Deformation change at $N = 89$: Proton inelastic scattering at 12 MeV on ^{151,152,153}Eu†

Robert G. Lanier, Lloyd G. Mann, and Gordon L. Struble
Nuclear Chemistry Division, Lawrence Livermore Laboratory, Livermore, California 94550

Ivan D. Proctor and Dale W. Heikkinen
Experimental Physics Division, Lawrence Livermore Laboratory, Livermore, California 94550
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Scattered protons from ^{151,152,153}Eu were measured with an Enge split-pole spectrograph at a bombarding energy of 12 MeV. Rotational states up to $I^\pi = 7^-$ were observed in ^{152}Eu. Values of the deformation parameters were extracted from the scattering data using distorted-wave and coupled-channels techniques. The analysis suggests values of β_2 for ^{151,152,153}Eu to be 0.13, 0.28, and 0.28, respectively. For ^{152,153}Eu β_4 is found to be +0.06. The data for ^{152}Eu suggest that the low-lying members of the $K = 4^-$, $[\pi 3/2(411), \nu 11/2(505)]$ band are populated in the (p,p') reaction. This population is consistent with estimates of the degree of Coriolis mixing of this band with the $K = 3^-$, $[\pi 5/2(413), \nu 11/2(505)]$ ground band.

NUCLEAR REACTIONS ^{151,152,153}Eu(p,p'), $E_p = 12$ MeV; measured $E_{p'}$ and $\sigma(\theta)$, split-pole spectrograph; DWBA and couple-channel analyses; deduced levels, J^π, β_2, and β_4; isotopically enriched and radioactive targets.

NUCLEAR STRUCTURE ^{152}Eu, assigned Nilsson configurations.

I. INTRODUCTION

The europium isotopes in the region centered about $A = 152$ are of special interest because they apparently span an abrupt transition region. At $N = 89$, a change occurs in the ground state equilibrium shape and in other nuclear properties as well. These changes are experimentally well documented[1] and their abrupt nature is suggested by isotope shift data[2] on the europium nuclei between $151 \leq A \leq 154$. These data show that there is a strong increase in the change of the mean square nuclear charge radius when one neutron is added to ^{151}Eu.

For the odd-A europium isotopes centered about $N = 89$ ($A = 151, 153$), the properties of the low-lying excited states have been well measured and extensively studied. Early Coulomb excitation experiments on ^{151}Eu suggested that the low-energy structure could be interpreted as resulting from the coupling of a proton quasiparticle to a 2^+ vibration.[3] A subsequent calculation by Sen[4] based on very similar assumptions was only partially successful. Dracoulis and co-workers have attempted to describe the low-lying structure of both ^{151}Eu and ^{153}Eu in terms of the Nilsson model by including the effects due to the Coriolis interaction. By assuming that ^{151}Eu is a weakly deformed rotor[5,6] ($\beta_2 \sim 0.16$), the calculations suggest that the ground state is the $\frac{5}{2}^+$ member of a severely distorted $\frac{3}{2}[411]$ rotational band. A similar calculation[7] with $\beta_2 \sim 0.32$ in ^{153}Eu indicates that the general features of the $\frac{5}{2}[413]$ ground band and of other low-lying structures are fairly well reproduced. These Nilsson model calculations qualitatively explain some features of the two-nucleon transfer data[8,9] and suggest that the model can be applied equally well across the $Z = 63$ transition region.

The $N = 89$ species ^{152}Eu has been the subject of intense experimental study[10-13] and available evidence suggests that all the low-lying levels can be interpreted in terms of two quasiparticles strongly coupled to a well deformed core. For example, early work by Takahashi *et al.*[11] suggested a deformed structure for both the ^{152}Eu ground state and for other low-lying structures as well. Subsequent charged particle experiments,[10] particularly those of Jolly *et al.*[12] showed that the ground state can be interpreted as resulting from the antiparallel coupling of two Nilsson type orbitals: $\pi\frac{5}{2}[411]$ and $\nu\frac{11}{2}[505]$. By contrast, the work of Borovikov *et al.*[13] reaffirms the idea[14] that states with quite different natures may exist near the ground state in ^{152}Eu.

Single nucleon transfer data[10,15] connecting the europium isotopes between $151 \leq A \leq 153$ suggests a similarity in shape and structure between the ground and low-lying states of ^{152}Eu and ^{153}Eu but not between those of ^{151}Eu and ^{152}Eu. In particular a recent study of the ^{152}Eu(d,t) reaction[15] indicates that the observed cross sections cannot be explained solely on the basis of configuration differences between the target state and states of the ^{151}Eu residual nucleus. It appears that a change in the nuclear shape plays a significant role in explaining the observed strong (d,t) hinderences.

This observation is consistent with the trend suggested by the isotope shift data and somewhat inconsistent with the interpretation of Dracoulis and co-workers.

To further probe the nature of the shape transition in the region of europium nuclei, we have investigated the inelastic scattering of 12-MeV protons from isotopically enriched targets of ^{151,153}Eu and from a specially constructed ^{152}Eu radioactive (13 yr) target. We have also compared the data with the results of distorted-wave Born approximation and adiabatic coupled-channels calculations. Some of these results have been reported previously.[16]

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 each europium isotope were obtained from selectively enriched samples of europium oxide using the LLL magnetic isotope separator. In all cases, the targets were supported on a 50-μg/cm^2 carbon substrate and each had a thickness on the order of 40 μg/cm^2.

A special fabrication of the ^{152}Eu target began by neutron irradiating a 1.7-mg sample of enriched $^{151}Eu_2O_3$ for 41 h at the Oak Ridge high flux isotope reactor. After irradiation, the sample contained substantial amounts of the short-lived decay products ^{152}Sm and ^{152}Gd which cannot be separated from ^{152}Eu by a magnetic separator. These impurities were removed prior to isotope separation by ion exchange chemistry in a remotely controlled hot cell. The details describing the preparation of this target have been published elsewhere.[17]

The elastic and inelastic proton groups were momentum analyzed in an Enge split-pole magnetic spectrometer. For the various experiments, particle detection was achieved in the spectrometer by either photographic plates, a Si(Li) position-sensitive detector, or a position-sensitive delay-line proportional counter.[18] Due to the small dispersion of the spectrometer and the relatively poor position resolution (1 mm) of the delay-line proportional counter, high resolution spectra were taken with photographic plates ($\Delta E \sim 7$ keV). The range of excitation energy covered in each experiment depended on the detection apparatus mounted in the spectrometer focal plane. The energy range of the Si(Li) position sensitive detector was limited to about 250 keV and the delay-line proportional counter extended the range to about 1 MeV. In principle, the photographic plates viewed a range extending to many MeV but analysis was not pursued beyond 800 keV. The spectrometer was calibrated using scattered proton groups form ^{153}Eu. The energies of the levels populated by inelastic scattering in this nucleus are precisely known.[1]

Angular distributions were measured for proton scattering on ^{152}Eu and ^{153}Eu at 10° intervals beginning at 30° using both the Si(Li) and the delay-line wire proportional counters. Scattering from ^{151}Eu was recorded at 30° and at a few selected back angles. A Si(Li) surface barrier detector was mounted at 120° to monitor the 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 120° and 30°. Using these data, the elastic events registered in the monitor at 120° 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 calculated elastic cross sections 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 sections used for normalization were obtained for ^{151}Eu through a distorted-wave Born-approximation (DWBA) calculation.[19] For ^{152,153}Eu similar calculations were made using an adiabatic coupled-channels code[20] (see Sec. IV). For the europium isotopes considered, the calculated elastic cross section at 30° does not appreciably differ ($< \pm 3\%$) 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 ^{151,152,153}Eu. The energies for the $A = 151, 152$ isotopes were measured by using ^{153}Eu as the energy standard. A composite display shown in Fig. 1 compares the proton spectra below ~600 keV observed at 130° for each nucleus. The data were obtained with the delay-line proportional counter and are plotted on the same energy scale to facilitate comparison. The spectra are intensity normalized so that the number of integrated counts in the elastic peak is the same for each spectrum.

A proton spectrum of scattering from ^{152}Eu taken at 120° and recorded on photographic plates is shown in Fig. 2. The overall energy resolution is ~7 keV and is the best we were able to obtain. The inelastic scattering peak at 122 keV due to ^{152}Sm noted in Fig. 1 is not present in the plate data because there was a ~4 mo interval between the two experiments. During this time, the radioactive ^{152}Eu target accumulated ~1% by weight of the ^{152}Sm

TABLE I. Low-energy levels in ^{151,152,153}Eu populated by proton inelastic scattering. The ^{153}Eu level energies were taken from Ref. 1. Values quoted for ^{151,152}Eu are measured using ^{153}Eu as the energy standard.

^{151}Eu		^{152}Eu		^{153}Eu	
E (keV) [a]	I^{π}	E (keV) [a]	I^{π}	E (keV)	I^{π}
0	$\frac{5}{2}^{+}$ [b]	0	3^-	0	$\frac{5}{2}^{+}$ [b]
195.5 ± 1.5	$(\frac{3}{2}^{+})$	89.7 ± 0.5	4^-	83.37	$\frac{7}{2}^{+}$
308 ± 2		200.9 ± 1.0	5^-	193.06	$\frac{9}{2}^{+}$
506 ± 3	$\frac{9}{2}^{+}$	281 ± 3		325.06	$(\frac{11}{2}^{+})$
583 ± 5 [c]	$(\frac{5}{2}^{+})$	286 ± 3		481.05	$(\frac{13}{2}^{+})$
600 ± 5	$(\frac{9}{2}^{+})$	333.0 ± 1.5	6^-		
		(406 ± 4)			
		(472 ± 4)			
		490 ± 2	7^-		

[a] The quoted energy values represent an average of two or more angles. The errors quoted are statistical.
[b] Spin parities for the levels in ^{151,153}Eu are taken from Ref. 1.
[c] Complex peak.

decay product. In the spectrum and extending beyond an excitation energy of ~600 keV, there are a number of peaks that correspond to light impurities present in the commercially produced carbon substrate.

The differential cross sections measured for proton scattering from ^{151,152,153}Eu are given in Table II. Angular distributions for ^{152,153}Eu are plotted in Fig. 3. In ^{151}Eu a state at 22 keV has been observed in a number of experiments.[1] Figure 4 shows a plot of the ^{151}Eu elastic peak and emphasizes the region in which a peak due to the excitation of the 22-keV level is expected. Within the experimental uncertainty of the data, there is no evidence that the level is inelasticly excited. We can use the data in Fig. 4 to set an upper limit on the excitation of this state if we assume that the maximum height of a possible inelastic peak is $\sim 2\sigma$, where σ represents the statistical uncertainty of an average data point shown in the inset of Fig. 4. In this way, we determine that the possible excitation of the 22-keV level is almost certainly <0.07 mb and very probably no more than half that value.

IV. DISCUSSION

A. Scattering from ^{152}Eu and ^{153}Eu

The spin parity of the ^{152}Eu ground state is measured[21] and is 3^-. The energy level data in Table I are assigned rotational spin parities based on 3^- as a bandhead. The assignments are supported by the near constant rotational parameter $\hbar^2/2\mathscr{I} = 11.2 \pm 0.1$ keV, derived from the measured energy differences of adjacent states strongly populated in the (p,p') reaction. For the low-spin states our results agree with the detailed study of von Egidy

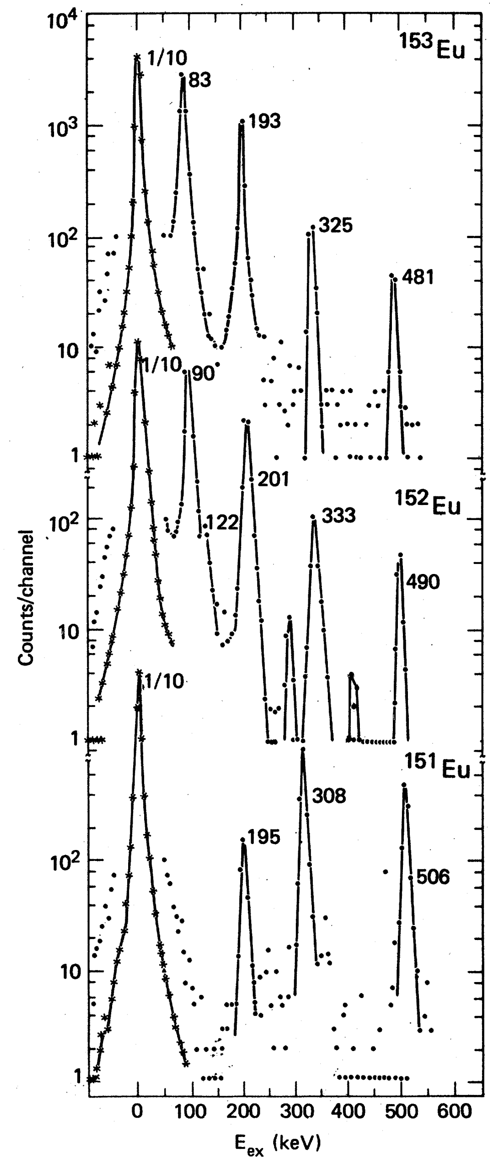

FIG. 1. Proton scattering spectra from ^{153,152,151}Eu obtained at 130° with the delay-line proportional counter mounted on the magnet focal plane. The peak at 122 keV in the ^{152}Eu spectrum is due to scattering from ^{152}Sm. The data are normalized so that each elastic peak has the same integrated count.

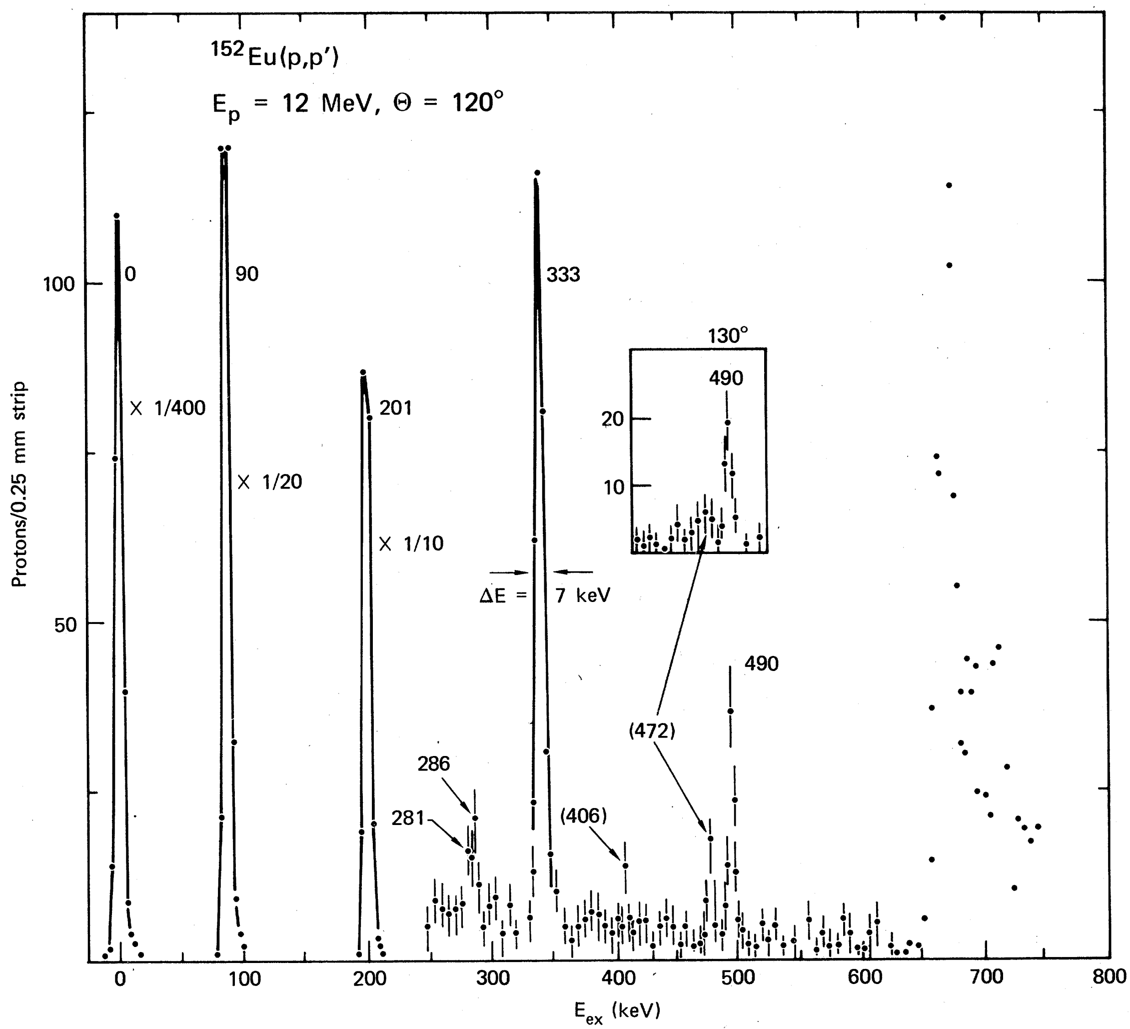

FIG. 2. High resolution proton spectrum recorded on photographic plates from the ^{152}Eu (p,p') reaction. The inset shows the weak excitation of the 472-keV level at 130°.

et al.[10] In ^{153}Eu the measured rotational parameter is 12.0 keV and implies that the moment of inertia and hence the deformation is somewhat larger (~7%) for ^{152}Eu.

The data in Fig. 1 strikingly exhibit the similarity of the (p,p') excitation of ^{152}Eu and ^{153}Eu and the corresponding dissimilarity of ^{151}Eu. Since both ^{151}Eu and ^{153}Eu have the same ground-state spin parity $\frac{5}{2}^+$, the difference in their corresponding excitation patterns emphasizes the existence of the ground-state deformation change at $N=89$ first noted in the isotope shift measurements.[2] An additional measure of the deformation change is obtained by comparing the total collective strength observed in the excitation of the three nuclei. Although impurities in the target backing preclude considering the strength contributed by higher excited states, we have made the comparison for levels with $E_{ex} < 600$ keV. With this constraint, we estimate that the observed collective strength for the ^{152}Eu or ^{153}Eu is larger than that for ^{151}Eu by only a factor of 2 or 3.

The proton angular distributions measured for ^{152}Eu and ^{153}Eu were compared with calculations using a coupled-channels technique which employs the adiabatic coupling approximation[20] (ACC) and with calculations using the distorted-wave Born approximation[19] (DWBA). The use of ACC for inelastic scattering is a good approximation when the nucleus is well deformed and when the projectile energy is much larger than the rotational excitations. Also, making the calculation with ACC is advantageous because it includes all the rotational states of the excited band in the coupled-channels problem.

TABLE II. Absolute differential cross sections.[a]

θ_{lab}	0 keV	83 keV	193 keV	325 keV	481 keV
	^{153}Eu(p,p')(mb/sr)[b, c]				
30	8302 ±800	...	...	...	...
40	2167 ±132	2.48±0.63	0.82±0.21	...	...
50	894 ± 51	3.03±0.73	1.35±0.26	0.09±0.02	...
60	426 ± 27	2.27±0.58	1.06±0.13	...	...
70	256 ± 14	2.10±0.18	0.93±0.09	0.10±0.02	...
80	125 ± 7	1.63±0.16	0.64±0.10	0.04±0.01	...
90	65.4± 4.7	1.50±0.14	0.61±0.06	0.04±0.01	0.013±0.004
100	49 ± 5	1.5 ±0.3	0.6 ±0.1	...	...
110	38.1± 2.3	1.61±0.14	0.65±0.05	0.05±0.01	0.020±0.005
120	29.2± 1.8	1.52±0.14	0.63±0.05	0.07±0.01	0.022±0.005
130	21.1± 1.3	1.25±0.12	0.54±0.05	0.07±0.01	0.023±0.005
140	16.2± 1.0	1.11±0.11	0.51±0.05	0.07±0.01	0.024±0.005

θ_{lab}	0 keV	90 keV	201 keV	333 keV	490 keV
	^{152}Eu(p,p')(mb/sr)[b]				
30	8310 ±800	...	...	...	...
40	2176 ±133	2.38±0.61	0.70±0.18	...	...
50	941 ± 57	4.15±0.83	1.40±0.28	...	...
60	420 ± 26	2.51±0.63	1.01±0.13	...	...
70	266 ± 15	2.29±0.20	0.75±0.07	0.10±0.02	...
80	131 ± 8	1.71±0.17	0.57±0.09	0.05±0.01	...
90	68.6± 4.4	1.44±0.14	0.51±0.05	0.04±0.01	0.010±0.003
100	48.9± 3.0	1.68±0.32	0.55±0.12	0.05±0.01	0.013±0.004
110	40.2± 2.5	1.67±0.16	0.57±0.05	0.06±0.01	0.014±0.003
120	32.0± 2.0	1.68±0.16	0.61±0.05	0.07±0.01	0.025±0.005
130	23.7± 1.5	1.41±0.13	0.52±0.04	0.08±0.01	0.017±0.004

θ_{lab}	0 keV	195 keV	308 keV	506 keV	583+600 keV
	^{151}Eu(p,p')(mb/sr)				
30	8257 ±800	...	...	...	...
110	46.6± 2.9	0.109±0.011	0.62±0.05	0.31±0.03	0.075±0.010
120	34.4± 2.2	0.096±0.010	0.56±0.04	0.31±0.03	...
130	24.1± 1.5	0.084±0.009	0.48±0.04	0.26±0.02	0.046±0.007

[a] The errors indicated in each column are statistical only and do not include the error in the absolute cross section which is probably about 15–20%.
[b]The quoted cross sections for levels below 250 keV are the average of two independent experiments.
[c]Except for the points at 100° and 140°, the quoted cross sections for levels below 250 keV are the average of two independent experiments.

As indicated by the data in Fig. 3 the agreement between experiment and the ACC calculations for ^{153}Eu and ^{152}Eu shows that these nuclei both have rather large quadrupole deformations and measurable hexadecapole deformations. The optical potential (see Sec. IV C) used to achieve the fits in Fig. 3 is identified as row ACC in Table III and the appropriate deformation parameters are summarized in Table IV.

The sensitivity of the coupled-channel calculations to β_4 is illustrated in Fig. 5. Calculations using $\beta_2=0.28$ and various values of β_4 are compared with the scattering data for the $I^\pi=6^-$, 333-keV level in ^{152}Eu. The effect is identical for the 7^- state as well as for the corresponding excited rotational states in ^{153}Eu. The calculations unambiguously require a positive value of β_4 to fit the upsloping trend in the experimental data. Moreover, the result $\beta_4=0.06$ is consistent with values obtained for other strongly deformed nuclei in the general mass region[22] $150 \leq A \leq 160$.

We note that the values of the deformation parameters β_2 and β_4 used for the ^{152}Eu and ^{153}Eu calculations are identical. This is in contrast to the observation that the rotational energy spacings suggest a somewhat higher deformation for ^{152}Eu. The

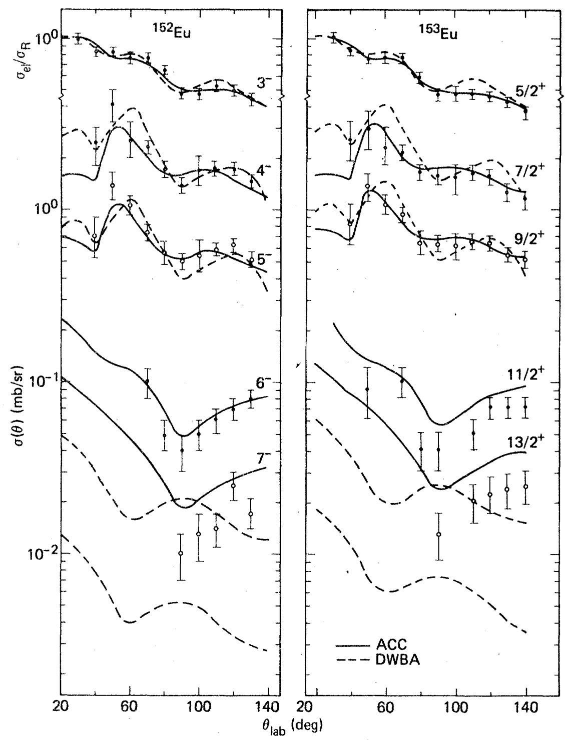

FIG. 3. Angular distributions for levels observed in the ^{152,153}Eu (p,p') reactions. Comparisons of the data with results from the ACC and DWBA calculations are noted. The various calculations use the optical model parameters noted in Table III.

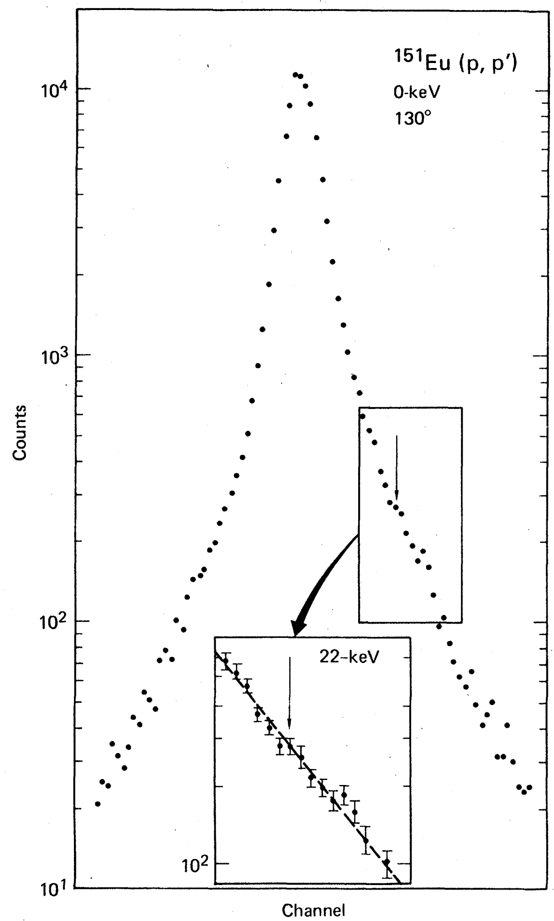

FIG. 4. Elastic peak from the ^{151}Eu(p,p') reaction. The inset accentuates the region of the elastic peak where the excitation of the 22-keV level is expected. Within experimental error, the data show no evidence for exciting this level.

errors in the scattering data and the inherent uncertainties (see Sec. IV C) in the coupled-channels calculations preclude a meaningful adjustment of β_2 and β_4 to achieve agreement with the differences in the inferred moments of inertia.

The importance of using the coupled-channels calculation for ^{152}Eu and ^{153}Eu is emphasized in Fig. 3 where calculations using ACC and DWBA are compared with experiment. The DWBA calculations were made with the program[19] DWUCK using the β_2 and β_4 values also used in the ACC calculation. Additionally, the same coupled-channel optical potential was used except that the surface absorption term was increased by 20% to account for the collective channels which are not explicitly considered in DWBA. These parameters are summarized in Table III.

The agreement of the DWBA results with the elastic and inelastic $\lambda = 2$ states (those connected by one-step $l = 2$ transitions from the ground state) is fair, while the calculation misses reproducing the excitation of the $\lambda = 4$ states by factors of 5 to 10. The failure to correctly reproduce the scattering from the $\lambda = 4$ states occurs because DWBA neglects the virtual two-step process which connects the strongly excited $\lambda = 2$ states through β_2 with the $\lambda = 4$ states.

TABLE III. Parameters of the optical potential for proton scattering by Eu nuclei.

Calculation	V (MeV)	R (fm)	a (fm)	W (MeV)	W_D (MeV)	$\bar{R}$ (fm)	$\bar{a}$ (fm)	V_{so} (MeV)	R_C (fm)
ACC	56.7	1.204	0.741	0	10.5	1.311	0.590	0	1.201
DWBA	56.7	1.204	0.741	0	12.6	1.311	0.590	0	1.201

TABLE IV. Summary of deformations derived from the proton inelastic scattering experiments.

Nucleus	Calculation	β_2	β_4
^{151}Eu	DWBA	0.13	···
^{152}Eu	ACC	0.28	0.06
^{153}Eu	ACC	0.28	0.06

B. Scattering from ^{151}Eu

The scattering data measured from the ^{151}Eu (p,p') reaction at 110°, 120°, and 130° were analyzed with a DWBA calculation. The nucleus was assumed to be a spherical harmonic vibrator and the calculations were done using a complex collective model form factor. The optical model parameters (Table III) were those used in the DWBA analysis of ^{152}Eu and ^{153}Eu. With this optical model set, the measured elastic cross sections are reproduced to within a few percent by the DWBA calculation.

Experimentally we have estimated (Sec. IV A) that the collective strength in ^{151}Eu is over a factor 2 less than that in either ^{152}Eu or ^{153}Eu. This reduction in the collective strength is not sufficient to abandon a coupled-channels calculation in favor of DWBA.[23] However, in both deformed europium nuclei, it was further noted that after an appropriate change in the optical potential, the excitation of states directly coupled to the ground state through β_2 can be reasonably reproduced by a DWBA calculation. On this basis, we assume that a DWBA calculation can be used in ^{151}Eu to extract a value of β_2 which should not differ radically from one derived from a coupled-channels calculation.[24] This assumption is weakly supported by the good correspondence of the ^{151}Eu elastic scattering data to the DWBA calculation.

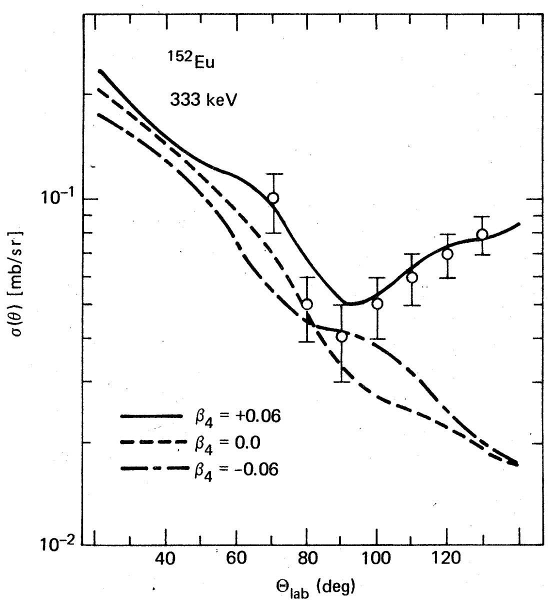

FIG. 5. The effect of changing β_4 on the ACC calculation of the angular distribution for the 333-keV state in ^{152}Eu. The calculations were made with $\beta_2 = 0.28$ and unambiguously show that the data require a positive value of β_4.

TABLE V. Summary of the quadrupole deformations (β_2) derived from the DWBA analysis of the ^{151}Eu (p,p') reaction.

E_{ex} (keV)	I^{π} [a]	β_2 110°	β_2 120°	β_2 130°
195.5	$\frac{3}{2}^+$	0.131	0.117	0.120
308	$\frac{5}{2}^+, \frac{7}{2}^+, \frac{9}{2}^+$	0.128	0.116	0.117
506	$\frac{9}{2}^+$	0.140	0.134	0.134

[a] The assigned spin parities are in accord with Ref. 25. See text.

The β_2 values were extracted from the experimental data in Table II using the relation

$$\beta_2{}^2 = \frac{(2I_i+1)\cdot(2l+1)}{(2I_f+1)} \frac{\sigma_{exp}(\theta)}{\sigma_{DW}(\theta)}, \quad (1)$$

where $\sigma(\theta)$ is the differential cross section at a scattering angle θ. The subscripts identify $\sigma(\theta)$ as either an experimental (exp) or a DWBA calculated (DW) cross section. Additionally, I_i, l, and I_f are, respectively, the initial target spin, the transferred angular momentum ($l = 2$ for excitation of levels connected by β_2), and the final state spin. A summary of the extracted values of β_2 for ^{151}Eu is given in Table V. The strongly excited states in the inelastic scattering reaction are given spin-parity assignments based on the results of Ref. 25. As noted in the table the level at ~308 keV is interpreted as an unresolved triplet of states and the extracted values of β_2 are based on this interpretation. A simple average of the data in Table V gives $\beta_2 = 0.13 \pm 0.01$. This result is somewhat smaller than β_2 values derived from $B(E2)$ measurements quoted in the tables [26] of Stelson and Grodzins for even-even vibrators isotonic with ^{151}Eu: 0.190, ^{150}Sm; 0.165, ^{152}Gd. This suggests that the ^{151}Eu levels strongly populated in the (p,p') reaction can be most simply interpreted as arising from simple 2^+ core excitations.

As a group the derived values of β_2 are constant to within ±10% but show systematic variations. The values obtained from the cross sections at 110° are systematically higher than those obtained from measurements at either 120° or 130°. Similarily, these values obtained for the 506-keV level are also systematically higher than those obtained for the other levels. The source of the deviations with respect to the scattering angle is not clear but the discrepancies are probably not serious in view of the inherent uncertainties in the DWBA analysis. The variations noted for the 506-keV level may be due to the presence of a low-spin positive-parity level which neither our experiments nor previous experiments have been able to isolate.

C. Comments on the scattering calculations

Kurepin[22] and, more recently, Feix *et al.*[27] have pointed out the importance of the assumed charge distribution in coupled-channel calculations involving the scattering of low-energy particles. In our ACC calculations, we have used a deformed homogeneous charge distribution and because our proton bombarding energies are near the Coulomb barrier energy, the derived values of β_2 are very likely somewhat higher than would be admitted if we had used a more realistic charge distribution. For example, Kurepin[22] has pointed out that the 12-MeV (p,p') excitation of the 2^+ ($\lambda=2$) state in ^{154}Sm is found to be larger when calculated with a more realistic diffuse (Fermi) charge distribution. An equivalent excitation which is calculated using a homogeneous charge distribution would require a value of β_2 about 15 percent larger than that used with the Fermi distribution. A related study[27] by Feix *et al.* measured 17-MeV deuteron scattering from ^{238}U and compared the data with coupled-channel calculations using the Fermi charge distribution. This treatment differed from Kurepin's because the charge and mass distributions were differently parametrized. However, these data also suggest that a homogeneous charge distribution tends to overestimate β_2.

Possible uncertainties in the derived values of β_4 are quantitatively more difficult to estimate but arise both because we use an idealized charge distribution and because the multipole expansion of the optical potential is treated only to fourth order. Kurepin obtains only a few percent difference between calculations for the excitation of the $4^+(\lambda=4)$ state in ^{154}Sm using the homogeneous and Fermi charge distributions. Corrections of only a few percent are also expected if the higher order terms are included in the potential expansion. Both these corrections are estimated to act coherently and to increase the relative separation between the calculated $\lambda=2$ and $\lambda=4$ angular distributions for ^{152}Eu and ^{153}Eu. This suggests that a more refined calculation with appropriately adjusted values of β_2 and β_4 might better fit the $\lambda=4$ states and thereby improve the overall agreement with the data. Whether a consideration of these higher order effects can account, say, for the discrepancy of nearly a factor of 2 in the excitation of the 7^-(^{152}Eu) and $\frac{13}{2}^+$(^{153}Eu) states seems rather doubtful.

The optical parameters used to fit the ^{152,153}Eu scattering data are a slightly modified version of those obtained from Kurepin's analysis of the ^{154}Sm (p,p') reaction at 12 MeV. We used an identical real-volume potential but changed both the depth and the shape of the imaginary-surface potential to achieve a better overall fit. Our absorptive potential is 20% deeper and has radial and diffuseness parameters which differ by ~5%. The effect of the spin-orbit potential was tested by doing a somewhat truncated calculation on ^{152}Eu. Over the angular range spanned by our data, the results of calculations with and without the inclusion of the spin-orbit interaction were virtually identical. For this reason, effects due to this interaction have been excluded in both the ACC and DWBA calculations.

The scattering data from ^{151}Eu were not analyzed with a coupled-channels calculation because the appropriate odd-*A* spherical problem could not be done with our version of the computer code. However, as outlined in Sec. IV B, a limited but meaningful and consistent analysis of the scattering from ^{151}Eu, ^{152}Eu, and ^{153}Eu was made with DWBA. The important feature of these calculations is that the same optical potential was used to treat all three nuclei. This implies that the explicit collective effects neglected in DWBA but accounted for in the absorption potential (W_D) are the same. In general, this cannot be true for nuclei which have significant variations in their collective properties. However, the estimated difference in the collective strength of only a factor 2 or 3 between ^{151}Eu and ^{152,153}Eu is not significantly large[23] and maintaining the same DWBA potential for all three nuclei is a good first order approximation. Thus, the DWBA analysis as it was applied to ^{151}Eu very probably underestimates β_2 because W_D in the optical potential should be somewhat smaller than that for either ^{152}Eu or ^{153}Eu. A small downward adjustment in W_D would not significantly change the agreement with the ^{151}Eu elastic data but would give a smaller value of $\sigma_{DW}(\theta)$ and, thus, referring to Eq. (1), this would give a somewhat higher β_2.

Major differences in the optical potential for ^{151}Eu, ^{152}Eu, and ^{153}Eu should not exist if all three nuclei were treated with a coupled-channels calculation. In principle, explicit treatment of collective effects removes fluctuations in the optical model parameters across nuclei with varying collective properties. This situation has been described in some detail by Glendenning *et al.*[28]

V. SUMMARY AND CONCLUSIONS

We have measured elastically and inelastically scattered protons from ^{151}Eu, ^{152}Eu, and ^{153}Eu at a bombarding energy of 12 MeV. An analysis of the scattering data shows the unambiguous presence of very well-behaved ground-state rotational bands in ^{153}Eu and in ^{152}Eu. On the other hand, the levels strongly excited in ^{151}Eu are consistently interpreted by assuming that the nucleus has a spherical structure near the ground state. The quadrupole deformations for ^{152}Eu and ^{153}Eu derived from these experiments are probably accurate to ±20%, although they agree to ±10% with tabulated values derived from ground-state quadrupole moment measurements.[30] A determination of β_4 for ^{152}Eu and ^{153}Eu was also made and is consistent with values observed for well-deformed nuclei in the range $150 \leq A \leq 160$.

The extremely well-behaved ground-state rotational structure in ^{152}Eu is very probably due to the influence of the $\frac{11}{2}[505]$ Nilsson orbital in the intrinsic part of the ground-state wave function.[16] The transition at $N=89$ suggests that, as has been found[8,9,15,29] in ^{151}Eu, other low-lying states in ^{152}Eu may not have a large and stable deformation if the neutron is not in this orbital. This hypothesis may be checked by a ^{154}Eu(p,t) reaction. Although ^{154}Eu also has a 3^- ground state, there is reason to believe that, unlike ^{152}Eu, the intrinsic configuration is $\pi\frac{3}{2}[411]$, $\nu\frac{3}{2}[521]$. For the $N>89$ stable deformed Gd nuclei, the odd neutron is known to be in the $\frac{3}{2}[521]$ orbital.[31] If the odd neutron is constrained to this orbital, then a 3^- ground state can most reasonably be accommodated by having the odd proton in the $\frac{3}{2}[411]$ orbital. This situation for ^{154}Eu would be consistent with the Gallagher-Moszkowski coupling rules[32] for odd-odd nuclei where the parallel alignment of the nuclear spins (3^-) would be expected to have a lower energy than the corresponding antiparallel alignment (0^-). If ^{152}Eu has a stable deformation independent of the single quasiparticle status of the $\frac{11}{2}[505]$ orbital, then, as was the case in a recent ^{176}Lu(p,t) reaction,[33] the ^{154}Eu(p,t) reaction will show an excited rotational band with the appropriate unfragmented intensity pattern. On the other hand, fragmentation of the (p,t) strength will indicate the possible coexistence of spherical or weakly deformed states. The observation of a large degree of fragmentation would be particularly interesting since the proposed structure of the ^{154}Eu ground state occurs as a very low excited state[10] (~76 keV) in ^{152}Eu. Finally, a (p,t) reaction on ^{152}Eu would be interesting because it provides the possibility of observing whether the $N=87$ species, ^{150}Eu has a strong deformation associated with the $\pi\frac{5}{2}[413]$, $\nu\frac{11}{2}[505]$ configuration.

A number of other states in ^{152}Eu have been weakly populated in the (p,p') reaction. Although there is insufficient data from our studies alone to make any definitive assignments, we speculate that these additional states probably arise from the neutron occupying the $\frac{11}{2}[505]$ orbital. On the basis of electromagnetic transition data, von Egidy *et al.*[10] have assigned a level at 287.2 keV as the bandhead of the 4^-, $[\pi\frac{3}{2}(411),\ \nu\frac{11}{2}(505)]$ configuration. The 5^- rotational state is tentatively identified with a level at 397.0 keV. In our (p,p') studies we observe a level at 286 ± 3 and a possible level at 406 ± 4 keV. These levels are believed to be the spin 4^- and 5^- members of the excited $\frac{11}{2}[505]$ band proposed by von Egidy *et al.*[10] This excited band is expected to mix weakly with the $K=3^-$, $[\pi\frac{5}{2}(413),\ \nu\frac{11}{2}(505)]$ ground band through the Coriolis force and this interaction would provide the mechanism whereby the levels could be excited in the (p,p') reaction. On this basis and using the experimental (p,p') intensities of the 90- and 286-keV levels we estimate that the degree of mixing between both levels is ~1%. This estimate is in excellent accord with calculations using strongly deformed ($\beta_2 \sim 0.3$) Nilsson wave functions, where the mixing effect is predicted to be ~0.7%. As noted in Fig. 2 the 286-keV level is partially resolved from a level at 281 keV. Studies of the (^{3}He, α) reaction[12] populating states in ^{152}Eu have noted a broad peak centered at 284 keV which sug-

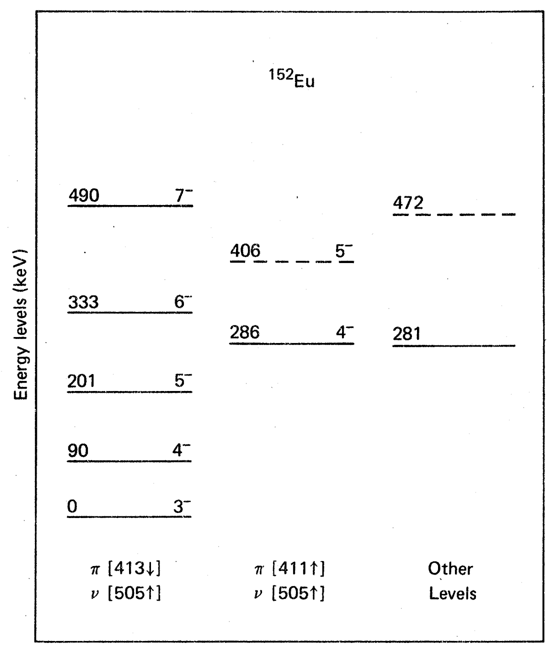

FIG. 6. Levels and configuration assignments for levels populated in the ^{152}Eu(p,p') reaction.

gests that both the 281- and 286-keV states are probably being populated. Population of the 286-keV level by the (^{3}He, α) reaction represents additional confirmation for the proposed assignment, since this reaction preferentially populates levels which require high values of l transfer.

The assignment of the 406-keV level as the 5^- rotational state is based primarily on (p,p') relative intensity considerations. Using the energy of this level we estimate a rotational parameter of ~12 keV which is very similar to that measured for the ground band. Although the evidence for the population of this level in our studies is rather weak, we note that the energy value 406 ± 4 keV does not overlap well with the value 397.0 keV quoted in Ref. 10.

A specific interpretation of the remaining levels at 281 and 472 keV is not clear. Figure 6 presents a summary of the levels and configuration assignments suggested for ^{152}Eu by the (p,p') studies.

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