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Proton inelastic scattering at 12 MeV on ^{154}Eu

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Scattered protons from ^{154}Eu were measured with an Enge split-pole spectrograph at a bombarding energy of 12 MeV. Rotational states in the ground band of ^{154}Eu were excited to $I^{\pi} = 8^-$. Values of the deformation parameters were extracted from the scattering data using a coupled-channels calculation. The analysis yields $\beta_2 = 0.30$ and $\beta_4 = 0.04$. A comparison of the ground band rotational properties of both ^{152}Eu and ^{154}Eu suggests that both nuclei have the same ground state configuration: $\pi_{5/2}[413]$, $\nu_{11/2}$ [505].

NUCLEAR REACTIONS ^{154}Eu (p,p'), $E_p=12$ MeV; measured E'_p and $\sigma(\theta)$, split-pole spectrograph; adiabatic coupled-channel analysis; deduced levels, J^{π}, β_2, and β_4; isotopically enriched radioactive target.
NUCLEAR STRUCTURE ^{154}Eu, assigned Nilsson configuration.

I. INTRODUCTION

A number of studies[1-5] have been carried out to determine the level structure of ^{154}Eu. Most of the previous work emphasizes the complexity of this nucleus because the data show a high level density and five isomeric states ($t_{1/2} > 10$ ns) are observed below 200 keV. Underlying this observed complexity are the well-known structural features[6-9] determined in odd-A nuclei with $89 \leq N \leq 93$ which admit a multiplicity of combinations of $\Delta N = 2$ mixing and strong Coriolis coupling. The task of unraveling rotational band structures for odd-A nuclei around the $N=89$ transition region has generally been nontrivial. Rotational band assignments for transitional odd-odd nuclei[10] in general, and for ^{154}Eu in particular, are undoubtedly even more difficult.

Recently, a careful study by the Riga–Grenoble groups[11] of (n,γ) data and associated internal conversion spectra from ^{154}Eu suggests the existence of five rotational bands below ~250 keV. The ^{154}Eu 3^- ground state has been assigned the configuration $\pi\frac{5}{2}[413];\nu\frac{11}{2}[505]$ by Stöffl *et al.*,[5] and the Riga–Grenoble data suggest a 4^- rotational state at 80.654 keV.

In the present study we have measured the scattered proton spectrum from the ^{154}Eu(p,p') reaction using a mass separated target of radioactive (8.5 yr) $^{154}Eu_2O_3$. The reaction selectively populates states of the ^{154}Eu ground band and is ideal for isolating the specific features of this band from other complicating structural aspects of the nucleus. Additionally, the measured angular distributions are used to determine the static deformation parameters β_2 and β_4.

This experiment is the last in a series of (p,p') measurements made in our laboratory of the ground band properties of transitional Eu nuclei. In previous publications[12,13] we have discussed (p,p') experiments on isotopically enriched targets of ^{151}Eu, ^{152}Eu, and ^{153}Eu.

II. EXPERIMENTAL PROCEDURE

The experiments were performed using a beam of 12-MeV protons from the EN-tandem accelerator stage of the Lawrence Livermore Laboratory (LLL) cyclograaff facility. Isotopically enriched targets of radioactive (8.5 yr) $^{154}Eu_2O_3$ were obtained from mass separating an enriched sample of $^{153}Eu_2O_3$ which had been neutron irradiated at the Oak Ridge High-Flux Isotope Reactor. Several targets were made, each with a thickness of ~40 μg/cm^2. The target material was supported on a commerical carbon substrate with a thickness of ~50 μg/cm^2.

The primary decay product of ^{154}Eu is ^{154}Gd and, since target fabrication began ~1 yr following neutron irradiation of the ^{153}Eu sample, we estimated that ~9% of the original ^{154}Eu had converted to ^{154}Gd. Ordinarily, such a mixture of rare-earth isobars would need to be separated by ion-exchange chemistry prior to magnetic separation. In this case, however, it was possible to eliminate a chemical purification step because the relative ionization efficiency of gadolinium in the isotope separator ion source is appreciably smaller than that of europium. In fact, europium was chemically separated from gadolinium in the ion source. This technique would not work if samarium were also present because the Eu and Sm relative ionization efficiencies are similar. Further details of our techniques for fabricating and handling radioactive targets are described in Ref. 14.

The elastic and inelastic proton groups from the ^{154}Eu(p,p') reaction were momentum analyzed in an Enge split-pole magnetic spectrometer. Particle detection was achieved in the spectrometer by a position-sensitive delay-line proportional counter.[15] The spectrometer was calibrated using scattered proton groups from ^{153}Eu. The energies of the levels populated by inelastic scattering in this nucleus are precisely known.[1]

Angular distributions were measured for the ^{154}Eu (p,p') reaction at 10° intervals between 30° and 140°. A Si(Li) surface-barrier detector was mounted at 90° to monitor elastic events during the scattering experiments. The monitor counter was calibrated in separate experiments when elastic events were simultaneously recorded in the monitor and in the spectrometer at settings of 90° and 30°. Using these data, the elastic events registered in the monitor at 90° during an exposure could be converted to an equivalent number registered by the spectrometer if it were set at 30°.

Absolute differential cross sections were obtained by combining the calculated elastic cross section at 30° with the number of counts registered by the spectrometer for a particular proton group and the suitably converted monitor counter recording. The elastic cross section used for normalization was obtained for ^{154}Eu from an adiabatic coupled-channels (ACC) calculation.[16] The ACC-calculated elastic cross section at 30° does not differ appreciably (< ±3%) from the results of a simple Rutherford scattering calculation.

III. RESULTS

Table I gives the energies of the low-lying levels populated by proton inelastic scattering from ^{154}Eu and from the calibration target ^{153}Eu. Levels up to $I^\pi = 8^-$ are observed. Within our limits of detection, no other levels near the ground band were populated. The scattered proton spectrum observed at 130° and a portion of the spectrum measured at 140° are shown in Fig. 1. A level at 596 keV is weakly but clearly populated at both angles. The spectrum further shows that there is no evidence for contaminant lines from either ^{154}Sm or ^{154}Gd.

The experimental system allowed the acquisition of scattered protons up to an excitation energy in ^{154}Eu of ~1.2 MeV. Unfortunately, the carbon substrate contained several unidentified impurities which obscured most of the spectrum beyond ~600 keV. Consequently, only information on the ^{154}Eu ground band was obtained from these experi-

TABLE I. Low-energy levels in ^{153,154}Eu populated by proton inelastic scattering. The ^{153}Eu level energies were taken from Ref. 1. Values quoted for ^{154}Eu are measured using ^{153}Eu as the energy standard.

^{153}Eu E (keV)	I^π	^{154}Eu E^a (keV)	I^π
0	$\frac{5}{2}^+$	0	3^-
83.37	$\frac{7}{2}^+$	80.8 ± 0.8	4^-
193.06	$\frac{9}{2}^+$	181.7 ± 1.1	5^-
325.06	$(\frac{11}{2}^+)$	300.7 ± 1.5	6^-
481.04	$(\frac{13}{2}^+)$	439.6 ± 2.0	7^-
654.69	$(\frac{15}{2}^+)$	596 ± 4	8^-

^{a}The quoted energy values represent an average of two or more angles. The errors quoted are standard deviations.

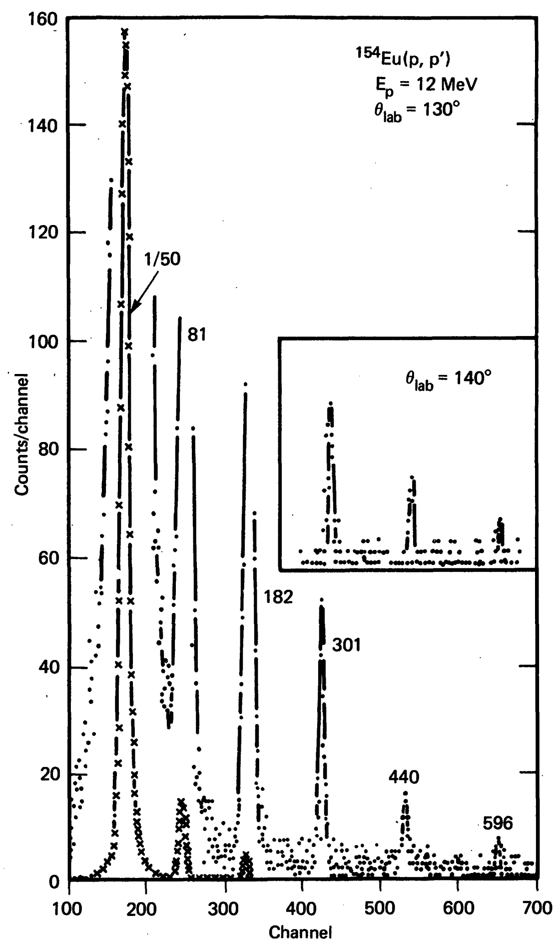

FIG. 1. Proton spectrum from the ^{154}Eu (p,p') reaction. The inset confirms the weak excitation at 140° of the 596-keV level.

TABLE II. Absolute differential cross sections in mb/sr for proton scattering from ^{154}Eu.[a]

θ_{lab}	0 keV	81 keV	182 keV	301 keV	440 keV	596 keV
30	8282 ± 800[b]	1.41 ± 0.42	···	···	···	···
40	2395 ± 144	1.71 ± 0.19	1.02 ± 0.12	···	···	···
50	814 ± 50	3.19 ± 0.28	1.50 ± 0.15	···	···	···
60	435 ± 26	2.57 ± 0.22	1.03 ± 0.09	···	···	···
70	215 ± 13	2.11 ± 0.17	0.753 ± 0.067	0.168 ± 0.024	···	···
80	116 ± 10	1.81 ± 0.14	0.745 ± 0.063	0.092 ± 0.013	···	···
90	68.3 ± 5.1	1.76 ± 0.13	0.566 ± 0.046	0.045 ± 0.006	0.025 ± 0.005	···
100	48.4 ± 3.4	1.76 ± 0.13	0.626 ± 0.051	0.048 ± 0.007	0.016 ± 0.004	···
110	37.6 ± 2.6	1.73 ± 0.13	0.596 ± 0.048	0.063 ± 0.008	0.022 ± 0.005	···
120	28.8 ± 2.0	1.55 ± 0.12	0.566 ± 0.045	0.066 ± 0.008	0.023 ± 0.004	···
130	21.8 ± 1.5	1.46 ± 0.11	0.536 ± 0.042	0.060 ± 0.007	0.021 ± 0.003	0.009 ± 0.003
140	16.5 ± 1.5	1.40 ± 0.11	0.477 ± 0.044	0.057 ± 0.009	0.018 ± 0.003	0.012 ± 0.004

[a]The quoted errors are statistical only.
[b]Normalization point. An impurity line with an intensity of ~10% of the elastic peak was observed to be partially resolved from the elastic group. The effect of this line on the normalization has been taken into account.

ments. The typical energy resolution observed was ~9 keV.

The differential cross sections measured for proton scattering from ^{154}Eu are given in Table II. Because of the contaminants in the target backing, weak population of some of the higher-lying levels was obscured at the forward angles.

IV. DISCUSSION

The ^{154}Eu ground state has a measured[17] spin-parity of 3^-. The energy level data in Table I are assigned rotational spin-parities based on 3^- as a band head. We note that the assignment of the 80.654-keV level by the Riga–Grenoble groups[11] as the 4^- ground-state rotational member is confirmed by our experiment. Stöffl *et al.*[5] have tentatively assigned to the ground band the configuration $\pi\frac{5}{2}[413];\nu\frac{11}{2}[505]$ by comparing several similarities of the ground-state properties of ^{152}Eu and ^{154}Eu. The ground-state structure of ^{152}Eu in terms of these neutron-proton orbitals seems well established.[10,12,13]

Our scattering measurements can be used to extend the comparison of the ground band properties of these nuclei. In Fig. 2 we have plotted $(E_{I+1}-E_I)/2(I+1)$ vs $(I)^2$ for the ground-state bands in both ^{152}Eu and ^{154}Eu. For additional comparison, the data[1] from ^{153}Eu are also plotted. The data for both odd-odd Eu nuclei show a similar I^2 dependence and one which is quite different from the behavior of ^{153}Eu. This can be interpreted as additional confirmation that the ^{154}Eu ground-state configuration is the same as that for ^{152}Eu.

Although all three nuclei have the same ground-state proton orbital component ($\frac{5}{2}[413]$), the coupling of the $\frac{11}{2}[505]$ neutron in the odd-odd systems seems to stabilize the rotational structure. A pure unperturbed rotational structure would trace a horizontal line. Clearly, none of the data plotted in Fig. 2 show such a trace; however, the two odd-odd Eu nuclei are considerably more monotonic than ^{153}Eu and imply that their rotational structure is relatively less perturbed.

The angular distributions were analyzed using

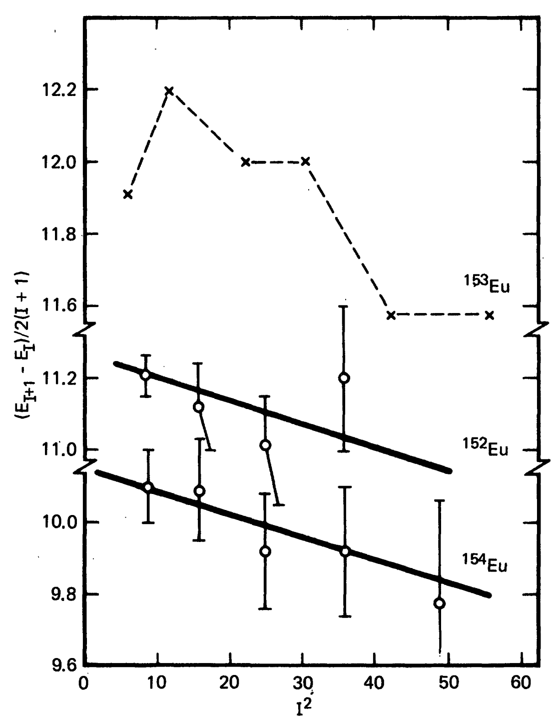

FIG. 2. Plot of $(E_{I+1}-E_I)/2(I+1)$ vs I^2 for the ground state bands in ^{152,153,154}Eu. The lines drawn in the figure are intended only to guide the eye. Experimental uncertainties for ^{153}Eu are smaller than the plotted points.

the coupled-channels code (JUPITOR) of Tamura.[16] Adiabatic coupling was used and the optical model parameters in the calculation were those given in Table III of Ref. 13. The values of β_2 and β_4 were adjusted to yield a reasonable fit to the data.

A plot of the data and calculation are shown in Fig. 3. The data are well reproduced using $\beta_2 = 0.30$ and $\beta_4 = 0.04$. For ^{154}Eu the value of β_2 is determined to be ~7% larger than that for ^{152}Eu. This increase is consistent with the comparison of the ground band moments of inertia as determined from the energy of the first-excited state in both nuclei.

The values of β_2 and β_4 cannot be altered by more than ±5% without destroying the agreement of the calculated angular distributions with experiment.

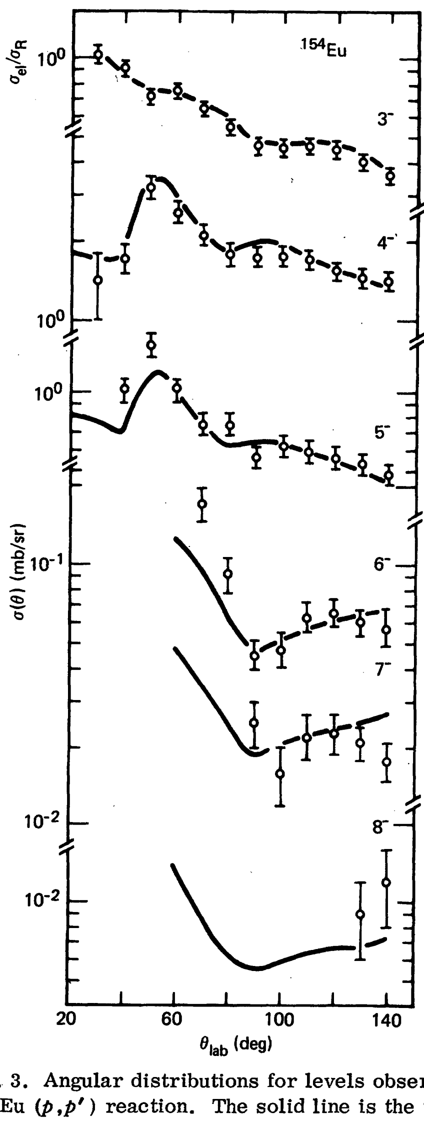

FIG. 3. Angular distributions for levels observed in the ^{154}Eu (p,p') reaction. The solid line is the result of a coupled-channel calculation using $\beta_2 = 0.30$ and $\beta_4 = 0.04$.

Uncertainties associated with both the optical potential and the nuclear charge distribution[13] are probably more serious and preclude any meaningful estimate of the uncertainties of β_2 and β_4. We note, however, that our values of the deformation parameters are consistent[18] with those observed for well-deformed nuclei in the range $150 \leq A \leq 160$.

V. SUMMARY AND CONCLUSIONS

We have now completed a systematic study of the ground-state properties of $^{151-154}$Eu and find several interesting features: (1) There is an abrupt increase in deformation between ^{151}Eu and ^{152}Eu, (2) ^{152}Eu and ^{154}Eu both have the same ground-state configuration, viz. $\{\pi\frac{5}{2}[413], \nu\frac{11}{2}[505]\}_{K=3^-}$, although ^{154}Eu has a slightly larger (~7%) deformation, and (3) the rotational stability of the odd-odd nuclei ^{152}Eu and ^{154}Eu is greater than that of ^{153}Eu.

These features may be qualitatively understood by considering that the total energy of the nucleus is obtained by summing the energies of the single particle orbitals. In Fig. 4 we present a Nilsson diagram for neutron numbers near $N = 89$. For nuclei with neutron numbers greater than $N = 82$, the nuclear potential energy surface as a function of N becomes progressively softer because the extra-core neutrons will tend to occupy down-sloping orbitals. As the orbitals outside the core fill, the valence nucleons can gain energy by deforming. At some neutron number, this will eventually overcome the rigidity of the $N = 82$ core and the nucleus will deform.

The $\frac{11}{2}[505]$ orbital plays a particularly important role in the structure of nuclei near the $N = 89$ transition region.[19-21] It is the most steeply rising orbital in this region and it is also the $N = 82$ core orbital closest to the Fermi surface. Hole states involving the orbital are particularly

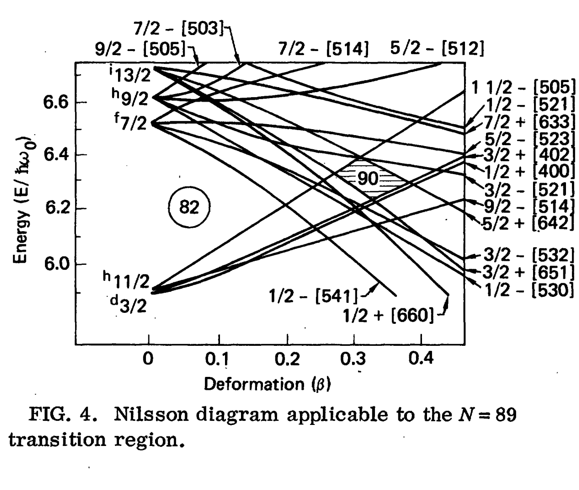

FIG. 4. Nilsson diagram applicable to the $N = 89$ transition region.

interesting since they will involve promoting a particle from this steeply upsloping orbital to one that is downsloping. The associated increase in single particle energy can be compensated in part by a decrease in the energy of the total system through greater deformation.

In such excitations it is possible that the energy gained through deformation can compensate completely for the increase in single particle energy so that the $\frac{11}{2}[505]$ orbital becomes the ground state. This apparently happens in the Eu nuclei at a deformation of $\beta_2 \sim 0.28$. Adding two more nucleons to ^{152}Eu to form ^{154}Eu involves a competition between filling the $\frac{11}{2}[505]$ orbital and filling the steeply downsloping $\frac{3}{2}[651]$ orbital, with a consequent increase in deformation. The latter alternative is more favorable, hence, the $\frac{11}{2}[505]$ orbital remains at the Fermi surface for $N = 91$.

The fact that the odd-odd nuclei are more rigid than ^{153}Eu may be understood in terms of the resistance to deformation that is produced by nucleons that are confined to the steeply upsloping $\frac{11}{2}[505]$ orbital. For even N, the occupation probability of this orbital decreases with increasing deformation, while for odd N it remains constant (due to blocking) at a value of 0.5. Thus, the centrifugal force due to nuclear rotation will be less effective in producing deformation in the odd-N isotopes than it is in ^{153}Eu, and the odd-N isotopes will therefore have greater rotational stability.

These arguments can be made quantitative only by complex calculations that include accurate estimates of the potential energy surfaces for both odd and even numbers of nucleons, estimates of the effect of rotational forces on such surfaces, and the neutron-proton residual interaction.

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