumption of the number of neutrons emitted per fragment, one can obtain final kinetic energies after neutron emission. Then one obtains range-energy relationships for products of asymmetric fission. These range-energy relationships are extrapo-

† Work done under the auspices of the U. S. Atomic Energy Commission.
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