The cases permitted by these selection rules are represented by dots.

From this table, we can deduce some properties of the meson; for instance, the τ meson should be PS or PV_{pv}, the χ meson decaying into a π meson and γ should be V or PV, and the χ meson decaying into $\pi^{\pm}$ and π^0 should be S or V. Therefore if we wish to identify the χ meson with the τ meson, we see that this is possible only if $\chi^{\pm}(\chi^{\pm}\rightarrow\pi^{\pm}+\gamma)$ is PV_{pv}, but it is not possible for us to identify $\chi^{\pm}(\chi^{\pm}\rightarrow\pi^{\pm}+\pi^0)$ with the τ meson. In other words, we may have the possibility that $\chi^{\pm}\rightarrow\pi^{\pm}+\gamma$ is an alternative decay scheme of the τ meson, but $\chi^{\pm}(\chi^{\pm}\rightarrow\pi^{\pm}+\pi^0)$ should be regarded as different from the τ meson. The above argument is valid under the assumption, now well established, that the π meson is a pseudoscalar.

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* National Research Laboratories Postdoctoral Fellow.

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Rotational Nuclear Energy Levels from Coulomb Excitation

G. M. Temmer and N. P. Heydenburg
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
(Received April 16, 1954)

One of the predictions of the so-called collective model of the nucleus[1] concerns the existence of a low-lying rotational level spectrum in strongly deformed nuclei encountered in regions between closed shells. In the simplest strong-coupling approximation, the positions of these levels are given by the following expressions involving the spin I and moment of inertia $\mathfrak{J}$ ($\sim$square of nuclear deformation):

(a) even-even nuclei: $E_I=\dfrac{\hbar^2}{2\mathfrak{J}}I(I+1);\quad I=0^+,\ 2^+,\ 4^+\cdots,$

(b) odd-A nuclei: $E_I=\dfrac{\hbar^2}{2\mathfrak{J}}[I(I+1)-I_o(I_o+1)];$

$I=I_o,\ I_o+1,\ I_o+2,\ \cdots$ (same parity as I_o).

Bohr and Mottelson in their original article[1] pointed out that Coulomb excitation was especially suited to investigate this level system, and the celebrated case of Ta^{181} discovered by Huus and Zupančič[2] exhibits the first two excited states where predicted. Because of the limitation to $E2$ transitions in the excitation process[3,4] we expect only two levels to be excited in odd nuclei, and only one (2^+) in even-even nuclei. A number of cases of great regularity in the even-even nuclei of the heavy element region studied by alpha and gamma spectroscopy have been noted.[5,6] Encouraged by one more apparent case of agreement with rotational interpretation (Eu^{153}) in our last publication,[4] called to our attention by Bohr and Mottelson,[7] we have carefully reexamined the nuclei of mass number between 150 and 190 (mainly rare earth region) where excessively large quadrupole moments (strong deformations) are known to exist. We used alpha particles as in our previous work[3,4]; since only the oxides of the rare earths are available, this turns out to be the only way to avoid prohibitive gamma-ray backgrounds. We raised our bombarding energy to 3.4 Mev, thus gaining a factor of two or more in the excitation cross section[8] of energy levels lying between 200 and 300 kev; we also used some 30 mils of copper absorber to cut down on the x-ray as well as the first excited state gamma intensity. Our work was of course done with ordinary isotopic mixtures of the elements (some separated isotopes are on order), but the inherent difference in the spectra of even and odd nuclei permits a rather simple identification in most cases. In Table I we present the results obtained. We list in turn: the element; the number and total percent abundance of the even-even isotopes; the number and total percent abundance of the odd isotopes; the spins I_o of the latter; the theoretically predicted ratio $\rho=(2I_o+3)/(I_o+1)$ of second excited state energy to first excited state energy for the odd isotopes; the experimental values of the energies of the gamma rays; and finally, the predicted value for the second excited state energy, considering the lowest-energy gamma ray to come from the first excited state. It is likely that the latter gamma peak contains not only the odd first excited states, but also the even-even gamma rays in some cases, so that the intensities observed are not directly meaningful. However, there seems to be a systematic difference between the moments of inertia of neighboring even and odd nuclei, in such a direction as to depress the first excited states of the odd species (larger $\mathfrak{J}$). In the cases of Sm and Lu we were able to resolve the higher-energy gamma ray probably belonging to the even nuclei. In addition to the nuclei listed in Table I, we have preliminary evidence concerning similar agreement in $_{64}$Gd; this case as well as $_{60}$Nd and $_{72}$Hf will be reexamined with separated isotopes. In the case of $_{65}$Tb the results are inconclusive; in $_{69}$Tm there seem to be no higher excited states. It is perhaps interesting that the latter nucleus has spin 1/2 and is not expected to exhibit simple regularities.[1]

Table I. Summary of results on rotational energy levels in the region $150<A<190$. Z = element; $A(e-e)$ = number and (total percent abundance of even-even isotopes); $A(o)$ = number and (total percent abundance of odd isotopes); I_o = ground-state spin of odd isotopes; ρ = theoretical ratio of second to first excited state energies for odd isotopes; E = observed gamma-ray energies; E_{I_o+2} = energy predicted for second excited state. Italicized numbers designate second excited state gamma rays.

Z	$A(e-e)$	$A(o)$	I_o	ρ	$E\gamma$	E_{I_o+2}
$_{60}$Nd[a]	5(79.5)	2(20.5)	$7/2^-$	2.222	70,[b] 128, *290*	285
$_{62}$Sm	5(71.1)	2(28.9)	$7/2^-$	2.222	82, 122,[b] *186*	182
$_{63}$Eu	···	2(100)	$5/2^+$	2.286	81, 108,[c] *189*	185
$_{66}$Dy	5(56.1)	2(43.9)	$7/2^-$	2.222	76, *166*	169
$_{67}$Ho	···	1(100)	$7/2^+$	2.222	93, *205*	207
$_{68}$Er	5(77.1)	1(22.9)	$7/2^-$	2.222	79, *174*	175
$_{70}$Yb	5(69.6)	2(30.4)	$5/2^-$, $1/2^-$[d]	2.286	81, 114,[b] *180*	185
$_{71}$Lu	···[e]	1(97.4)	$7/2^+$	2.222	113, 183,[f] *248*	251
$_{72}$Hf[a]	4(67.8)	2(32.2)	$3/2^-$ or $1/2^-$	2.400	93,[b] 112, *250*	269
$_{73}$Ta	···	1(100)	$7/2^+$	2.222	137, 167,[c] *303*	304
$_{77}$Ir	···	2(100)	$3/2^+$	2.400	133, 219,[c] *360*	319

[a] Tentative pending study with separated isotopes.
[b] Known or presumed first excited state(s) of even-even isotope(s).
[c] Probable or known cascade gamma ray from second to first excited state.
[d] Yb^{171} (14.3 percent) has spin $1/2^-$ and hence uncertain level positions (see reference 1).
[e] Odd-odd nucleus Lu^{176} (2.6 percent).
[f] Unassigned line.

Since the ratios are not far from two, it is difficult to resolve the cascade transition (if any) between second and first excited states; we were able to see it only in the cases of Ta (167 kev),[9] Eu (108 kev), and possibly in Ir (219 kev). We intend to locate these transitions by coincidence studies. They are of course important in determining absolute transition probabilities. Within the limits of our rough preliminary results, the relative excitation cross sections of first and second excited states also agree with the simple predictions of the collective model in terms of the intrinsic quadrupole moment Q_0.[1] By way of summary, we would like to point out the following:

(1) The upward trend of the positions of the first excited states is clearly discernible as we approach the 82-neutron and 126-neutron closed shells, being more rapid toward the former than toward the latter. This trend, for even-even nuclei, has been variously noted.[10,11]

(2) In spite of these variations, and the variations in the ground-state spin from 3/2 to 7/2, the second excited state positions seem to agree with the simple predictions within our experimental

errors in all cases except Hf and Ir. The rotational character of these levels seems difficult to refute.

(3) If the rotational interpretation is accepted, we of course automatically obtain spin and parity assignments for all levels. The second rotational states will probably never be observed except in Coulomb excitation because of their high spins.

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Mean Lives of Positive and Negative Mu Mesons*

N. N. Biswas and M. S. Sinha
Bose Institute, Calcutta, India
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It is now well established that the apparent mean life of negative mu mesons decreases very rapidly as the atomic number of the absorbing medium increases and that this is entirely due to the rapid increase in the capture probability of the mu mesons by the gradually increasing positive charge of the nucleus.[1–5] The mean life for free decay of negative mu mesons is the same as that of the positives, and the apparent mean life of negative mesons is given by $1/\tau_- = 1/\tau_+ + \Lambda$, where Λ is the capture probability of the negatives by the nucleus. Under these circumstances the number of mesons remaining undecayed at any time t is given by

$$N_t = N_0^+ \exp(-t/\tau_+) + N_0^- \exp(-t/\tau_-), \qquad (1)$$

where N_0^+ and N_0^- are the number of positive and negative mu mesons available for decay at $t=0$. The number of negatives remaining undecayed after a time t equal to three times its apparent mean life is less than five percent. Hence if an integral decay curve is plotted with points close together, starting from a time as small as possible avoiding counter lags, we expect that the line joining the first few points would show a slope much sharper than that joining the points where the number of negative decays has falled to a very low value. The slope of the latter part of the curve, in fact, would give the mean life of positives as has been shown by Morewitz and Shamos[6] in the case of sulfur.

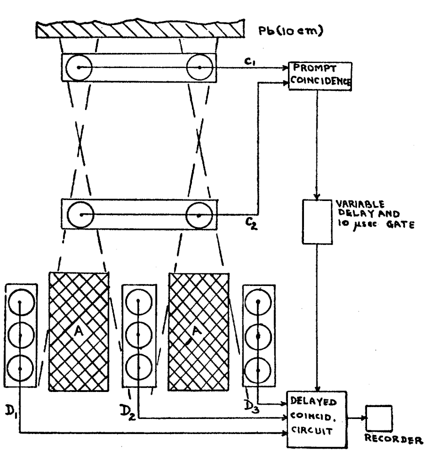

Fig. 1. Experimental arrangement.

The integral decay curves for a composite beam of mesons in Al, S, C, and Pb have been obtained in this laboratory by the delayed-coincidence technique. In the experimental arrangement as shown in Fig. 1, the twofold counter telescopes select an almost vertical beam of mesons and the trays D_1, D_2, D_3 detect the decay electrons. The meson-absorbing medium has been split up into two (A,A) in order to reduce the path length that a decay electron has to traverse to enter any of the D trays. The arrangement as a whole favors to increase the counting rates of the decay events.

Of the decay curves shown in Fig. 2, those for Al and S show

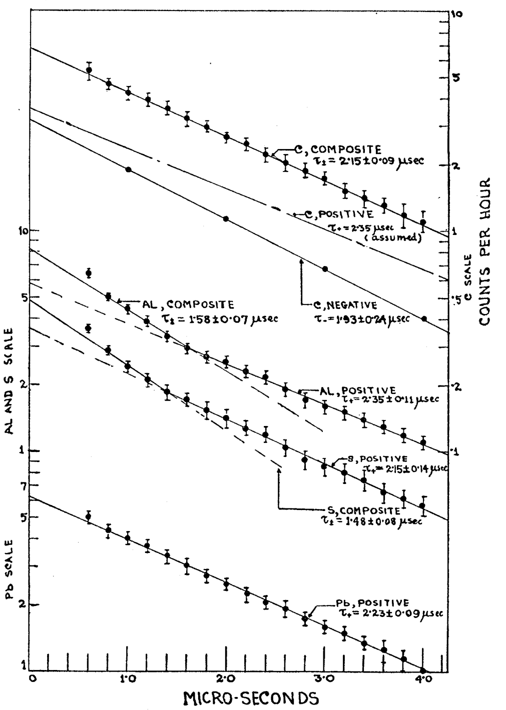

Fig. 2. Decay curves for μ mesons in C, Al, S, and Pb.

distinctly two separate slopes while those for C and Pb with the same experimental setup show only one. This is expected since the apparent mean life of negatives in C is not much less than that of the positives, which implies that the negatives were still available for decay at 4.0 microseconds. In the case of Pb the decay curve yields a mean life of 2.23 ± 0.09 microseconds, which can be attributed to the decay of positives alone, because the number of negatives recorded in this case is negligible on account of their high capture probability by the lead nucleus. The point corresponding to 0.6 μsec was not given much importance because it is suspected to include some spurious events due to the distribution of random lags in the discharge of the G.M. counters.[7] This has also been the case with curves obtained by Rossi and Nereson[8] and Sigurgeirsson and Yamakawa.[9]

For elements of $Z \leq 16$, the composite decay mean lives show a gradual increase with decrease of Z, thereby indicating that τ_- increases as Z decreases and reaches the limit of τ_+ for $Z<6$. In Al and S, the determination of the mean lives of negatives alone could be done by subtracting the extrapolated dashed line (positive decays) from the composite curve, but this was not attempted since the statistical errors were too large to estimate the values of