When the incident particle is a deuteron, the deuteron stripping and heavy particle stripping can compete. In these cases the angular distribution can be written

$$W(\Theta)=A_1G_1^2(K_1)j_l^2(k_1R_1)+A_2G_2^2(K_2)j_{l'}^2(k_2R_2),$$

where

$$K_1=\{k_n^2+\tfrac{1}{4}k_i^2-k_ik_n\cos\Theta\}^{\frac{1}{2}},$$

$$k_1=\left\{k_i^2+\left(\frac{M_i}{M_f}\right)^2k_n^2-2k_ik_n\left(\frac{M_i}{M_f}\right)\cos\Theta\right\}^{\frac{1}{2}},$$

l= capture angular momentum for deuteron stripping, and R_1= the radius of interaction for deuteron stripping.

Figure 2 illustrates a calculation in which both types of stripping might occur.

Figure 1 shows a calculation of heavy particle stripping for the $Be^9(\alpha,n)C^{12}$ reaction at 1 Mev and 4 Mev. The increase of intensity in the backward direction is evident. Figure 2 shows the results for the $B^{11}(d,n)C^{12}$ reaction to the ground state. The dotted curve indicates the contribution of heavy particle stripping using the parameters shown. The solid curve shows the sum of the usual deuteron stripping, plus the heavy particle stripping. The curves are drawn for a bombarding energy of 4.1 Mev, and the experimental points of Class, Price, and Risser[4] are superposed. The theoretical curves were drawn so that the heavy particle stripping is normalized at 160° where the contribution from deuteron stripping is very small, and the deuteron stripping is normalized at 20°. The fit seems fairly good, suggesting that a heavy particle stripping process may exist, in spite of the fact that the stripped neutron comes from a closed P shell and is strongly bound. Calculations at an energy of 3.5 Mev and 4.7 Mev also show agreement with the experimental data.[4]

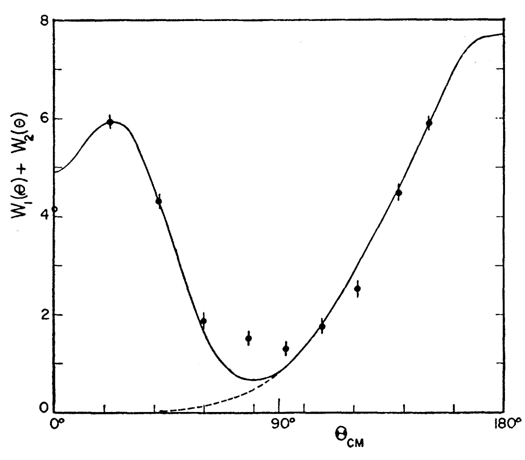

FIG. 2. The angular distribution of the neutrons from the reaction $B^{11}(d,n)C^{12}$ illustrates the type of reaction in which both deuteron stripping and heavy particle stripping can occur. The radius of interaction for both processes is $4.5\times(10)^{-13}$ cm. $E=4.1$ Mev. The experimental points are those of Class, Price, and Risser.

If indeed the heavy particle stripping accounts for the backward component of the angular distribution of the neutrons from the reaction $B^{11}(d,n)C^{12}$, the cross section for this process must be comparable with that for the deuteron stripping. An estimate of the nuclear matrix element can be obtained by using the partial width technique suggested by Bhatia.[1] This involves an estimate in this particular reaction of the sticking probability for a deuteron and the "B^{10} core." From the available data it appears that the cross sections for the reactions involving a deuteron and B^{10} are relatively high, suggesting that the heavy particle stripping in $B^{11}(d,n)C^{12}$ could be of the same order of magnitude as the deuteron stripping. The fact that the outgoing neutron can belong to the target nucleus has been suggested by Grant,[2] by considering the effect of exchange terms in the stripping problem. We have not considered these effects in our simple calculation.

We are indebted to Professor Calvin Class for discussing his recent results with us. We would like to thank Professor T. H. Berlin for many stimulating discussions.

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Fast $E2$ Transition Probabilities from Coulomb Excitation*

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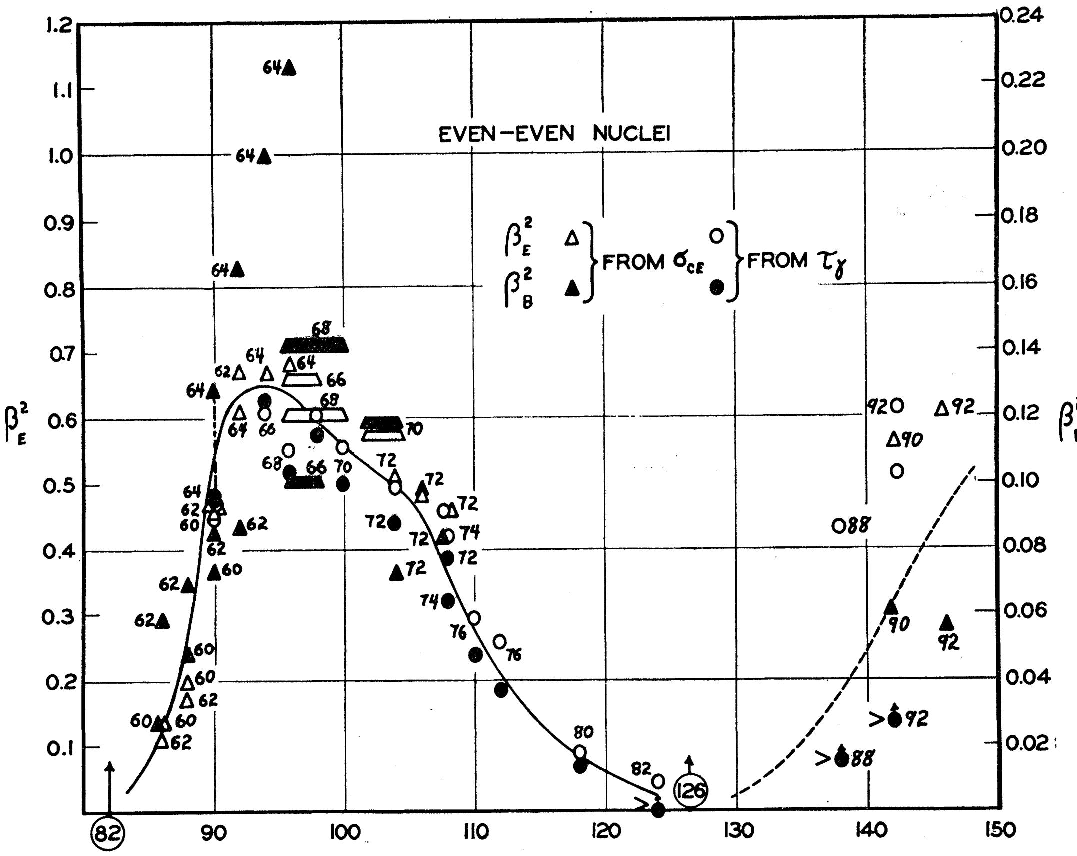
WE thought it worthwhile to present a summary of our results on positions and lifetimes of excited states of nuclei in the region $Z=60$ to $Z=92$ ("strong coupling region")[1] and $Z=22$ to $Z=48$ ("weak coupling region").[1] We shall confine ourselves to even-even nuclei because they lend themselves more readily to a systematic description. $E2$ Coulomb excitation allows us to observe only one excited state in all cases (the first-excited state having character 2^+); the systematic trend in the positions of these states is well known.[2] Our studies of thin-target excitation functions using alpha particles,[3] as well as some thick-target excitation functions extending from 2.5 Mev to 7.00 Mev alpha-particle energy (a range in yields of $>10^4$), in perfect agreement with the semiclassical $E2$ theory,[4] convince us that we are able to extract meaningful reduced $E2$ transition probabilities $B(E2)$ from measurements of the total excitation cross sections. A few cases of overlap with conventional electronic lifetime measurements in the rare-earth region ($\tau_{\text{exp}} \gtrsim 10^{-9}$ sec, see below) confirm this belief.

We have been able to determine the properties of about 50 first-excited states in even-even nuclei, of which about 15 are newly discovered levels. Some 10 lifetimes had been determined electronically for $62 \leq Z \leq 80$, and two by resonance fluorescence.[5] The former method is presently limited to this range of Z by the fifth-power dependence of the transition probability upon the gamma-ray energy, and by the speeding-up effect of the high internal conversion coefficients for the low-lying transitions encountered in the actinide and transuranic elements ($E_{2^+} \leq 50$ kev).

All our results were obtained with He^{++} particles of up to 7.00 Mev and some 25 isotopically enriched targets.[6] We shall now discuss the two regions of the periodic table in some detail.

Strong-coupling region (*Rare earths*, Th, U).—The evidence for the occurrence of rotational bands in the highly deformed nuclei of this region has been extensively discussed.[7–12] Our detailed report on both even and odd nuclei in this region will appear shortly.[12] Sunyar[5] has recently summarized the available information on fast $E2$ lifetimes; following his presentation of the results in terms of the nuclear distortion parameter β, we have plotted both his results (circles) and our Coulomb excitation results (triangles) in Fig. 1. Open symbols refer to deformation parameters β_E derived from level positions (moments of inertia) and are read from the left-hand scale; full symbols refer to deformation parameters β_B derived from reduced transition probabilities to or from the levels and are read from the right-hand scale. Note the factor of *five* between the two ordinate scales. β is related to the intrinsic quad-



Neutron Number $N \rightarrow$

FIG. 1. Summary of deformations for even-even nuclei in the "strong coupling" region ($Z=60$ to $Z=92$). Open symbols represent deformations derived from level positions (β_E) and are read from the left-hand scale; full symbols refer to deformations deduced from reduced transition probabilities (β_B) and are read from the right-hand scale. Note factor of *five* between those scales. *Triangles* represent our data from Coulomb excitation (σ_{CE}); *circles* are from lifetime and resonance fluorescence measurements as summarized by Sunyar (τ_γ, reference 5). Numbers near points stand for Z of the elements. Wide symbols covering several neutron numbers refer to targets without available enriched isotopes (Dy, Er, Yb), and represent averages. Vertical dotted line at $N=90$ links two points referring to the same transition in $_{64}Gd^{154}$; for discussion of high points at $Z=64$, see text. Points with > represent lower limits. Magic numbers are circled.

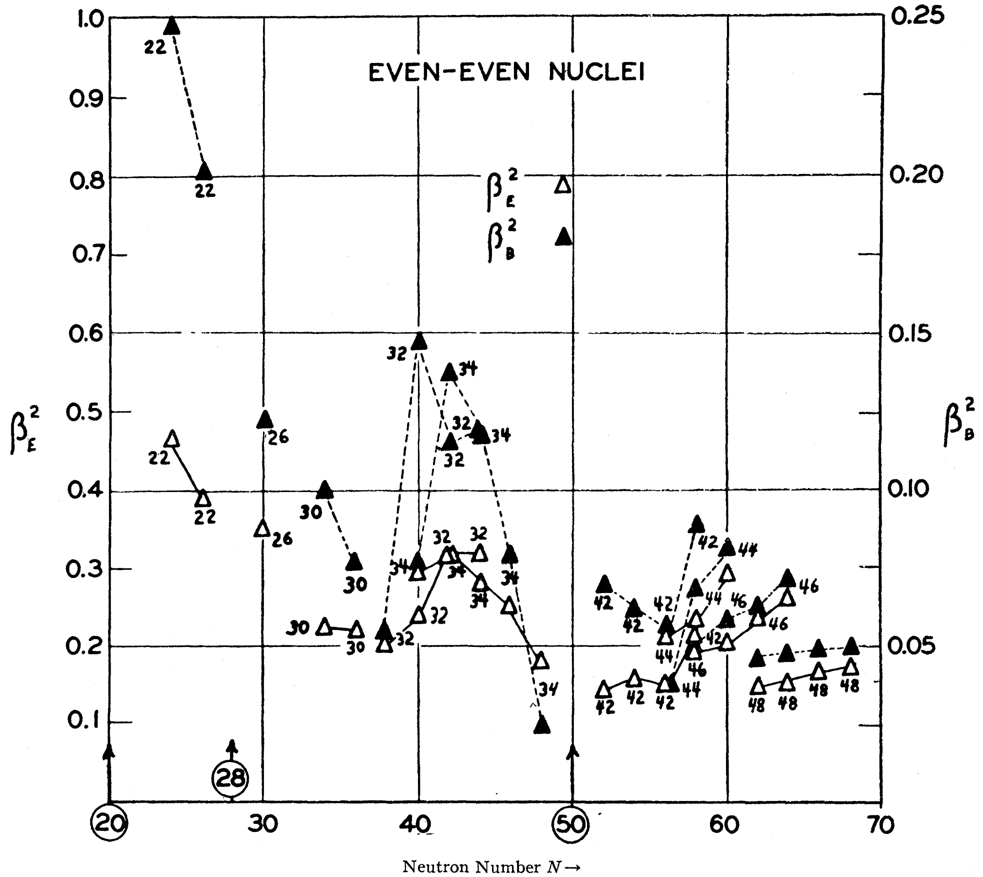


FIG. 2. Summary of results for even-even nuclei in the "weak coupling" region ($Z=22$ to $Z=48$). For explanation of symbols, see caption of Fig. 1. Note factor of *four* between left-hand and right-hand ordinate scales. Solid and dotted lines link points of the same Z.

rupole moment Q_0 by[7]

$$Q_0=\frac{3}{(5\pi)^{\frac{1}{2}}}ZR_0^2\beta. \tag{1}$$

The reduced transition probability $B(E2)$ for a $0^+\rightarrow 2^+$ transition is given in terms of Q_0 by[7]

$$B(E2)=(5/16\pi)e^2Q_0^2. \tag{2}$$

Using $R_0=1.2\times 10^{-13}A^{1/3}$ cm, we obtain the following relation between the parameters β^2 and the observed quantities E and $B(E2)$:

$$\begin{aligned}\beta_E^2&=2.43\times 10^5/A^{5/3}E;\\ \beta_B^2&=8.48\times 10^4B(E2)/Z^2A^{4/3},\end{aligned} \tag{3}$$

where Z and A are the atomic number and mass number, respectively, E is the excited-state energy in kev, and $B(E2)$ is the reduced transition probability (divided by e^2) in 10^{-48} cm^4. Since we observe gamma radiation, our results for $B(E2)$ must be multiplied by $(1+\alpha_t)$, where α_t is the total $E2$ internal conversion coefficient. We are indebted to A. W. Sunyar for supplying the estimates of α_t, and refer to his paper[5] for an appraisal of their reliability. The over-all agreement of the results from these vastly different methods of measurement is indeed gratifying. The particularly high points for $Z=64$ (numbers near the points refer to Z) belong to the lowest energy transitions and can undoubtedly be blamed in part on an overestimate of α_t due to neglect of screening. It should be remembered that Coulomb excitation and direct lifetime determinations differ by a factor of $(1+\alpha_t)^2$. The two points for $N=142$ and $N=146$ represent our measurements in Th^{232} and U^{238},[13] using $\alpha_t\sim 1000$. $(\beta_E/\beta_B)^2$ is more nearly 7–8 for these two cases.

The "favored" factor F (ratio of observed to single-particle transition probability) ranges from 40 to 200 in these nuclei.

Weak-coupling region.—Without wanting to ascribe particular significance to the deformation parameter here, we have plotted in Fig. 2 the same quantities as shown in Fig. 1 above, mainly for the sake of comparison. We have previously reported the results for $_{46}Pd$ and $_{48}Cd$.[14] Note that the left-hand scale is now only *four* times the right-hand scale. From an analysis of first-excited states of even-even nuclei and isotope-shift measurements near $N=82$, Ford has pointed out a similar discrepancy factor.[15] A rather remarkable correlation still exists between most level positions and transition probabilities. The cases of $_{34}Se$, $_{46}Pd$, and $_{48}Cd$ are particularly noteworthy in this respect. $_{42}Mo$ seems to depart from this trend, however. Internal conversion is negligible in all these transitions, and does not contribute any uncertainty. Note that whereas the two β^2 differ by a factor of about *four* near $N \sim 66$, this factor is more nearly *three* near $N \sim 44$, and perhaps only about *two* at $N \sim 26$. We have plotted our results in terms of β^2, a description which actually presupposes sizeable equilibrium deformations; however, a number of symptoms have been noted recently[16] attesting to the inadequacy of the "strong coupling" description in this region (e.g., departure from simple rotational level spacings and spin sequences). It is worth noting that the favored factor F (see foregoing) ranges from 10 to 60 for these nuclei; we encountered similar factors in odd-A nuclei.[3,17]

Bohr and Mottelson, in a recent study of rotational moments of inertia,[18] have offered an explanation of the $\beta_E - \beta_B$ discrepancy in the rare earths (which is evidently due to β_E) in terms of residual internucleon interactions. They also derive the following rough criterion to be satisfied by the energy of the first-excited state in order that one may expect a conventional rotational spectrum:

$$E_{2^+} < 9.22 \times 10^5 / A^{5/3} \text{ kev.}$$

It is interesting to note that, in addition to the nuclei shown in Fig. 1, a number of our cases in Fig. 2 satisfy this condition.

A detailed report on the data of Fig. 2 is in preparation.

* The contents of this note were presented at the Ann Arbor Conference on Nuclear Structure, June 27–July 1, 1955 (unpublished).

1 We employ this terminology mainly to distinguish regions of the periodic table. See reference 7.

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Mass Measurements of Particles and Existence of 1450 m_e Mesons

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Recent measurements we have made on fast particles from stars in G5 nuclear emulsions, 600μ thick, exposed to cosmic rays in balloon flights[1] give no indication of the existence of a group of mesons with mass about 1450 m_e, such as has been tentatively put forward by Fowler and Perkins.[2] Their work suggested a group intermediate in mass between conventional K mesons ($\simeq 965$ m_e) and protons, with intensity about 8% that of protons. Some work by Husain and Pickup[3] gave similar indications, although the statistical accuracy was such that this group could have been a statistical fluctuation on the edge of the proton distribution.

Ionization (blob counting) and scattering measurements were made on tracks in three emulsions, each track being measured only in one emulsion. Blob density, b, was plotted against the scattering parameter, $p\beta$, thus giving curves corresponding to the different mass values, the individual standard errors of measurement being mostly 6–10% for scattering and $\gtrsim 1\%$ for blob counting. Masses were then determined relative to the best proton line, and the combined results for 119 tracks in three emulsions are shown in the mass histogram in Fig. 1. The dashed curves superimposed on the histogram are normal distributions for a standard error of 9%. Scattering measurements were corrected for noise, and any distortion corrections were negligible. Some of the earlier results of Husain and Pickup[3] are included in the mass histogram, although most of the particles of "intermediate mass" are now excluded because they do not satisfy the minimum statistics.

It will be seen that the present results are adequately explained on the basis that the particles emitted in the stars are pions, K mesons ($\simeq 965$ m_e), protons, deuterons, and tritons. One particle is also very probably a hyperon with mass 2470 ± 210 m_e. The presence of a group with mass $\simeq 1450$ m_e should, with our statistics, have given a small continuous distribution between the K mesons and protons, but there is no indication of this here, and we would conclude that 1450 m_e mesons, if they exist at all, are less frequent than conventional K mesons.

If the 1450 m_e group were real, the mesons must be unstable and, according to the path length observed by Fowler and Perkins,[2] they would have a lifetime long enough to come to rest before decaying (rather than decay in flight). The τ meson mass (965 m_e) and mode of decay into three pions are well known, and an examination of the collected mass data from emulsion work[4] on K mesons decaying at rest into single charged par-