Evidence for Compound Nucleus Formation Using (p,p') and (α,p) Scattering in Nickel

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Spectra for (p,p') and (α,p) reactions have been obtained by bombarding nickel targets with the beam of the Livermore 90-inch cyclotron and magnetically analyzing protons emitted at 135°. These reactions were studied for several energies of incident protons between 7.8 and 11.4 Mev, and incident alphas between 9.65 and 12.8 Mev. When the differential scattering cross section is divided by the emitted channel energy and the black nucleus cross section for protons, results are obtained for different incident proton energies which have the same relative shape when plotted vs excitation energy. This is strong evidence for formation of compound nucleus in these reactions. A large peak is observed in the spectrum at 4.75 Mev, an excitation energy where the level density is sufficiently high that it is difficult to attribute this peak to a single level. An anomalous peak at about this energy has been previously observed for 23-Mev (p,p') scattering and 30-Mev (α,α') scattering on nickel targets by Cohen, and Sweetman and Wall. Results obtained for the (α,p) spectrum are in good agreement with predictions of the statistical model of the compound nucleus assuming a level density of the form $\exp[2(aE)^{\frac{1}{2}}]$.

I. INTRODUCTION

A NUMBER of scattering experiments have been performed investigating the theory of the formation of a compound nucleus. The usual procedure is to examine the emitted particle spectrum as a function of angle at which the scattered particle is detected. In the present experiment, the emitted particle spectrum was studied as a function of incident particle energy and detection was performed at a fixed backward scattering angle. The emitted protons were examined at 135° with a particle selector and magnetic energy analyzer. Thin, natural nickel targets were bombarded by the beam of the Livermore 90-inch cyclotron using protons varying between 7.8 and 11.4 Mev, and alpha particles varying between 9.65 and 12.8 Mev.

II. EXPERIMENTAL ARRANGEMENT

The experimental setup is shown schematically in Fig. 1. The proton energy was analyzed by means of a bending magnet placed between the target and the detector. Energy resolution of the system was about 6% for these measurements. The detector was a scintillation counter that used a 10-mil thick CsI crystal with cross-section dimensions of $\frac{1}{8}$ in. $\times 1$ in. To ensure that only protons were detected, remotely changeable absorbers were placed between the magnet and detector.

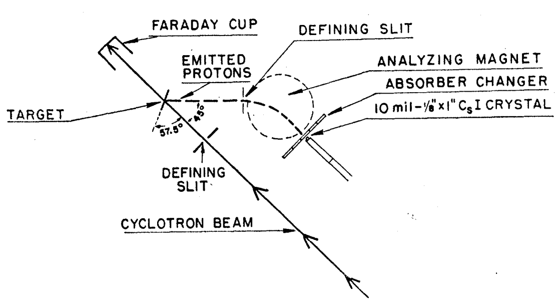

Fig. 1. Block diagram of experimental apparatus.

The experimental setup, designed to have low background and high stability, had the following features:

(1) Low-energy protons, far below the Coulomb barrier, could be examined without the problem of discriminating against a large intensity of higher energy protons or other particles.

(2) High-energy protons normally can degrade and scatter in the defining slits, and scatter off as low-energy protons. However, with the present 6-in. gap magnet geometry only those protons that scatter near 0° in the defining slits are counted. This is because it is not possible for particles to singly scatter off a wall of the magnet chamber and be counted. A gold target was used as a check on this background. It was found that the background due to these protons at all energies was less than 5%.

(3) The CsI detector was well shielded from all neutrons and γ's. The intervening space between the target, other major sources of γ's and neutrons, and the detector was filled with heavy shielding.

III. DISCUSSION OF RESULTS

The experimental data were corrected for energy variation of experimental resolution and energy loss in target. Figures 2 and 3 show relative intensities of proton energy distributions obtained for incident proton energies of 7.8, 8.4, 9.15, 10.05, 11.25, and 11.4 Mev. The inelastic proton data can be considered to be due primarily to the Ni^{58} isotope because of the following considerations:

(1) Ni^{58} is the most abundant isotope (67%) while the only other important isotope is Ni^{60} (27%).

(2) In Ni^{58}, most of the proton reaction cross section is due to proton emission because of the large (p,n) Q value, 10.4 Mev.[1] On the other hand, a calculation

[1] V. J. Ashby and H. C. Catron, University of California Research Report UCRL-5419, 1959 (unpublished).

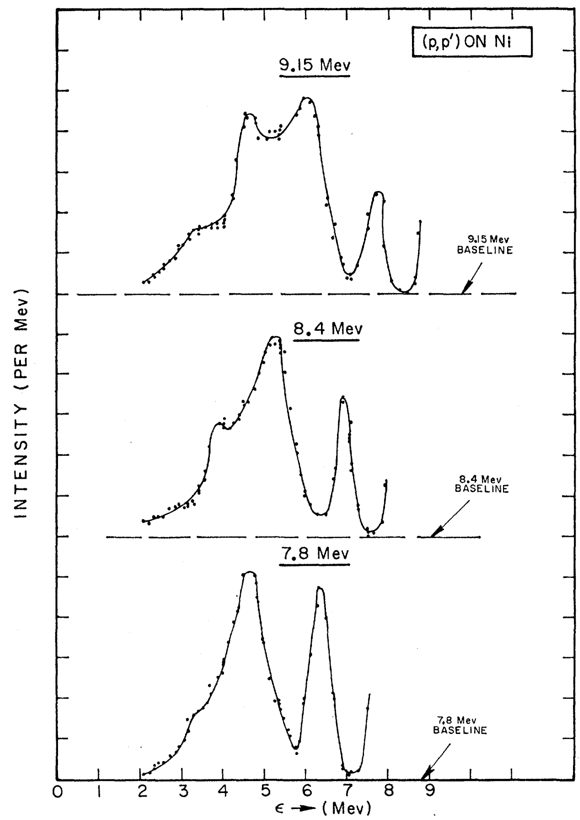

FIG. 2. Relative intensity distribution of emitted protons as a function of emitted channel energy for incident protons of 9.15, 8.4, and 7.8 Mev. The curves have been uniformly displaced from one another along the intensity axis.

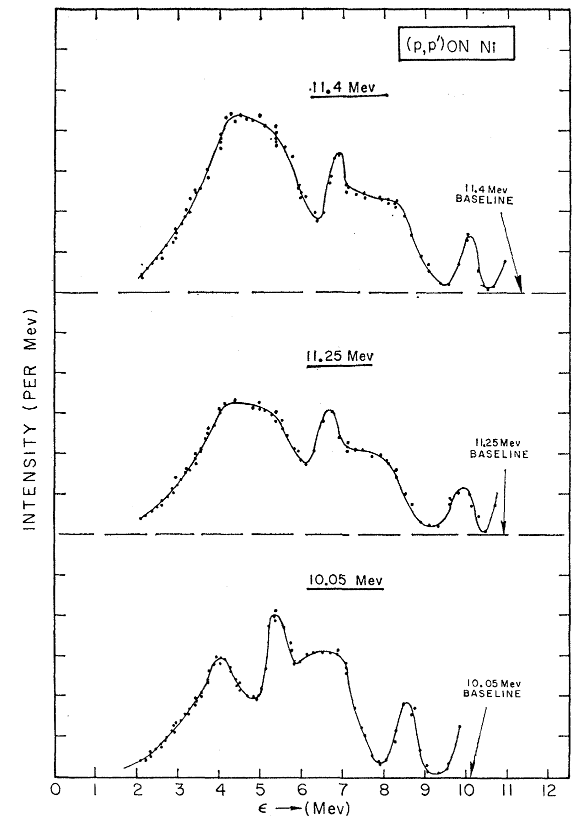

FIG. 3. Relative intensity distribution of emitted protons as a function of emitted channel energy for incident protons of 11.4, 11.25, and 10.05 Mev. The curves have been uniformly displaced from one another along the intensity axis.

using the statistical model of the nucleus indicates that for 10-Mev incident protons, about 90% of the emission from Ni^{60} is neutrons. This calculation assumes that the level density of the odd-odd nucleus which results from neutron emission is about 10 times the level density of the even-even nucleus resulting from proton emission.[2]

Figure 4 shows relative intensities of proton energy distributions obtained for incident alpha-particle energies of 9.65, 10.0, 10.35, and 12.8 Mev. The Q values[1] for this reaction are 3.77 for Ni^{60} and 3.12 for Ni^{58}. A statistical model calculation[3] indicates that for the Ni^{58} nucleus there is very little competition from neutron emission because of the large (α,n) Q value (9.7 Mev). In the case of the Ni^{60} nucleus, which has a lower (α,n) Q value (7.9 Mev), about 50% of the emission is neutrons. There is essentially no competition from deuterons because of large (α,d) and (p,d) thresholds combined with Coulomb barrier.

[2] G. Brown and H. Muirhead, Phil. Mag. **2**, 473 (1957).
[3] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

IV. INTERPRETATION OF THE EXPERIMENTAL RESULTS

1. Comparison with the Independence Assumption of the Formation of a Compound Nucleus

Using the Bohr assumption of the independence of the formation and decay of the compound nucleus, the following relation for the energy distribution of the emitted protons is obtained[3]:

$$I(\alpha,\epsilon)=K_\alpha\sigma(E,\epsilon)P(E), \tag{1}$$

where $I(\alpha,\epsilon)$ is the differential scattering cross section per Mev per steradian divided by the exit channel energy ϵ for an incident channel energy α, K_α is a function only of the incident channel energy α and is independent of E or ϵ, $\sigma(E,\epsilon)$ is the average cross section in an energy interval $\Delta\epsilon$ for a channel energy ϵ of a proton incident on the residual nucleus at an excitation energy E where the energy interval $\Delta\epsilon$ is defined by the experimental resolution, and $P(E)$ is the number of levels in the energy interval $\Delta\epsilon$ at an excitation energy E of the residual nucleus.

The intensity relation (1) may be rewritten as

$$I(\alpha,\epsilon)=K_\alpha\sigma_C(\epsilon)\rho(E,\epsilon)P(E) \tag{2}$$

by using the relation

$$\sigma(E,\epsilon)=\sigma_C(\epsilon)\rho(E,\epsilon),$$

where $\sigma_C(\epsilon)$ is the proton black nucleus cross section at energy ϵ, $\rho(E,\epsilon)$ is the ratio of the reaction cross section of the nucleus at an excitation E, to the black nucleus cross section for protons of channel energy ϵ, incident on the residual nucleus in its ground state.

Since we are interested only in the relative energy distribution caused by the nuclear part of the interaction, we define the following quantity $S(\alpha,E)$:

$$S(\alpha,E)=\frac{I(\alpha,\alpha-E)}{\sigma_C(\alpha-E)}\frac{\sigma_C(\alpha-E_0)}{I(\alpha,\alpha-E_0)}=\frac{\rho(E,\alpha-E)P(E)}{\rho(E_0,\alpha-E_0)P(E_0)}, \quad (3)$$

where E_0 is the energy at which the data are normalized.

The proton black nucleus cross section was calculated from the following expression[3]:

$$\sigma_C=\pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)\frac{4S_lKR}{\Delta_l^2+(KR+S_l)^2}, \quad (4)$$

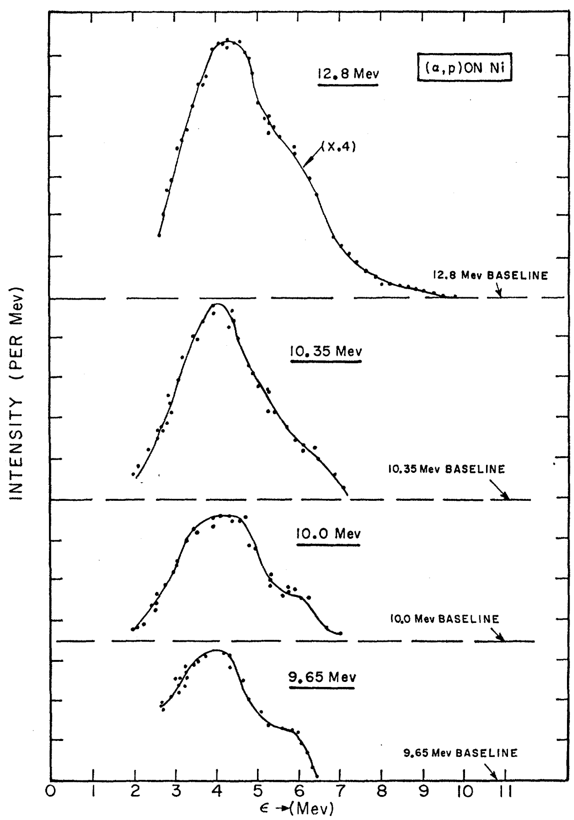

FIG. 4. Relative intensity distribution of emitted protons as a function of emitted channel energy for incident α's of 12.8, 10.35, 10.0, and 9.65 Mev. The curves have been uniformly displaced from one another along the linear intensity axis.

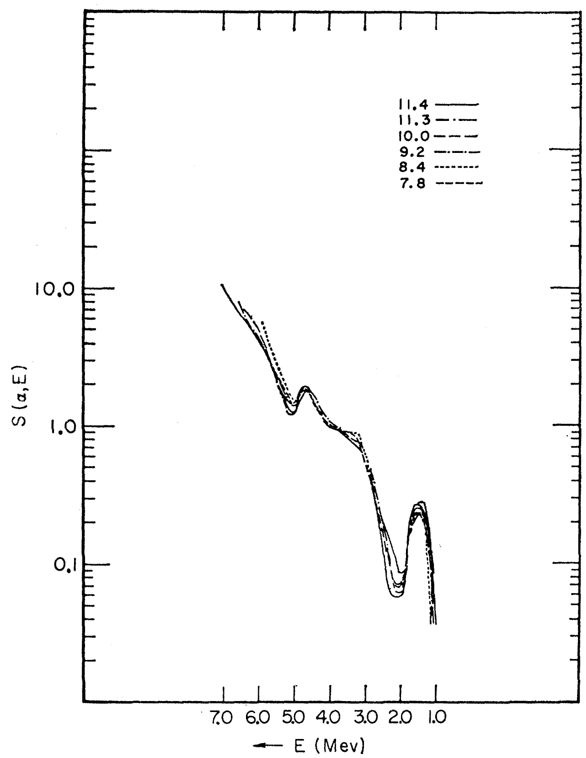

FIG. 5. $S(\alpha,E)$ for (p,p') scattering on Ni plotted semilogarithmically as a function of E.

where $\lambda\!\!\!^{-}$ is the wavelength of the incident proton divided by 2π, K is the wave number of the proton inside the nucleus, R is the nuclear radius,

$$\Delta_l=R\left[\frac{G_l(dG_l/dr)+F_l(dF_l/dr)}{F_l^2+G_l^2}\right]_{r=R},$$

$$S_l=R\left[\frac{G_l(dF_l/dr)-F_l(dG_l/dr)}{F_l^2+G_l^2}\right]_{r=R}.$$

F_l and G_l, the regular and irregular solutions of the Coulomb wave equation, were generated by means of an IBM-650 coded program. In calculating K, a nuclear potential of 45 Mev was used. The radius used for σ_C in (3) was $R=5.81\times10^{-13}$ cm.

The (p,p') data were reduced according to the above procedure to give $S(\alpha,E)$ which is shown plotted vs E in Fig. 5 ($E_0=4$ Mev). The large peak at 4.75-Mev excitation energy, which is evident here as well as in the (p,p') spectra previously discussed (Figs. 2 and 3), is in an energy region where the level density is sufficiently high that it is difficult to attribute this peak to a single level. This peak has been previously reported by Cohen[5] who observed inelastic scattering of 23-Mev protons in

[4] M. Mazari, W. W. Buechner, and R. P. de Figueido, Phys. Rev. **108**, 373 (1957).

[5] Bernard L. Cohen, Phys. Rev. **105**, 1549 (1957).

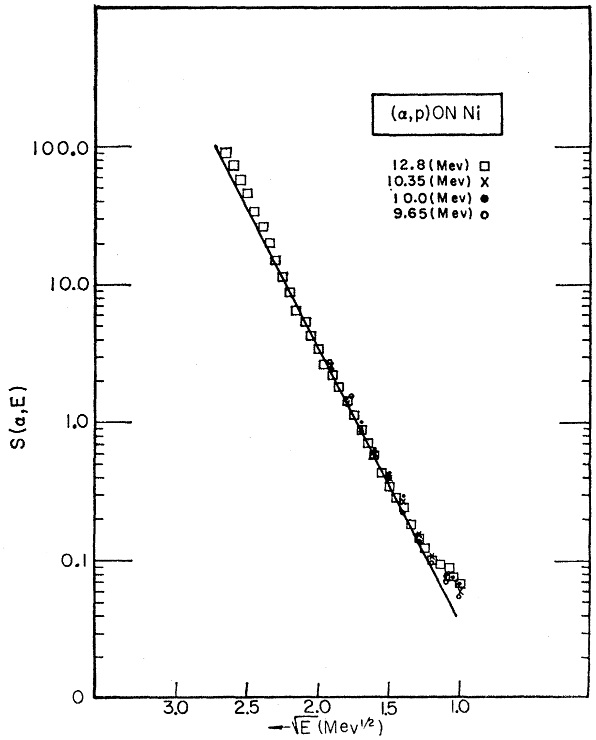

FIG. 6. $S(\alpha,E)$ for (α,p) scattering on Ni plotted semilogarithmically as a function of $\sqrt{E}$.

a natural nickel target, and by Sweetman and Wall[6] who observed inelastic scattering of 30-Mev alpha particles in a Ni^{58} target.

However, it is interesting to note that all of the $S(\alpha,E)$ curves superimpose on one another. In other words, when the differential scattering cross section is divided by the emitted channel energy and the black-nucleus proton cross section, the results obtained for different incident proton energies have the same relative shape when plotted against excitation energy. This is strong evidence for formation of compound nucleus in these reactions. The high degree of correlation not only indicates formation of a compound nucleus, but from (3) also indicates that the ratio $\rho(E,\beta)$ is independent of the incident energy. This can be compared with the neutron inelastic scattering date of Beyster, Walt, and Salmi,[7] in which the (n,n') cross section was found to be flat from 4 to 14 Mev.

We find that the shape of $S(\alpha,E)$ for (p,p') scattering in Ni^{58} is not dependent on incident proton energy. On the other hand, Gugelot[8] measured (p,p') scattering on silver using two incident proton energies (18.3 Mev and 16.2 Mev) and found that the shape of $S(\alpha,E)$ does depend on incident proton energy.

There are two possible explanations for the different results obtained in these two experiments. First, because of the energy region in which our measurements were made, protons emitted from the Ni^{58} and Ni^{60} reactions experience little competition from emission of neutrons or other particles. Thus, the energy distribution of the emitted protons is characteristic of the primary mode of the reaction which appears to be via formation of the compound nucleus. On the other hand, in Gugelot's experiments[8] there is heavy competition from emission of particles other than protons. Consequently, the primary mode of reaction may still be via compound nucleus formation even though the proton energy distribution does not indicate compound nucleus formation. Second, the width of levels in the nucleus is larger at higher incident proton energy, and thus proton emission via direct mode of reaction is more probable in his experiment than in our experiment.

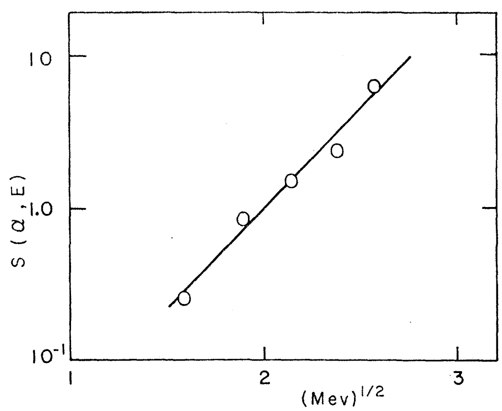

FIG. 7. $S(\alpha,E)$ for (p,p') scattering on Ni plotted semilogarithmically as a function of $\sqrt{E}$.

2. Comparison with the Statistical Model of the Compound Nucleus

The statistical model of the decay of the compound nucleus[3] predicts

$$S(\alpha,E)=\omega(E)=C\exp[2(aE)^{\frac{1}{2}}], \quad (5)$$

where $\omega(E)$ is the level density of the residual nucleus and C and a are constants.

$S(\alpha,E)$ is plotted semilogarithmically in Fig. 6 for the (α,p) data as a function of $\sqrt{E}$. A straight line appears to be a good fit to the data as predicted by Eq. (5). In this case the constant a, a function of the level density of the residual nucleus, was found to be equal to 4.4 (with E in Mev). This can be compared with the a value equal to $A/13$, obtained from (p,n) data for elements of odd atomic weight, where A is the atomic weight of the target nucleus.[9] Using this relation

[6] D. R. Sweetman and N. S. Wall, *Comptes Rendus du Congrès International de Physique Nucléaire; Interactions Nucléaires aux Basses Energies et Structure des Noyaux, Paris, July, 1958*, edited by P. Guggenberger (Dunod, Paris, 1959), p. 547.

[7] J. R. Beyster, M. Walt, and E. Salmi, Phys. Rev. **104**, 1319 (1956).

[8] P. C. Gugelot, Phys. Rev. **93**, 425 (1954).

[9] R. D. Albert, J. Anderson, and C. Wong, Phys. Rev., **120**, 2149 (1960).

for copper, the residual nucleus in our (α,p) experiment, we obtain $a=4.7$, which is very good agreement with the value of 4.4 obtained in this experiment.

$S(\alpha,E)$ is related to the level density of the residual nucleus. For (p,p') the residual nucleus is even-even, while for (α,p) the residual nucleus is odd-even. The odd-even nucleus has a level density estimated to be five times that of an even-even nucleus.[2] Thus $S(\alpha,E)$ for (p,p') shows much structure, while $S(\alpha,E)$ for (α,p) is very smooth. However, if we average the (p,p') data over 1-Mev energy intervals, most of the detailed structure is smoothed out and we may attempt to obtain level density information by applying statistical theory. Figure 7 is a plot of $S(\alpha,E)$ for (p,p') scattering on Ni as a function of $\sqrt{E}$. When this curve is fitted with a straight line, the result $a=2.4$ is obtained. This small value of a is consistent with smaller level densities that are observed for even-even nuclei.

ACKNOWLEDGMENTS

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Nuclear Moment of Ce^{137m} by Nuclear Alignment*

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Nuclei of Ce^{137} and Ce^{137m} have been aligned at low temperatures in a single crystal of neodymium ethylsulfate nonahydrate by means of the magnetic hfs coupling with the electrons of the Ce^{+3} ions. The anisotropy of their gamma radiation has been observed. The magnetic moment of Ce^{137m} is $|\mu_N|=0.96\pm0.09$ nm. The spin of Ce^{137m} is established as 11/2.

1. INTRODUCTION

CERIUM-137 is one of a large group of nuclides which has an $h_{11/2}$ isomeric state that decays by emission of $M4$ radiation to a $d_{3/2}$ ground state. Brosi and Ketelle[1] have studied this isomeric transition and the electron-capture decay of the ground state to La^{137} by gamma-ray, coincidence, and conversion-electron-spectroscopic techniques. Their results lead to the energy-level scheme shown in Fig. 1. A $g_{7/2}$ orbital was assigned to the ground state of La^{137} from its observde second-forbidden beta decay to Ba^{137} (spin 3/2), and a $d_{5/2}$ state to the first excited state from the $M1$ character of the 10-kev gamma ray. The shell model is in good agreement with these assignments, and further predicts that the 455-kev level is either in a $s_{1/2}$ or a $d_{3/2}$ state.

We have measured the magnetic moment of Ce^{137m} by aligning Ce^{137m} nuclei and measuring the anisotropic distribution of the gamma radiation. Further information was obtained about the decay scheme of Ce^{137}, which was also aligned.

2. EXPERIMENTAL PROCEDURE

Cerium-137m was prepared by a $(p,3n)$ reaction of 21-Mev protons on natural lanthanum (99.911% La^{139}) in the ORNL 86-inch cyclotron. Cerium was separated from the target material by oxidation to the +4 state, followed by solvent extraction,[2] which yielded about 10^{12} atoms of Ce^{137m}. The cerium was then reduced to the +3 state and grown into a single crystal of neodymium ethylsulfate nonahydrate so that it replaced some of the Nd^{+3} ions. The crystal was mounted in

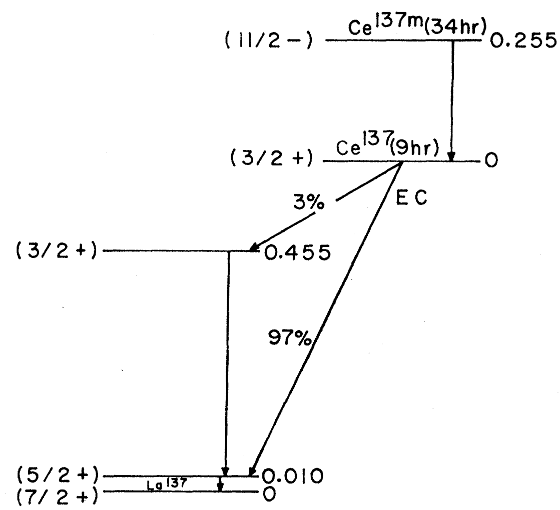

FIG. 1. Energy level scheme.

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[1] A. R. Brosi and B. H. Ketelle, Phys. Rev. **100**, 169 (1955); **103**, 917 (1956).

[2] L. E. Glendenin, Anal. Chem. **27**, 50 (1955).