Li^6 Plus Neutron Configuration in Li^7†*

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(Received June 5, 1961)

Energy levels of Li^7 are examined in the Li^6 cluster plus neutron configuration. The main purpose is to determine whether a positive-parity level does exist at 6.54 Mev as indicated by some experiments. Our results show that the formation of such a state is not favored by the fundamental nucleon-nucleon interaction which yields the deuteron binding energy and explains the s- and p-wave scattering data. The energy of the $^2P_{\frac{3}{2}}$ state has also been computed. The resultant value of -27.2 Mev is in fair agreement with the experimental value of -31.7 Mev.

I. INTRODUCTION

THE present investigation is an attempt to determine by a theoretical calculation whether there exists a broad positive-parity level at around 6.5 Mev excitation in either Li^7 or Be^7.[1] At the present moment, there seems to be some experimental evidence both for and against its existence. In an analysis of the $Li^6(p,\alpha)He^3$ reaction, Marion *et al.*[2] contended that a broad peak observed in the total cross section was due to the presence of a $(3/2+)$ state. On the other hand, Hamburger and Cameron[3] searched for this level in the reaction $Li^6(d,p)Li^7$ and found that the previous observation of a level at 6.54 Mev excitation by Levine *et al.*[4] might arise from a contaminant in their experiment. In view of this conflicting information, it thus seems worthwhile to carry out a theoretical calculation to determine whether a reasonable nucleon-nucleon interaction could allow for the formation of such a positive parity state around this excitation energy in Li^7 and Be^7.

From the viewpoint of the cluster model,[5,6] this positive-parity state, if it exists, should have either an alpha cluster plus a triton cluster configuration or a Li^6 cluster plus a neutron configuration. The former would yield a $(1/2+)$ state while the latter would give rise to a $(3/2+)$ level. At present, there does not seem to be any experimental information which reveals the cluster nature of this level. However, a theoretical calculation[7] based on the alpha cluster plus triton configuration produced definitely the result that a two-body interaction which gives the correct deuteron binding energy and explains the nucleon-nucleon s-wave and p-wave scattering data does not favor the formation of a positive-parity level in this configuration. Thus, we are left with only the alternative of a Li^6 cluster plus neutron configuration (i.e., an alpha cluster plus a broken-up triton cluster configuration) for this state in Li^7. Based on the experience from previous cluster model calculations,[8] we firmly believe that if the result again indicates the nonexistence of such a state, then the chance of finding a positive-parity state around an excitation of 6.5 Mev by experimental means should be very slim indeed.

To lend further support to the present belief that the $(5/2-)$ level at 7.47 Mev in Li^7 is not a member of the ^2F doublet but of the term $^2P_{5/2}$,[9] we have also computed the energy of this level in the Li^6 cluster plus neutron representation. A previous calculation[8] using the same method as employed here but in the alpha cluster plus triton cluster representation indicated that a $(5/2-)$ level can indeed exist in that representation at around 5.6 Mev.[10] However, the same calculation also revealed that this level should have a large level width (approximately 1 Mev) which clearly contradicts the experimental finding of a rather sharp level.[1] Thus, from this calculation alone, one should be able to conclude that the 7.47-Mev level in Li^7 does not have the nature of an alpha cluster plus a triton cluster. Therefore, it seems interesting to test whether another $(5/2-)$ level can form with a Li^6 cluster plus neutron configuration, and if it does, how close would its energy agree with experiment.

In the next section, a brief description of the two-body force and of the method of calculation will be presented. Section III is devoted to the numerical analysis of the problem. Finally, in Sec. IV, we will discuss and summarize the results of this investigation.

† Submitted (by F.C.K.) in partial fulfillment of the requirements for the Ph.D. degree at the Florida State University.

* Work partially supported by the U. S. Office of Naval Research.

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II. METHOD OF CALCULATION

To get the total energies for the $^{24}P_{5/2}$ and $^{24}S_{3/2}$ states in Li^7, we make use of a variational method. For the trial function, we use

$$\Psi = A[\psi(1234;56;7)\xi(\sigma,\tau)] = A[\psi_0(\varrho_1,\varrho_2,\varrho_3)\varphi_0(\varrho_5)\chi_1(\mathbf{R}_1)\chi_2(\mathbf{R}_2)\xi(\sigma,\tau)], \quad (1)$$

where

$$\psi_0(\varrho_1,\varrho_2,\varrho_3) = \exp\left(-\frac{\alpha}{2}\sum_{i=1}^{4}\rho_i^2\right),$$

$$\varphi_0(\varrho_5) = \exp\left(-\frac{\alpha}{2}\sum_{j=5}^{6}\rho_j^2\right),$$

$$\chi_1(\mathbf{R}_1)\chi_2(\mathbf{R}_2) = R_1^{n_1}R_2^{n_2}\exp(-\tfrac{2}{3}\beta_1 R_1^2 - (3/7)\beta_2 R_2^2) \times Y_{l_1m_1}(\Omega_1)Y_{l_2m_2}(\Omega_2),$$

with

$$\varrho_i = \mathbf{r}_i - \mathbf{R}_a, \quad i=1,2,3,4.$$
$$\varrho_j = \mathbf{r}_j - \mathbf{R}_d, \quad j=5,6.$$
$$\mathbf{R}_a = \tfrac{1}{4}(\mathbf{r}_1+\mathbf{r}_2+\mathbf{r}_3+\mathbf{r}_4), \quad \mathbf{R}_d = \tfrac{1}{2}(\mathbf{r}_5+\mathbf{r}_6),$$
$$\mathbf{R}_1 = \mathbf{R}_a - \mathbf{R}_d, \quad \mathbf{R}_2 = \tfrac{1}{3}(2\mathbf{R}_a+\mathbf{R}_d) - \mathbf{r}_7.$$

In Eq. (1), $\xi(\sigma,\tau)$ describes the total spin and isotopic spin function for the system and A denotes the complete antisymmetrization of the wave function with respect to the exchange of all pairs of particles. The functions $\psi_0(\varrho_1,\varrho_2,\varrho_3)$ and $\phi_0(\varrho_5)$ describe the internal structure of the α cluster and the deuteron cluster, respectively, while $\chi_1(\mathbf{R}_1)$ and $\chi_2(\mathbf{R}_2)$ describe the two relative motions between the clusters. We choose this particular form for the trial function, since it has been found experimentally that the (5/2−) level has a large reduced width for the decay into the Li^6 plus neutron channel.[11] Also, the constants in the wave function describing the relative motions are chosen to have those particular values such that in the limit $\alpha=\beta_1=\beta_2$, the trial function goes over to the usual shell model wave function for the configuration $(1s)^4(1p)^3$ in a harmonic oscillator potential of width parameter α.

To simplify calculations, the L-S coupling scheme will be assumed. This is probably a fairly valid assumption, since the results of the intermediate-coupling calculations indicated that for the light nuclei in the beginning of the $1p$ shell, the intermediate-coupling scheme is near the L-S limit.[12]

The two-body force that we shall use in this investigation is an equivalent two-body central force of the Serber type that can explain the binding energy of the deuteron and the s-wave and p-wave nucleon-nucleon scattering data fairly well. It has the explicit form[13]

$$V_{ij} = -V_0\exp(-\kappa r_{ij}^2)[w(1+P_{ij}^r)+b(P_{ij}^\sigma - P_{ij}^r)], \quad (2)$$

with

$$V_0 = 68.6 \text{ Mev}, \quad \kappa = 0.416 \text{ f}^{-2}, \quad w=0.41, \quad b=0.09,$$

and P_{ij}^r, P_{ij}^σ, and P_{ij}^τ denote the space, spin, and isotopic spin exchange operators, respectively.

Since it is well known that an equivalent central force of the type (2) will not give the correct alpha-particle binding energy and rms radius correctly, it is again necessary to adopt the subtraction procedure which has been used in similar calculations done previously.[7,8] To describe briefly, what we do is to separate the total energy into two parts: the interaction energy between the clusters and the internal energies of the clusters. To calculate these energies we use the Serber force given by Eq. (2) for the interaction energy and the internal energy of the deuteron cluster and adopt the experimental value for the internal energy of the alpha cluster. It should be stressed here that this procedure is certainly somewhat ambiguous, especially when the mutual penetration of the clusters is appreciable. However, since we expect that in light nuclei, the clusters would normally be quite far apart, this procedure probably will not introduce serious errors. If one wishes to do a more exact calculation, then it is indeed necessary to use a more realistic two-body force complete with tensor component, hard core, and so forth. This latter force is however very tedious to work with; hence, for our investigation which is at best only of an exploratory nature, we shall merely use the simple force of Eq. (2).

The expression we shall minimize is

$$E = \int \Psi^* H \Psi d\tau \Big/ \int \Psi^* \Psi d\tau, \quad (3)$$

where

$$H = \sum_{i=1}^{7} T_i + \sum_{i<j} V_{ij},$$

with T_i referring to the kinetic energy of the ith particle and V_{ij} denoting the two-body potential. Explicit

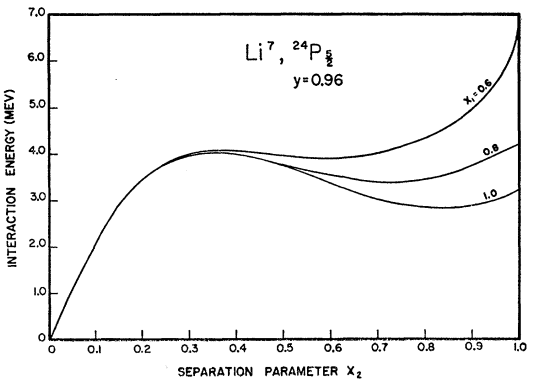

FIG. 1. Interaction energy as a function of the separation parameter for the neutron with respect to the Li^6 cluster in the $^{24}P_{\frac{5}{2}}$ state of Li^7.

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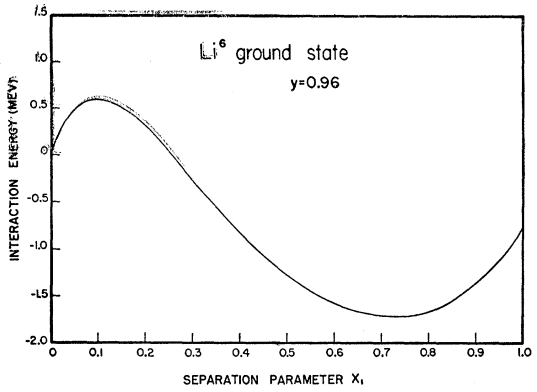

FIG. 2. Interaction energy as a function of the separation parameter for the alpha-deuteron configuration.

expressions for the normalization factor, the expectation value of the kinetic energy operator, and the expectation value of the potential energy operator are given in Appendix I. The variational parameters in our wave function are α, β_1, and β_2. From previous calculations,[7,8] we have found, however, that in the variational process the optimizing value of the width parameter for the alpha cluster does not differ much from the value for a free alpha particle. So, in our calculation, we shall fix α to give the correct alpha particle rms radius and shall vary only β_1 and β_2 freely to get the minimum value for the energy.

The choice of the values for n and l in the trial wave function will be done in exactly the same way as has been explained in previous papers,[7,8] namely, we shall use $n_1=2$, $l_1=0$, $m_1=0$, $n_2=2$, $l_2=0$, $m_2=0$ for the $^{24}S_{3/2}$ state and $n_1=2$, $l_1=0$, $m_1=0$, $n_2=1$, $l_2=1$, $m_2=1$ for the $^{24}P_{5/2}$ state.

III. NUMERICAL ANALYSIS

Numerical computations are carried out on an IBM-650 computer. For convenience, we use the notation

$$y=\kappa/\alpha, \quad x_1=\beta_1/\alpha, \quad x_2=\beta_2/\alpha.$$

As mentioned earlier, we shall keep y fixed at 0.96, a value which corresponds to the width parameter of a free alpha particle. The other two parameters, x_1 and x_2, will be varied to give the minimum value of the expectation value of the Hamiltonian. The results for the $^{24}P_{5/2}$ and $^{24}S_{3/2}$ states are discussed below separately.

(i) $^{24}P_{5/2}$ state. The interaction energy of the neutron relative to the Li^6 cluster as a function of x_2 is plotted in Fig. 1 for three values of the parameter $x_1=0.6$, 0.8, and 1.0. To this energy, we must further add the internal energies of the deuteron and alpha clusters and the interaction energy of the deuteron cluster with respect to the alpha cluster (Fig. 2) to obtain the total energy of this state as a function of x_1 and x_2. Since the interaction energy plotted in Fig. 2 is computed only with the nuclear part of the two-body interaction, a Coulomb contribution estimated to be around 0.8 Mev must still be added. Furthermore, we must remember that there is also a spin-orbit effect in this state, which in principle can be computed by inserting a two-body spin-orbit force into Eq. (2). This latter computation is, however, immensely tedious; hence, in our present investigation, we merely estimate it to be about -1 Mev from the experimental ^2P splittings in He^5 and Be^9.[1,14] With all those energies taken into account, we can then minimize with respect to x_1 and x_2. The resultant total energy thus obtained is -27.2 Mev, with the variation parameters $x_1=0.86$, $x_2=0.80$. Comparing with the experimental value of -31.7 Mev for this state,[1] we must concede that our calculated value seems to be a rather poor upper limit. However, we should point out that the major part of this discrepancy comes from the assumption of a single width parameter for both the alpha cluster and the deuteron cluster. Indeed, the total energy for the ground state of Li^6 calculated under the same assumption is only -29.3 Mev, while the experimental value is -32.0 Mev. Thus, we expect that if a more realistic deuteron cluster wave function had been used, our result would have been much improved.

(ii) $^{24}S_{3/2}$ state. The interaction energy of the neutron with respect to the Li^6 cluster as a function of x_2 is plotted in Fig. 3. We note that these curves possess no minima, which indicates the nonexistence of a positive-parity state in the Li^6 cluster plus neutron configuration with the term $^{24}S_{3/2}$.

IV. DISCUSSION

The most interesting result of this investigation is perhaps that a positive-parity level cannot be formed in the Li^6 cluster plus neutron configuration. Together with the previous finding that also the alpha cluster plus triton cluster configuration cannot properly describe a positive-parity resonant state, we are thus inclined to doubt the existence of such a state at 6.54

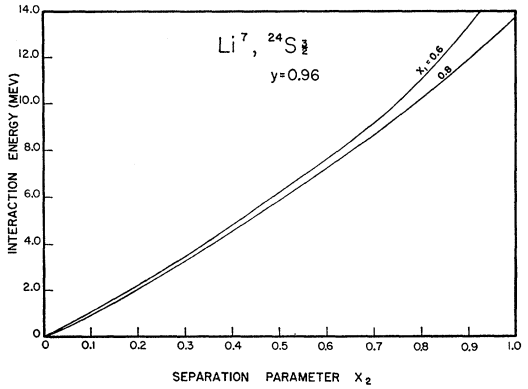

FIG. 3. Interaction energy as a function of the separation parameter for the neutron with respect to the Li^6 cluster in the $^{24}S_{3/2}$ configuration of Li^7.

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Mev in Li^7. Actual confirmation of this would of course come only from more careful experiments, but from the viewpoint of the cluster model, the occurrence of a positive-parity state at an excitation energy as low as 6.54 Mev would be hard to explain.

As has been explained in the last section, the rather poor value of -27.2 Mev for the calculated energy of the $^2P_{5/2}$ state is a consequence of an inadequate choice of the Li^6 cluster wave function. To see in a crude manner how much this result could be improved if a better trial function had been used, we subtract from this energy the energy of a free Li^6 nucleus to get the separation energy of the neutron. This comes out to be 2.1 Mev, which compares quite favorably with the experimental value of 0.22 Mev.[1]

Finally, we like to emphasize again that the present investigation is only of an exploratory nature. To perform a more careful analysis, one not only has to improve the trial wave function as mentioned above, but also needs to employ a more realistic two-body interaction.[15] This latter improvement is especially important, since the present procedure which involves a separation of the total energy into internal energies and interaction energies is somewhat arbitrary and might inject an uncertainty up to about 2 Mev into the results.

APPENDIX I

The normalization factor is easily shown to have the form

$$N^2=7!\int[A\psi(1234;\,56;\,7)\xi(\sigma,\tau)]^*\psi(1234;\,56;\,7)d\tau.$$

After summation over spin and isotopic spin coordinates, we get

$$N^2=7!\int\Theta^*(1234;\,56;\,7)\psi(1234;\,56;\,7)d\mathbf{r},$$

where the integration is over space variables only, with

$$\begin{aligned}\Theta(1234;\,56;\,7)=[1&-2P_{15}{}^r-P_{17}{}^r-P_{57}{}^r+P_{15}{}^rP_{26}{}^r\\&+P_{17}{}^rP_{26}{}^r+P_{57}{}^rP_{26}+2P_{17}{}^rP_{15}{}^r\\&-2P_{17}{}^rP_{15}{}^rP_{26}{}^r]\psi(1234;\,56;\,7),\end{aligned}$$

and

$$\begin{aligned}P_{15}{}^r\psi(1234;\,56;\,7)&=\psi(5234;\,16;\,7),\\P_{17}{}^rP_{15}{}^r\psi(1234;\,56;\,7)&=\psi(5234;\,76;\,1),\\P_{26}{}^rP_{17}{}^rP_{15}{}^r\psi(1234;\,56;\,7)&=\psi(5634;\,72;\,1),\end{aligned}$$

and so on.

For the expectation value of the kinetic energy operator, we have

$$\begin{aligned}\langle\sum_{i=1}T_i\rangle=&\left(\frac{7!}{N^2}\right)\int[A\psi(1234;\,56;\,7)\xi(\sigma,\tau)]^*\\&\times\sum_{i=1}^{7}T_i\psi(1234;\,56;\,7)\xi(\sigma,\tau)d\tau\\=&(\hbar^2/2m)[12\alpha+(2n_1+3)\beta_1+(2n_2+3)\beta_2]\\&-\left(\frac{7!}{N^2}\right)\left(\frac{\hbar^2}{2m}\right)\Big\{\int\Theta^*(1234;\,56;\,7)\\&\left[\alpha^2\sum_{j=1}^{6}\rho_j{}^2+\frac{4}{3}\beta^2R_1{}^2+\frac{6}{7}\beta_2{}^2R_2{}^2\right]\\&\times\psi(1234;\,56;\,7)d\mathbf{r}\Big\}\\&-\left(\frac{7!}{N^2}\right)\left(\frac{\hbar^2}{2m}\right)\Big\{\tfrac{3}{4}[(n_1+1)n_1-l_1(l_1+1)]\\&\times\int\Theta^*(1234;\,56;\,7)\frac{1}{R_1{}^2}\psi(1234)(56;\,7)d\mathbf{r}\Big\}\\&-\left(\frac{7!}{N^2}\right)\left(\frac{\hbar^2}{2m}\right)\Big\{\frac{7}{6}[n_2(n_2+1)-l_2(l_2+1)]\\&\times\int\Theta^*(1234;\,56;\,7)\frac{1}{R_2{}^2}\psi(1234;\,56;\,7)d\xi\Big\}.\end{aligned}$$

Finally, the expectation value of the potential energy operator is

$$\begin{aligned}\langle\sum_{i<j}V_{ij}\rangle=&\left(\frac{7!}{N^2}\right)\int\psi^*(1234;\,56;\,7)[(wW_0+bB_0)\\&-(wW_1+bB_1)P_{15}{}^r-(wW_2+bB_2)P_{17}{}^r\\&-(wW_3+bB_3)P_{57}{}^r+(wW_4+bB_4)P_{15}{}^rP_{26}{}^r\\&+(wW_5+bB_5)P_{17}{}^rP_{26}{}^r+(wW_6+bB_6)P_{57}{}^rP_{26}{}^r\\&+(wW_7+bB_7)P_{17}{}^rP_{15}{}^r\\&-(wW_8+bB_8)P_{17}{}^rP_{15}{}^rP_{26}{}^r\\&+2(w+b)(F_{37}P_{37}{}^rP_{15}{}^rP_{26}{}^r-F_{35}P_{35}{}^rP_{17}{}^rP_{26}{}^r\\&-F_{35}P_{35}{}^rP_{57}{}^rP_{15}{}^r-F_{37}P_{37}{}^rP_{17}{}^rP_{15}{}^r)]\\&\times\psi(1234;\,56;\,7)d\mathbf{r},\end{aligned}$$

with

$$\begin{aligned}W_0&=12F_{12}+6F_{15}+3F_{17}+F_{57}+2F_{56},\\W_1&=12F_{23}+32F_{12}+2F_{26}-6F_{15}+5F_{27}+2F_{17}+F_{67},\\W_2&=6F_{23}+12F_{12}+5F_{25}+2F_{15}+2F_{56}-3F_{17},\\W_3&=12F_{12}+6F_{15}+3F_{16}+4F_{56}-F_{57},\end{aligned}$$

[15] To take into account the hard-core part of this interaction properly, one needs to introduce into the trial wave function a short-range correlation factor of the form discussed in reference 8.

$$W_4=16F_{13}+2F_{17}+2F_{37}+6F_{12}-2F_{15},$$
$$W_5=2F_{35}+8F_{23}+8F_{13}-5F_{17}-5F_{26}+8F_{16}-2F_{15}+4F_{25}+4F_{12}+2F_{34},$$
$$W_6=6F_{13}+12F_{12}-F_{57}-3F_{26}+2F_{15}+4F_{27}+4F_{25},$$
$$W_7=8F_{27}+4F_{16}+12F_{23}-2F_{17}-6F_{15}-2F_{57}+12F_{12}+12F_{25}+2F_{26}+4F_{56}+4F_{67},$$
$$W_8=16F_{35}+8F_{13}+8F_{23}+4F_{37}+8F_{56}+4F_{12}+2F_{57}-2F_{15}-2F_{25}-2F_{17}+4F_{27},$$
$$B_0=2F_{56}+F_{57},$$
$$B_1=8F_{12}+2F_{17}+F_{67}-F_{27}-4F_{26},$$
$$B_2=2F_{56}+2F_{15}-F_{25},$$
$$B_3=4F_{56}-F_{57},$$
$$B_4=4F_{15}-8F_{13}+2F_{17}-F_{37},$$
$$B_5=F_{17}+F_{26}-F_{35}-4F_{23}-4F_{13}+2F_{16}-2F_{15}+4F_{25}+2F_{34}+4F_{12},$$
$$B_6=4F_{25}+4F_{27}-4F_{15}-F_{57},$$
$$B_7=2F_{27}+4F_{16}-2F_{17}-2F_{57}-4F_{26}+4F_{56}+4F_{69},$$
$$B_8=2F_{57}+4F_{15}+4F_{25}-2F_{17}+4F_{27}-8F_{35}-4F_{13}-4F_{23}-2F_{37}+8F_{56}+4F_{12},$$

where

$$F_{ij}=-V_0\exp(-\kappa r_{ij}^2).$$

PHYSICAL REVIEW VOLUME 124, NUMBER 2 OCTOBER 15, 1961

Once-Forbidden Beta Spectrum of Tl^{206}†

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(Received June 9, 1961)

The beta spectrum of 4.2-min Tl^{206} was investigated in a 4π scintillation spectrometer. The source was in secular equilibrium with the 2.6×10^6 year Bi^{210} parent. The electron distribution was observed to have a nonstatistical form which could be fitted with a once forbidden pseudovector shape factor. No necessity for the inclusion of any pseudoscalar contribution was observed. The energy release in the Tl^{206} decay is 1.571 ± 0.010 Mev.

INTRODUCTION

A DETAILED study of the Tl^{206} beta spectrum has been made in a 4π scintillation spectrometer. A nonstatistical distribution was observed which could be fitted with a pseudovector shape factor. The energy release in the decay of Tl^{206} was found to be 1.571 ± 0.010 Mev.

The beta decay of Tl^{206} to Pb^{206} is described as a $0^-\rightarrow0^+$ transition. According to the $V-A$ law,[1–5] only the pseudovector (A) coupling can appreciably influence the decay. If a pseudoscalar coupling were also to exist, this would also contribute, and many authors have used the $0^-\rightarrow0^+$ transition as tests of this point.[6–10] It will be shown that the nonstatistical shape of the Tl^{206} beta spectrum can be explained in terms of a pure pseudovector shape factor with no pseudoscalar contribution. Indeed, it would be an error to include the pseudoscalar interaction without also considering higher order terms in the pseudovector contribution.

Originally, this study was undertaken in order to determine the energy released in the Tl^{206} decay with greater accuracy. The knowledge of the end point is important in locating the energy levels of Bi^{210}. One state of Bi^{210}, the 5-day RaE isomer, decays by β emission to Po^{210}. Po^{210} alpha decays to Pb^{206}. The total energy release in this branch is 6.460 ± 0.006 Mev. The 2.6×10^6-yr isomer of Bi^{120} decays by α emission to Tl^{206}. Tl^{206} decays to Pb^{206}. At the time when work was started on this problem, it was believed that the (4.930 ± 0.010)-Mev α group of Bi^{210} (2.6×10^6 yr half-life) decayed to the ground state of Tl^{206}. The end point of the Tl^{206} β spectrum had been reported as 1.51 ± 0.01 Mev.[11] The end point of the Tl^{206} β spectrum had been reported as 1.51 ± 0.01 Mev.[11] Thus the total energy released in this branch was 6.440 ± 0.020 Mev. Since the energy released in the two branches was the same within the experimental errors, it was not clear which of the two isomers is the ground state of Bi^{210}. An accurate determination of the end-point energy of the β spectrum of Tl^{206} would possibly remove this uncer-

† Supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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