Nuclear Symmetry Energy*

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On the basis of a phenomenological theory proposed in an earlier paper the nuclear symmetry energy is recalculated. The value obtained is smaller than the one given before, which was incorrect. A relativistic calculation of the energy with the radius parameter $r_0=1.07\times10^{-13}$ cm of the electron scattering experiments yields about the correct symmetry energy. Compensating uncertainties due to inaccuracy in r_0, corrections due to the exclusion principle, and a possible difference in the radius of proton and neutron distributions make an accurate comparison with the empirical symmetry energy meaningless.

I. INTRODUCTION

IN a previous paper[1] an attempt was made to derive the nuclear forces from a combined vector and scalar field interaction, in a relativistic sense. The resulting velocity-dependent forces led to saturation. The strength of the fields were chosen so as to reproduce the correct volume energy and density at the minimum of the energy. It was shown that the nucleons by means of this interaction behave as if they had only about one half of their normal mass. The kinetic energy of the nucleons therefore is effectively doubled. Since the difference between the maximum kinetic energy of the neutrons and the protons is doubled this also led to an increase in the symmetry energy. However, the value given in I was in error. In part II we shall correct this value in the nonrelativistic approximation and also give the derivation in the relativistic form. In part III we investigate the effect of the Pauli exclusion principle on the symmetry energy. In part IV we recalculate the volume and symmetry energy with a radius parameter as suggested by the electron scattering experiments.

II. SYMMETRY ENERGY

For equal numbers of neutrons and protons the volume part of the energy per nucleon can be written[2]

$$E_V=\frac{1}{\gamma}E_k-V_1+V_2+R_1-R_2, \tag{1}$$

with

$$\begin{gathered}E_k=(3/10m)(3\pi^2/2)^{\frac{2}{3}}\rho^{\frac{2}{3}},\quad V_1=am\phi,\quad V_2=bm\phi_0,\\ R_1=\tfrac{1}{2}\mu_1^2\phi^2/\rho,\quad R_2=\tfrac{1}{2}\mu_2^2\phi_0^2/\rho,\quad \gamma=1-a\phi=m_{\mathrm{eff}}/m.\end{gathered} \tag{2}$$

E_k is the average Fermi energy of the nucleons; V_1 and V_2 are the interaction energies due to the scalar field ϕ and the vector field ϕ_0, respectively; R_1 and R_2 are the meson rest energies. Setting the variation of E_V with respect to ϕ and ϕ_0 equal to zero leads to the field equations of the infinite nucleus:

$$\mu_1^2\phi=\left(1-\frac{1}{\gamma^2}\frac{E_k}{m}\right)am\rho, \tag{3}$$

$$\mu_2^2\phi_0=bm\rho. \tag{4}$$

After minimizing with respect to ρ, we finally obtain for the volume energy at minimum

$$E_V{}^0=-\left(\frac{1}{\gamma^0}-\frac{4}{3}\right)\frac{1}{\gamma^0}E_k{}^0. \tag{5}$$

Here $E_k{}^0$ is the average kinetic energy for the equilibrium density ρ_0, and $\gamma^0=1-a\phi^0$ is the mass reduction parameter at equilibrium. With $E_k{}^0=19.25$ Mev which corresponds to $r_0=1.22\times10^{-13}$ cm, the choice $\gamma^0=0.559\approx0.56$ leads to the correct volume energy[3] $E_V{}^0=-15.75$ Mev. If one treats protons and neutrons as separate Fermi gases, then the kinetic energy becomes

$$E_k{}^{0\prime}=E_k{}^0[1+(5/9)\Delta^2], \tag{6}$$

with

$$\Delta=(N-Z)/(N+Z). \tag{7}$$

Since ρ, ϕ, and ϕ_0 do not change very much in the neighborhood of their minimum values ρ^0, ϕ^0, $\phi_0{}^0$, the binding energy for small Δ can be written

$$E_B=-\left(\frac{1}{\gamma^0}-\frac{4}{3}\right)\frac{1}{\gamma^0}E_k{}^0+\frac{5}{9}\frac{1}{\gamma^0}E_k{}^0\Delta^2 +E_{\mathrm{Cb}}+\text{surface terms} \tag{8}$$

where E_{Cb} is the Coulomb energy. This formula replaces Eq. (49) in I. The symmetry energy is only

$$E_{\mathrm{sym}}=\frac{5}{9}\frac{1}{\gamma^0}E_k{}^0=19.15\text{ Mev}, \tag{9}$$

in contrast to the value of Green's best fit[3] to the Weizsäcker mass formula $E_{\mathrm{sym}}=23.43$ Mev. This result agrees with the findings of Ross, Lawson, and Mark[4] who pointed out that in an independent-particle calcu-

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[1] H.-P. Duerr, Phys. Rev. **103**, 469 (1956).
[2] See reference 1, p. 473.
[3] A. E. S. Green, Phys. Rev. **95**, 1006 (1954).
[4] Ross, Mark, and Lawson **104**, 401 (1956).

lation with a velocity-dependent potential the proton well had to be chosen deeper than the neutron well in order to get agreement with experimental binding energies. As pointed out in I, any positive difference in volume between the neutron and proton distributions will make the theoretical value even smaller.

A more exact calculation of the energy minimum which uses the relativistic expressions instead of their nonrelativistic approximations does not improve the theoretical result for the symmetry energy. The expectation values of the Dirac matrices are

$$\langle\boldsymbol{\alpha}\rangle=\mathbf{v}=[(\gamma m)^2+p^2]^{-\frac{1}{2}}\mathbf{p}, \tag{10}$$

$$\langle\beta\rangle=[1-\mathbf{v}^2]^{\frac{1}{2}}=[(\gamma m)^2+p^2]^{-\frac{1}{2}}\gamma m, \tag{11}$$

where $\mathbf{v}$ is the velocity measured in units of the velocity of light. For equal numbers of protons and neutrons the total volume energy per nucleon can be written

$$E_V'=m+E_V=\langle[\gamma^2m^2+p^2]^{\frac{1}{2}}\rangle_{\text{Av}}+V_2+R_1-R_2. \tag{12}$$

For the square root an average value over the nucleon momentum distribution has to be taken. However, we can approximate.

$$\langle[\gamma^2m^2+p^2]^{\frac{1}{2}}\rangle_{\text{Av}}\approx[\gamma^2m^2+\langle p^2\rangle_{\text{Av}}]^{\frac{1}{2}},$$

with

$$\langle p^2\rangle_{\text{Av}}=2mE_k.$$

The error introduced by this replacement is of the order

$$\delta=\frac{1}{8\gamma^3m^3}[\langle p^4\rangle_{\text{Av}}-(\langle p^2\rangle_{\text{Av}})^2].$$

If p_0 is the maximum momentum of the Fermi distribution (in the case above, $p_0^2=2m\times 32.08$ Mev), we have

$$\delta=\frac{p_0^4}{8\gamma^3m^3}\left[\frac{3}{7}-\left(\frac{3}{5}\right)^2\right]\approx 2\times 10^{-3}\text{ Mev},$$

which certainly can be neglected.

The variation of the energy E_V' with respect to ϕ and ϕ_0 leads to the field equations of the infinite nucleus:

$$\mu_1^2\phi=\langle\beta\rangle am\rho=\left[1+\frac{2E_k}{\gamma^2m}\right]^{-\frac{1}{2}}am\rho, \tag{13}$$

$$\mu_2^2\phi_0=bm\rho. \tag{14}$$

If we minimize (12) with respect to ρ, we obtain the saturation condition

$$\rho\frac{\partial E_V'}{\partial\rho}=\frac{2}{3\gamma^0}E_k^0\left[1+\frac{2E_k^0}{(\gamma^0)^2m}\right]^{-\frac{1}{2}}-R_1^0+R_2^0=0. \tag{15}$$

The energy at minimum then becomes

$$E_V^{\prime 0}=m+E_V^0=\left[1+\frac{2E_k^0}{(\gamma^0)^2m}\right]^{-\frac{1}{2}}\left[m+\frac{4}{3\gamma^0}E_k^0\right]. \tag{16}$$

The nonrelativistic limit of this expression leads back to (5). In order to obtain a volume energy of -15.75 Mev, we have to choose

$$\gamma^0=0.536 \tag{17}$$

or

$$a\phi^0=0.464.$$

Then we have

$$b\phi_0^0=0.3863,\quad (1/\gamma^0)E_k^0=34.72\text{ Mev},$$
$$V_{12}=V_1-V_2=72.91\text{ Mev}, \tag{18}$$
$$R_1=203.6\text{ Mev},\quad R_2=181.2\text{ Mev}.$$

If we treat neutrons and protons separately we have to replace in (12)

$$\langle p^2\rangle_{\text{Av}}\rightarrow 2mE_k[1+(5/9)\Delta^2].$$

This leads to the symmetry energy

$$E_{\text{sym}}=\frac{5}{9\gamma^0}E_k^0\left[1+\frac{2E_k^0}{(\gamma^0)^2m}\right]^{-\frac{1}{2}}=18.75\text{ Mev}, \tag{19}$$

which is even slightly less than the value obtained from the nonrelativistic treatment.

With these parameters we have also calculated the energy per particle of an infinitely big polyneutron.[5] We find a minimum of the energy at a neutron density which is 0.595 times the nucleon density in the nucleus. The strength of the scalar field is reduced to 0.61 of its value in the nucleus. The average kinetic energy is 29.5 Mev, the potential energy is 49.6 Mev, and the mass is reduced to 0.72 its normal value. We obtain very weak binding of about 0.9 Mev per neutron. However, this result seems irrelevant in the light of the fact that the symmetry energy is too small in comparison with its empirical value. Any effect which will increase the symmetry energy to its correct value will very likely also make the energy of the polyneutron positive.

There are two effects which will increase the symmetry energy and we shall treat them separately. The first one is due to the Pauli exclusion principle and the finite range of nuclear forces; the second one is connected with the appropriate choice of a radius parameter for the infinite nucleus.

III. EXCLUSION PRINCIPLE CORRECTION

Because of the Pauli exclusion principle, neutrons are more densely surrounded by protons, and vice versa. In case of a finite range of the (attractive) forces and a larger number of neutrons, protons will experience a stronger interaction than neutrons. Hence the symmetry effect will be increased. To express this in a more quantitative way, we go back to our original nonrelativistic equations (1) ff. We insert the values of ϕ and ϕ_0 from Eqs. (3) and (4) into Eq. (1) and write for the

[5] M. G. Mayer and E. Teller, Phys. Rev. 76, 1226 (1949).

density $\rho = A/V$ with A the number of nucleons and V the volume of the nucleus. Then the total volume energy of the nucleus can be written

$$E_V{}^{\text{tot}} = E_V A = E_k A - \frac{1}{2}\left[\frac{a^2 m}{\mu_1{}^2 V}\left(1 - \frac{2E_k}{\gamma m}\right) - \frac{b^2 m}{\mu_2{}^2 V}\right] A^2, \quad (20)$$

where

$$\gamma \approx 1 - \frac{a^2 m}{\mu_1{}^2}\rho = 1 - \frac{a^2 m}{\mu_1{}^2 V} A.$$

If we disregard the ρ (or A) dependence of γ, the second term in Eq. (20) is of the form of a pair interaction, the strength of which is given by the quantity in square brackets.

The $\frac{1}{2}A(A-1) \approx \frac{1}{2}A^2$ pairs will consist of n pairs with symmetric space wave functions and $(\frac{1}{2}A^2 - n)$ pairs with antisymmetric space wave functions. Space antisymmetric pairs have to stay apart by a distance which is of the order of the wavelength of their relative motion. Since the interaction between the nucleons will have a finite range, the interaction of an antisymmetric pair will be in general decreased. We denote by g the relative probability of finding an "antisymmetric constituent" within the effective range of the potential due to the other particle, and by $(1-g)$ the relative probability for the "symmetric constituent." Then we have to replace the number of pairs $\frac{1}{2}A^2$ by

$$N_p = 2(1-g)n + 2g(\tfrac{1}{2}A^2 - n). \quad (21)$$

In case of very long-range interaction, we have $g = \frac{1}{2}$ and $N_p = \frac{1}{2}A^2$, i.e., the same result as before. In case of a very short range, g tends to zero since the antisymmetric pair interaction will be completely excluded. Then we get $N_p = 2n$. The exclusion of the space antisymmetric pairs from the interaction has the effect that essentially every neutron only interacts strongly with two protons and one neutron, which has opposite spin with respect to the first one, and vice versa.

The symmetry effect is readily exhibited by calculation of the number of symmetric pairs n. For heavy nuclei one finds approximately[6]

$$n = \tfrac{3}{16}A^2(1 - \tfrac{1}{3}\Delta^2), \quad (22)$$

with Δ as defined in (7). For the effective number of pairs we get

$$N_p = [n_0 - (1-n_0)\Delta^2]\tfrac{1}{2}A^2, \quad (23)$$

with

$$n_0 = \tfrac{3}{4} + \tfrac{1}{2}g. \quad (24)$$

If in (20) we replace $\frac{1}{2}A^2$ by the effective number of pairs (23), and minimize with respect to ρ, we derive for the volume part of the binding energy

$$E_V = -\frac{1}{\gamma^0}E_k{}^0\left[\left(\frac{1}{\gamma^0} - \frac{4}{3}\right) - (1-n_0)\left(\frac{1}{\gamma^0} - \frac{4}{3} + \frac{1}{3}\gamma_0\right)\right], \quad (25)$$

and the symmetry energy

$$E_{\text{sym}} = \frac{1}{\gamma^0}E_k{}^0\left\{\frac{5}{9} + (1-n_0)\left[\left(\frac{2}{3n_0} + \frac{8}{9}\right)\gamma^0 - \frac{17}{9} + \frac{1}{\gamma^0}\right]\right\}. \quad (26)$$

We have neglected here the fact that g and therefore n_0 will depend on the momentum and hence will be a function of the density ρ. In this calculation we shall simply assume that n_0 is constant and taken for some average momentum.

For $g = \frac{1}{2}$, i.e., $n_0 = 1$ (very long range) we come back to the previous equations (5) and (8). In case of an extremely short range $g = 0$, i.e., $n_0 = \frac{3}{4}$, we have to assume $\gamma^0 = 0.513$ to obtain the empirical volume energy. For the symmetry energy we get then (as an upper limit)

$$E_{\text{sym}} = 29.6 \text{ Mev}, \quad (27)$$

which is well above the empirical value of 23.42 Mev. We may estimate what range has to be assumed for the interaction in order to reproduce the empirical symmetry energy. We find that the choice

$$\gamma^0 = 0.538, \quad (28)$$

$$n_0 = 0.883 \quad (29)$$

will yield the correct values for volume and symmetry energy. The relative probability of finding an antisymmetric pair within the effective range is then

$$g_- = 2g = 4(n_0 - \tfrac{3}{4}) = 0.532. \quad (30)$$

From the graph given in Blatt and Weisskopf[7] we estimate that this corresponds to an effective range of about twice the average interparticle distance. If we take into account a possible (positive) volume difference between the neutron and proton distributions, smaller ranges have to be assumed.

With the parameters (28), (29) we get for the depth of the potential

$$V_{12} = 78.3 \text{ Mev}, \quad (31)$$

which may appear to be too deep. However, we may point out that in an independent-particle-model calculation we rather have to take for the potential depth

$$n_0 V_{12} \approx 69.2 \text{ Mev},$$

and an effective mass parameter

$$1 - n_0 a\phi^0 \approx 0.60 \text{ Mev}.$$

Since for a given range of the forces n_0 will depend on the momentum and will range between one for high momenta and $\frac{3}{4}$ for small momenta, this introduces an additional velocity dependence. For particles with high momenta we have to use a deeper potential and a smaller effective mass. Combined they will effect a lower binding energy for these particles as compared with a calculation which uses a fixed mass and a fixed

[6] See, for example, J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[7] See reference 6, p. 130, Fig. 3.1.

potential. In particular for scattering problems $n_0 \approx 1$ and hence the parameters (28) and (31) should be taken.

The relativistic expressions are derived in a similar fashion. However, it is much simpler not to eliminate ϕ and ϕ_0 from the energy equation but rather to minimize the expression

$$E_V' = m + E_V = N_p[(\gamma^2 m^2 + \langle p^2\rangle_{\text{Av}})^{\frac{1}{2}} + V_2 + R_1 - R_2] + (1-N_p)(m^2 + \langle p^2\rangle_{\text{Av}})^{\frac{1}{2}}, \quad (32)$$

with respect to ρ, ϕ, and ϕ_0. Only the pair interactions are treated correctly in this approximation.

We obtain for the volume energy

$$E_V' = \frac{m}{W}\left[1 + \frac{4}{3}\frac{E_k^0}{\gamma^0 m}\right] + (1-n_0)m\left[\frac{1}{W_0}\left(1 + \frac{4}{3}\frac{E_k^0}{m}\right) - \frac{1}{W}\left(1 + \frac{4}{3}\frac{E_k^0}{\gamma^0 m}\right)\right], \quad (33)$$

and the symmetry energy

$$E_{\text{sym}} = \frac{5}{9}\frac{E_k^0}{\gamma^0 m}\left[1 - (1-n_0)\left(1 - \frac{\gamma^0 W}{W_0}\right)\right] + (1-n_0)m\left\{\frac{1}{W_0}\left[1 + \left(1 + \frac{1}{2n_0}\right)\frac{4}{3}\frac{E_k^0}{m}\right] \frac{1}{W}\left[+ \frac{4}{3}\frac{E_k^0}{\gamma^0 m}\right]\right\} \quad (34)$$

where we used the abbreviations

$$W = \left[1 + \frac{2E_k^0}{(\gamma^0)^2 m}\right]^{\frac{1}{2}}. \quad (35)$$

$$W_0 = \left[1 + \frac{2E_k^0}{m}\right]^{\frac{1}{2}}. \quad (36)$$

One easily verifies that (33) and (34) reduce to (25) and (26) in the nonrelativistic limit, and to (16) and (19) if we set $n_0 = 1$. In case of a volume difference $\delta V = V_n - V_p$ between the neutron and proton distributions, the first term in (34) has to be multiplied by a factor $[1 - (1/\Delta)(\delta V/V)]$.[8]

IV. CHOICE OF RADIUS PARAMETER

There is another factor which will influence the energy considerations, and in particular the symmetry energy. We have calculated the Fermi energy of the nucleons by assuming a radius parameter

$$r_0 = 1.22 \times 10^{-13} \text{ cm}. \quad (37)$$

This parameter was taken from Green's best fit of the Weizsäcker mass formula. In Green's paper[3] $R_{\text{Cb}} = r_0 A^{\frac{1}{3}}$ is the radius of a homogeneous charged sphere which has the same electrostatic energy as the realistic nucleus. The investigations of the Stanford group[9] seem to indicate that the charge distributions of nuclei can be well represented by

$$\rho = \text{const}[1 + e^{\alpha(r-R)}]^{-1}, \quad (38)$$

with

$$R = 1.07 \times 10^{-13} A^{\frac{1}{3}} \text{ cm}. \quad (39)$$

The effective electrostatic radius for these distributions is approximately

$$R_{\text{Cb}} \approx 1.07 \times 10^{-13}[1 + (3/A^{\frac{2}{3}})]A^{\frac{1}{3}} \text{ cm}, \quad (40)$$

and agrees on the average with the radius derived by Green.

For the calculation of the volume energy we refer to the Fermi energy of an infinite nucleus, for which we then should take the smaller radius parameter $r_0 = 1.07 \times 10^{-13}$ cm if we neglect differences in the proton and neutron distributions. The corresponding average kinetic energy will be

$$E_k^0 = 25.22 \text{ Mev}. \quad (41)$$

The kinetic energy of a finite nucleus, of course, will be smaller due to "surface effects" and more closely approximated by the bigger radius parameter. We may point out, however, that we have evaluated the average kinetic energy of the nucleons by considering the nucleons to be completely free. Any correlation between particle motion will increase the kinetic energy above the Fermi value.

If we insert the value (41) into the relativistic equations (12) ff., we have to assume

$$\gamma^0 = 0.561, \quad \text{or} \quad a\phi^0 = 0.439 \quad (42)$$

to obtain the empirical volume energy. Further we get

$$b\phi_0^0 = 0.3467, \quad (1/\gamma_6)E_k^0 = 44.96 \text{ Mev}, \quad V_{12} = 86.6 \text{ Mev}. \quad R_1 = 190.3 \text{ Mev}, \quad R_2 = 162.6 \text{ Mev}. \quad (43)$$

For the symmetry energy we obtain

$$E_{\text{sym}} = 23.08 \text{ Mev}, \quad (44)$$

which is very close to the empirical value.

In a forthcoming paper we shall use this set of parameters to calculate nucleon and antinucleon scattering cross sections of nuclei for high energies.

With these parameters the energy minimum of the polyneutron occurs at about 0.51 the nuclear density. The effective mass is about $0.77m$. However, owing to the increased symmetry energy this does not lead to binding, as we expected. The energy per particle is about +2.1 Mev.

[8] Equation (57) in I contains a misprint. The factor $\frac{1}{2}$ should be omitted.

[9] Hahn, Ravenhall, and Hofstadter, Phys. Rev. **101**, 1131 (1956).

In this case of a small radius parameter for the infinite nucleus, the Pauli principle has only to account for a deviation of the symmetry energy which may result from differences in the proton and neutron distributions. To obtain some insight into this interrelationship we shall calculate one example: We shall assume that the range of the forces are of the order of the interparticle distance in which case[7] $n_0 \approx 0.8$. To obtain the empirical volume energy from Eq. (33), we have to choose for the mass parameter

$$\gamma^0 = 0.523, \quad \text{or} \quad a\phi^0 = 0.477. \tag{45}$$

This leads to

$$b\phi_0{}^0 = 0.3646 \quad \text{or} \quad V_{12} = 105.4 \text{ Mev}. \tag{46}$$

For bound particles this corresponds roughly to a mass parameter of 0.58 and a potential depth of 84.3 Mev.

In order to obtain with the parameters (45) the empirical symmetry energy, we have to reduce the first term in (34) by a factor 0.6, i.e., we have to assume

$$(1/\Delta)(\delta V/V) \approx 0.4.$$

Since $\Delta \approx 0.008 A^{\frac{2}{3}}$, we may use the average value

$$\langle 1/\Delta \rangle_{\mathrm{Av}} \approx 0.1.$$

Then we obtain for the relative volume difference

$$\delta V/V \approx 4\%,$$

which is a very reasonable value. We see that small differences in the volume of the neutron and proton distributions have quite a strong effect on the symmetry energy in agreement with findings of Ross, Lawson, and Mark.[4]

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Studies of Rare Earth Alpha Emitters*

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A series of bombardments using alpha particles from the Berkeley 60-inch cyclotron on rare earth oxides has resulted in the discovery and mass assignment of two new alpha-emitting isotopes, Dy^{153} (5 hr) and Dy^{154} (13 hr). Mass assignments have been made for two other alpha emitters, Dy^{152} (2.3 hr) and Tb^{151} (19 hr). A new 10-hr electron-capture isotope has been identified as Dy^{155}. Evidence is also presented for the discovery of another isotope, Dy^{149} (8 min), which was produced by a N^{14} ion bombardment on praseodymium.

INTRODUCTION

IN 1953 Rasmussen *et al.* reported on a detailed study of neutron-deficient isotopes in the rare earth region.[1] These isotopes exhibited alpha radioactivity. A number of such nuclides were discovered and studied individually.

Among the alpha-emitting nuclides reported were three dysprosium isotopes, whose alpha energies and half-lives were as follows:

(a) 4.2 ± 0.06 Mev, 7 ± 2 min.
(b) 4.06 ± 0.04 Mev, 19 ± 4 min.
(c) 3.61 ± 0.08 Mev, 2.3 ± 0.2 hr.

A limit was set on the mass numbers of the dysprosium activities, $153 \geq A \geq 149$.

The study presented here was begun with the intent of assigning a mass to the 2.3-hr activity, using alpha particles from the Berkeley 60-inch cyclotron. When the experiment was performed, new information was uncovered, which stimulated further work in this region. This paper is concerned with the study of hitherto unreported dysprosium activities and additional information that has been found in connection with previously known rare earth nuclides.

Table I summarizes the information available on the new isotopes. Figure 1 is a section of the isotope chart, which shows the nuclides that have been studied and used in the investigation.

EXPERIMENTAL METHOD

In the work reported here, elements of atomic number Z were bombarded with alpha particles in the Berkeley

TABLE I. Information on new isotopes.

Isotope	Half-life	Mode of decay seen	Alpha-particle energy (Mev)
Dy^{149}	8 min$\pm$2	E.C. and/or β^+	
Dy^{153}	5 hr$\pm$0.5	α	3.48 ± 0.05
Dy^{154}	13 hr$\pm$2	α	3.35 ± 0.05
Dy^{155}	10 hr	E.C.	

* This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] Rasmussen, Thompson, and Ghiorso, Phys. Rev. **89**, 33 (1953).