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ABSTRACT

The energy levels in ^{140}La were studied by means of (d,p) reaction spectroscopy using 10 MeV deuterons. The protons that emerged were analyzed by a single gap, broad-range magnetic spectrograph with 13 keV resolution. We obtained the reaction Q-value of 2938 ± 3 keV. Exposures were taken at eight angles ranging from 25 to 105 degrees. All spectra were fitted using a least squares code, up to an excitation energy of 1860 keV. Seventy states were observed and the angular distributions of the most prominent groups were analyzed by means of DWBA stripping theory. Spins of the ^{140}La levels determined from previous decay scheme studies and the present research and the proton intensities observed in the ^{139}La(d,p)^{140}La reaction can be satisfactorily explained in terms of the mixed configurations, $(1g_{7/2})_p(2f_{7/2})_n$ and $(2d_{5/2})_p(2f_{7/2})_n$. Above 600 keV, however, interpretation of states in terms of higher energy configurations appears also to require phonon particle coupling.

I. INTRODUCTION

Among the different nuclear species, odd-odd nuclei are perhaps the

most difficult to study. From the experimental point of view, this is true

for several reasons. Frequently the mass of a particular odd-odd nucleus is

greater than that of both its neighboring even-even isobars. This makes it

impossible to observe levels in the odd-odd nucleus by beta-ray and gamma-ray

spectroscopy. In the case where levels in an odd-odd nucleus can be populated

by beta decay, the daughter nucleus itself is usually unstable and this situation

demands difficult experimental techniques for the spectroscopist. Finally the

decay occurs from a state with 0+ spin and parity and only states with small

spins will be observed. In principle, reaction spectroscopy offers a means of

observing more states in odd-odd nuclei but the high level density in heavier

odd-odd nuclei creates an obstacle because usually the experimental resolution

is ten to one hundred times poorer than that obtainable with beta- and gamma-

ray studies.

Interpreting the experimental levels in odd-odd nuclei is also difficult

since simple phenomenological models inadequately describe the low energy spectra.

The ordering of the levels in the multiplets resulting from a specific neutron

and proton configuration is sensitive to the nature of the neutron-proton resid-

ual interaction. However it is just this feature which makes the study of odd-

odd nuclei so important, since the detailed level structure can then give informa-

tion about this interaction.

Although odd-odd nuclei near magic configurations have been studied in

detail,[1] little work has been attempted either in deformed nuclei[2,3] or in the

so-called vibrational nuclei. In this and in the following paper we examine the
nucleus ^{140}La, a nucleus with one neutron outside the 82 shell and 7 protons outside
the 50 shell. Experimentally this is a favorable nucleus for nuclear reaction
studies because ^{139}La is stable, monoisotopic and the reaction ^{139}La(d,p)^{140}La
has a Q-value which makes it possible to study ^{140}La by this reaction with 10 MeV
deuterons. Thus unambiguous data may be obtained using a deuteron beam from a
Tandem Van de Graaff accelerator, a natural ^{139}La target, and a magnetic spectro-
graph to analyze the reaction products. Theoretically the nucleus is expected to
be of intermediate difficulty. That is, although there is extensive configuration
mixing due to interactions of the seven protons, it is in a region where quasi-
particles which are defined by a special Bogolubiov transformation give good
descriptions of even-even and odd-A systems.[4] Also since there is only one neutron
outside the 82 magic neutron configuration, one would expect very small vibrational
phonon amplitudes in the lower single quasi-proton states.[5] It should be possible
to describe the states below 1 MeV by an effective quasi-proton neutron interaction
using an odd-odd quasi-particle model.

    In section II, the results of previous experimental investigations are
reviewed. In sections III and IV, a discussion of the experimental technique
and the results from the studies of levels below 1.858 MeV by (d,p) reaction
spectroscopy are given. A qualitative discussion of the odd-odd quasi-particle
model is presented in section V and an interpretation of our levels below 600 keV
is given. In the second paper we give the mathematical details of the odd-odd quasi-
particle model and apply this model to ^{140}La.

II. PREVIOUS INVESTIGATIONS

The investigation of the negatron decay of ^{140}Ba to ^{140}La has been performed

by many different groups.[6]   The high resolution work of Geiger, Graham,

and Ewan[7] strongly suggested a number of spin-parity assignments and accurate

energy levels. These assignments have been confirmed by the gamma-gamma angular

correlation measurements of Agarwal et al.[8] and lifetime measurements of Burde

et al.[9] Burde et al. confirmed the original level assigned by Geiger et al. at

581.1 keV which had been reassigned at 566 keV by Agarwal et al.

A level scheme consistent with these results is given in Fig. 1. Low

energy gamma-rays from thermal neutron capture[10] could not be placed consistently

in the existing scheme but the study of high energy gamma rays following neutron

capture[11] defined some additional new levels. (See Fig. 1). Study of ^{140}La by

the (d,p) stripping reaction was performed by Bingham and Sampson[12] with an

energy resolution of approximately 70 keV. Angular distributions were measured

and the ℓ transfers were determined for a few groups. Comparison of these

results with the decay-scheme results (Fig. 1) shows that the resolution was

not good enough to resolve some of the known states. Since our instrumentation

is appreciably better in this respect, a reinvestigation of the reaction seemed

worthwhile.

III.   EXPERIMENTAL METHOD

Targets were prepared by evaporating La_2O_3 [13] from a small carbon crucible under a high vacuum onto thin carbon backings. The required temperature was achieved by using an electron gun technique.[14] The backings were obtained by depositing carbon by an electric arc in a high vacuum onto glass slides that had previously been coated with Teepol*. After ^{139}La was evaporated, the target was floated on deionized water and mounted on an aluminum frame. Targets prepared by this method have a thickness of approximately 100 $\mu g/cm^2$ and the carbon backings a thickness of 10-30 $\mu g/cm^2$.

The targets were then exposed to the 10 MeV deuteron beam of the Florida State University Tandem Van de Graaff. This beam was collimated by $1/4 \times 3$ mm slits before reaching the target and the Faraday cup. The emerging protons were analyzed in a single gap magnetic Browne-Beuchner spectrograph.[15] The solid angle of this spectrograph is of the order of 0.7×10^{-4} sr. As a detector we used an array of three 5×25 cm fifty micron thick nuclear emulsion plates which are manufactured by Eastman Kodak Company. These plates were covered with an Aluminum foil 0.12 mm thick in order to stop elastically scattered deuterons. After exposure, the proton tracks were counted in 1/2 mm strips under microscopes equipped with calibrated stages. A more detailed description of this general experimental procedure is given in a recent publication by Kenefick and Sheline.[16]

The resulting spectrum was analyzed by use of a nonlinear least squares code[17] in order to determine the individual components of the spectrum. This method of analysis was necessary because many of the peaks were unresolved. The shape of the line profile and the line width were inferred from the most prominent peaks. This resulted in a profile with a symmetric Gaussian curve that has a small low energy tail (approximately 5% of the total intensity) which was, in general, neglected.

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*A Shell product.

The position of the peaks, as determined by the least squares analysis, was then entered in a code written for an IBM 709 in order to extract Q-values and excitation energies. This code used an empirical energy calibration and determined if any of the entered peaks could be due to reaction with one of the impurities that might have contaminated the target. Such impurities could come from the Teepol, the glass slide, or possibly from the Tungsten filament of the electron gun.

Calculations of the average, weighted average and corrected average of the excitation energies were made. As a weight a quantity approximately inversely proportional to the standard deviation of the peak position, as determined by the least squares code, was used. In the corrected average, values whose dispersions were greater than five times the standard deviation for a single value were discarded.

In order to obtain meaningful angular distributions, either we needed to determine absolute cross sections or to insure that the target thickness and the luminosity of the spectrograph remained unchanged at the different angles. We chose the first method. To obtain absolute cross sections, we bombarded the target at each angle with 4 MeV deuterons prior to and/or after the (d,p) experiment assuming that the same geometrical configuration was maintained at the spectrograph. (In fact the Aluminum foil covering the emulsion plates had to be removed for this experiment). From the known Rutherford cross section, it was then a straightforward procedure to obtain the absolute cross sections.

IV. RESULTS

Eight exposures were taken at angles ranging from 25 to 105 degrees. Table 1 gives a summary of some of the details of the experiments. The resolution given here is the full width at half maximum of the ground state peak. It was found that the energy resolution decreases slowly along the plates when going toward smaller proton energies. For example, it is about 3 keV larger at 1800 keV excitation than at the ground state. The differential cross section corresponding to one track is given as a measure of the ultimate sensitivity in a particular exposure. This quantity, together with the exposure, gives some indication about the relative target thickness. We see, for instance, that the target used at 85 degrees is appreciably thicker than the others, and this resulted in a broadening of the lines.

When the value at 85 degrees is disregarded, the agreement of Q-values determined at various angles is very satisfactory. The corrected average is $Q = 2938.3 \pm 0.4$ keV. The good reproducibility of the Q-value, even though the plate distance from the calibration peak (carbon) to the ground state peak varies considerably, indicates that the systematic error of the calibration is small, and we therefore give the value of $Q = 2938 \pm 3$ keV. This gives a binding energy of the last neutron $B_n = 5.163 \pm 0.004$ MeV.

Our experimental number is in disagreement with and outside the experimental error of Everling, et al.[18] who give the value $B_n = 5.021 \pm 0.07$ MeV. It is considerably closer to the value of 5.145 ± 0.015 MeV determined in the (n,γ) work of Groshev et al.[11] and the value of 5.11 MeV derived from the (d,p) Q-value of Bingham and Sampson.[12] In view of the high resolution available and the internal consistency of these experiments, we believe that the B_n-value reported here is the most accurate.

A typical spectrum is displayed in Fig. 2. The exact position of the intense ^{13}C and ^{17}O peaks are obtained by short exposures made before and after the main experiment. These peaks are used to recalibrate the incident energy and test the stability of the magnet. They appear outside the range of interest at backward angles, but fall inside it at angles less than 80 degrees. As their cross sections are also much larger at forward angles, it is necessary to subtract a background from under the peaks lying close to them. Because of the large level density, this subtraction is somewhat arbitrary and so we do not attempt to compute cross sections and errors for small peaks in these areas.

The least squares technique was essential in order to unfold the first group of peaks. In Fig. 3 the individual components and their sum are compared with the experimental spectrum at 25 degrees. A satisfactory fit can also be found when peak 1 is suppressed. However, the fit is then, in general, not as good, and the line width seems too large. Furthermore the correspondence with the levels of Fig. 1 is much better when level 1 is added.

Table 2 gives the results of the present investigation for energy values and differential cross sections. Below each value we give the standard deviation. For the energies these quantitites have been computed from the deviations of the single values from the average value. For the intensities they are statistical sums of the standard deviation calculated by the fitting program, the error for the solid angle calibration and the error for the Rutherford scattering experiment which is estimated to be 5%. Systematic errors may arise from an error on the energy calibration, use of an approximate fitting function, which may be especially important in the cases of close multiplets, undetected impurities and an incorrect number of components in the analysis. With regard to energies, the figures given

take into account only the statistical errors. It is therefore expected that the true error can be appreciably larger. It may be assumed that the error due to the calibration amounts to 0.5 keV below 600 keV and 1 keV above. We have been tempted to increase arbitrarily the standard deviation by these amounts in order to avoid discrepancies with more precise measurements. But this would also make it impossible to detect meaningful discrepancies. For example, the energy standard deviation 0.2 keV quoted for level 1 at 30.6 keV is too small when compared with the accurately measured energy of 29.97 ± 0.05 keV. As will be shown in section V, the number of components used in fitting this region is probably incorrect and the discrepancy supports this view. A biased standard deviation would have masked the difficulty. We will use possible large differences between the values given here and more accurate energy values that can be obtained by gamma-ray measurements to help locate systematic errors. For the levels where a background has been subtracted (denoted with an asterisk), the error is estimated. When a known impurity contributes to the cross section, an estimated value of its contribution is given in the comments when possible.

Although we have analyzed all spectra down to peaks with a few tracks, we have excluded from the table peaks with a cross section of only a few microbarns. Such small peaks may reproduce at many angles with an acceptable energy spread. Nevertheless, we believe that usually it is accidental and that the inclusion of such peaks in the table would only be misleading.

To fit the angular distributions we have used the DWBA code TSALLY of Bassel, Drisko and Satchler.[19] We know of no experimental values of the optical model parameters of ^{139}La for 10 MeV deuterons. Since ^{140}La is radioactive, the

parameters for [140]La and ~13 MeV protons would be very difficult to determine

experimentally. For these reasons we have started with parameters extracted

from the work of Perey[20] for protons and Perey and Perey[21] for deuterons. We

varied them slightly in order to fit the $\ell = 3$ distribution of the first group

of peaks (Fig. 4A) and simultaneously the $\ell = 1$ distribution of the peaks

10 + 13 + 14. This simultaneous fitting put severe constraints on the possible

variations. The fit represented in Fig. 4 was obtained with the parameters given

in Table 3, using the "independent Saxon plus derivative" option.

The values for the proton potential were extracted with no modifications from
the work of Perey.[20]
For the deuteron potential, we used the set of values A from Perey and Perey[21]

and changed only the real radius (from 1.15 to 1.26 F). A lower cut-off radius

of 5 F was used in the calculation.

The fit that is obtained is very satisfactory. It is possible that small

adjustments of the optical potential parameters compensate some of the approxima-

tions of the theory. The fact that our experimental distributions could be so

well fitted is our only evidence that the reaction under study is essentially

direct.

The use of the least-squares fit to analyze the data has generally

resulted in little dispersion in energy values for components of unresolved

multiplets. The intensities, however, often have large uncertainties. For

this reason it is better, in general, to compare only the intensity sum of

badly or unresolved peaks with the theoretical curves. A meaningful result

is obtained only if the ℓ transferred is the same for each of the components.

The angular distribution of such groups are plotted in Fig. 4. By a normaliza-

tion of the total intensity, it is possible to compute the average relative

amplitude of each component. The normalized intensities of a number of peaks

belonging to different groups are given in Table 4. The level diagram in Fig. 5

collects all the information on energy and ℓ transfer obtained in this work.

For an extended region, from 1130 to 1330 keV excitation, no ℓ assignment

could be obtained. We were also unsuccessful in locating levels with $\ell = 5$

and $\ell = 6$ transfer. The multiplicity of these levels should be equal to the

multiplicity of the $\ell = 3$ levels, but their cross section should be an order

of magnitude smaller. The large level density may preclude observing such

states.

V.   INTERPRETATION OF RESULTS

The nucleus ^{140}La with 57 protons and 83 neutrons has one neutron out-

side the 82 magic core. The energy level systematics of neighboring isotonic

odd-A nuclei strongly suggest that this neutron occupies the $2f_{7/2}$ orbital. Out-

side the 50 magic core are seven protons which are probably in the $1g_{7/2}$ orbital.

If the $1g_{7/2}$ orbital were separated from other proton orbitals by an energy of at

least 1 MeV, it might be possible to describe the low-lying states as arising from

a configuration consisting of a $2f_{7/2}$ neutron particle and a $1g_{7/2}$ proton hole.

However in ^{139}La the $2d_{5/2}$ proton orbital appears at 166 keV of excitation. This

suggests that there is strong configuration interaction in the proton system and

indeed proton-proton pairing correlations seem to explain the position of this

state.[4]

The effects of the proton-proton pairing correlations have a particularly

simple physical interpretation in terms of quasi-particles. These quasi-particles

are independent excitations which are hole excitations for orbitals well below the

Fermi surface. They are particle excitations for orbitals well above the Fermi

surface, but they have mixed particle and hole nature near the Fermi surface.

The use of this independent quasi-particle picture has had great success in

quantitatively explaining many of the low energy features of odd-A and even-

even nuclei in the mass region which we are considering. It's quantitative

application to many odd-odd nuclei is as yet untested but qualitatively we

would expect the gross structure of the odd-odd nucleus to be very similar to

that predicted by the two particle shell model.

For example, if we consider ^{140}La and attempt to predict the lowest

energy states, then there are two configurations of importance that arise

from the neutron in the $2f_{7/2}$ orbital and a quasi-proton in either the $1g_{7/2}$

orbital or the $2d_{5/2}$ orbital. From the first configuration, we expect an

octuplet of levels that have spins 0 - 7 and negative parity. From the second

configuration, there will be a sextuplet of levels that have spins 1 - 6 and

negative parity. The ordering of the levels within each multiplet will be

different from that predicted by the two particle (or hole) shell model since

each quasi-particle is part particle and part hole. Therefore in the case of

^{140}La, there are both particle-particle and particle-hole interactions. It is

not surprising, then, that Brennen and Bernstein's coupling rules[22] are violated.

These rules predict a ground state spin and parity of 6- for a particle

hole configuration while for a particle particle configuration they predict a

0- ground state. However it is believed the ground state has a spin and parity

of 3-. The situation is further complicated by the fact that two configurations

generating states of the same parity are very close to each other in energy.

This suggests that there might be considerable configuration mixing due to the

residual neutron quasi-proton interaction. The (d,p) reaction is a sensitive

test of this prediction. If there is no configuration interaction, then because

of the well-known selection rule that proton excited configurations are not

excited by direct (d,p) reactions, the sextuplet of states $|2d_{5/2}(p)2f_{7/2}(n);$

$J\pi = 1-, \cdots, 6- >$ will not be observed. Further the octuplet of states

$|1g_{7/2}(p)2f_{7/2}(n); J\pi = 0-, \cdots, 7- >$ will have intensities proportional to

$(2J+1)$. The next states populated in the (d,p) reaction would then presumably

be $|1g_{7/2}(p)3p_{3/2}(n); J\pi = 2-, \cdots, 5- >$. Of course the quartet of states

$|2d_{5/2}(p)3p_{3/2}(n); J\pi = 1- \cdots, 4- >$ should also be close in energy and possibly

mix. The states that arise from the $2f_{7/2}$ neutron configuration should all

have $\ell = 3$ angular distributions. Those from the $3p_{3/2}$ configuration should

have $\ell = 1$ angular distributions.

Finally in this qualitative discussion of the quasi-particle model, it

should be pointed out that in order to explain even-even nuclei and odd-A nuclei

in many mass regions vibrational states must be considered. However in ^{140}La we

have a particularly favorable case. An examination of Kisslinger and Sorensen's

^{139}La and ^{141}Ce wavefunctions[4] shows that the lowest levels are essentially pure

quasi-particle in nature. This results because in ^{139}La (a single closed shell

nucleus) the one phonon quadrupole vibration is ~1.5 MeV. In ^{140}La we may hope

to explain our states as pure two quasi-particle excitations without the complica-

tion of considering collective admixtures. The analysis which follows is summarized

in Table 5.

(1) Let us first consider level 6 at 284.2 keV. It is the most intense

peak in the (d,p) spectrum below 600 keV of excitation and has a relative inten-

sity of 35.7. (See Table 4a.) This state has an $\ell = 3$ angular distribution,

and is assigned as the $|1g_{7/2}(p)2f_{7/2}(n); J\pi = 7- >$ state. This assignment is
based on the fact that no other state with a spin and parity 7- is expected in
the low energy portion of the spectra. Therefore the 7- state should be very
pure. According to the (2J+1) rule, this must be the most intense state in the
multiplet $|1g_{7/2}(p)2f_{7/2}(n); J\pi = 0-\cdots7- >$. Configuration mixing in other
members of this multiplet does not change this conclusion since configuration
mixing can only reduce the intensities of the individual mixed states. Besides
knowing that the state is pure, we see also that the peak at 284.2 keV is well-
defined and its area is accurately determined. Thus we may safely use it to
measure configuration mixing in other states by determining their relative
intensity with respect to this state.

(2) The ground state has a spin and parity of 3-. This has been deduced
both from its beta decay[6] and from atomic beam studies.[23] This state has a meas-
ured $\ell = 3$ angular distribution, consistent with the neutron being in the $2f_{7/2}$
orbital and has a relative intensity of 13.6. If the state were pure
$|1g_{7/2}(p)2f_{7/2}(n); J\pi = 3- >$, then the (2J+1) rule would predict that $(I_{3-}/I_{7-})_{th}$
= 0.47. The experimental ratio is $(I_{0.}/I_{284.2})_{exp}$ = 0.38 ± .02. Because of argu-
ments given earlier in this section, let us suppose that the pairing scheme in
^{139}La is good. Then to good approximation[24] we need to consider only two quasi-
proton states in ^{140}La, viz $|1g_{7/2}(p) >$ and $|2d_{5/2}(p) >$ so that for spins 1 - 6
there are only the state vectors:

$$|J M >_1 = \alpha_1|1g_{7/2}(p)2f_{7/2}(n); JM > + \beta_1|2d_{5/2}(p)2f_{7/2}(n); J M >$$

$$|J M >_2 = \alpha_2|1g_{7/2}(2)2f_{7/2}(n); JM > + \beta_2|2d_{5/2}(p)2f_{7/2}(n); J M >$$

If we choose phases so that the α's are positive, then $\beta_1 = \pm\sqrt{1-\alpha_1^2}$,

$\alpha_2 = |\beta_1|$ and $|\beta_2| = \alpha_1$. In direct reaction theory, the cross section for

a state is proportional to the spectroscopic factor. For the (d,p) reaction,

this is the square of the overlap integral of the target ground state plus the

incident neutron and the final state in the daughter nucleus. Thus for state 1,

the spectroscopic factor will be proportional to α_1^2 while for state number 2, it

will be proportional to β_1^2. The theoretical ratio of intensities for mixed

states will be $(I_{J-}/I_{7-})_{th} = \gamma^2(2J+1)/15$ where for states labeled 1, $\gamma = \alpha_1$

and for states labeled 2, $\gamma = \beta_1$. Solving this expression for γ using the experi-

mental intensity ratio, we find that for the ground state $|\alpha| = 0.90$ and $|\beta|$

$= 0.43$. In fitting transition probabilities Burde et al.[9] assume that this state

is pure.

(3) If there are only two contributing configurations, then we expect a

second 3- state with $\alpha = 0.43$ and $|\beta| = 0.90$. The predicted relative intensity

of this state is $(I_{3-}/I_{7-})_{th} = 0.09$. Level 7 at 319.2 keV has an experimental

relative intensity of $(I_{3-}/I_{7-})_{exp} = 0.09\pm0.01$ units. On the basis of the evidence

we conclude that level 7 is the second 3- state.

(4) Level 4 at 63.2 keV has a $\ell = 3$ angular distribution and a relative

intensity of 20.5. This yields the experimental ratio $(I_{63.2}/I_{284.2})_{exp} = 0.58$

$\pm$ .03. This is in excellent agreement with the theoretical prediction of the

(2J+1) rule for an unmixed 4- state, viz. $(I_{4-}/I_{7-})_{th} = 0.60$. Therefore we con-

clude that the state at 63.2 keV has $J\pi = 4-$ and $\alpha = 1.0$. Because of its high

spin, this level would not be observed in the beta decay of ^{140}Ba and since

$\alpha = 1.0$, the second 4- state is not expected to be observed in the (d,p) experiment.

(5) Level 3 at 49.2 keV has a $\ell = 3$ angular distribution and a normalized intensity of 30.4. Using the (2J+1) rule for unmixed states, one would conclude that $(I_{6-}/I_{7-})_{th} = 0.87$. If we take the ratio of the relative intensity of this level and the 7- level, we find that $(I_{49.2}/I_{284.2})_{exp} = 0.85\pm0.03$. Considering the experimental errors, this is sufficiently close to the theoretical ratio to conclude that the 49.2 keV level has $J\pi = 6-$ and $\alpha = 1.0$. Here also the large spin of this state precludes its observation in the beta decay of ^{140}Ba, and since $\alpha = 1.0$, the second 6- state should not be observed in the (d,p) experiment.

(6) Level 9 at 578.6 keV corresponds to the level observed in beta decay of ^{140}Ba [7,9] at 580 keV. This level has tentatively been assigned 0- spin and parity. This state, like the 7- state, should be essentially pure. Because of its very small intensity, it was not feasible to measure its angular distribution. However its normalized intensity is 1.7 so that $(I_{578.6}/I_{284.2})_{exp} = 0.05 \pm 0.01$. The theoretical value for the ummixed 0- state is $(I_{0-}/I_{7-})_{th} = 0.067$. This agreement strongly supports the spin 0 assignment.

(7) Level 5 at 161.6 keV has also been observed in the beta decay of ^{140}Ba. [7,8,9] The 162 keV transition to the ground state is almost entirely M1 and so the fact that it has been populated directly in the beta decay of ^{140}Ba makes the spin and parity assignment of 2- unique. This state has an $\ell = 3$ angular distribution and a normalized intensity of 6.0. Therefore for this state $\alpha = 0.72$ and $|\beta| = 0.69$. This would imply that the normalized intensity of the second 2- state is 5.7. Burde et al.[9] have also found that the 2- states are highly admixed.

(8) Level 8 at 466.6 keV has been observed in the beta decay of ^{140}Ba. [7,8,9] Both angular correlation measurements and measurements of the mean life of the state[9]

suggest that it has $J\pi = 1-$. This level has an angular distribution consistent

with $\ell = 3$ and a normalized intensity of 2.4. This yields the experimental

ratio $(I_{466.6}/I_{284.2})_{exp} = 0.07 \pm .01$ while the theoretical ratio from the

$(2J+1)$ rule for unmixed states is 0.20. Therefore $\alpha = 0.59$ and $|\beta| = 0.81$.

This is in contrast to the results of Burde et al.[9] who argue from transition

probabilities that the two 1- states are only slightly admixed. The normalized

intensity of the second 1- state is predicted to be 4.6 units.

(9) Level 1 at 30.6 keV is certainly the state observed in the decay

of ^{140}Ba at 29.6 keV.[7,8,9] The 29.6 keV gamma transition to the ground state

is predominantly M1 and so the fact that it is observed in beta decay from the

0+ ground state of ^{140}Ba makes the spin assignment of 2- unique. This state

has an $\ell = 3$ angular distribution and a relative intensity of 14.4. The predicted

value for the normalized intensity of this state (see paragraph 7) is only 5.7.

But even if this state were pure, the $(2J+1)$ rule would predict a normalized

intensity of only 11.8 units. Clearly this is impossible and indicates that

there are either more levels in the first grouplet of peaks than the least

squares analysis indicates and/or there is not sufficient experimental detail

to accurately determine the relative intensities of the states labeled 1 and 2.

This is suggested by the fact that an acceptable fit in the least squares sense

can be obtained by omitting peak 1 and that there appears to be a large systematic

error in the excitation energy measured in the (d,p) experiment.

(10) From the beta decay of ^{140}Ba,[7,8,9] it is deduced that there is a

state at 43 keV. The fact that it does not decay to the ground state strongly

suggests that its spin and parity are 1-. We find no state at 43 keV. However

if the state were pure $|2d_{5/2}(p)2f_{7/2}(n); J\pi = 1- >$, then it would not be excited

in the (d,p) reaction. Assuming that the values of α and $|\beta|$ extracted in (8)

are an accurate measure of the mixing of these two states, then we would expect

a normalized intensity for this 1- state of 4.6 units. Although our experimental

detail is insufficient to define this peak, its arbitrary inclusion helps to

explain the discrepencies cited in paragraph (9).

(11) We have now accounted for seven of the eight states expected from

the multiplet $|1g_{7/2}(p)2f_{7/2}(n); J\pi = 0-, \cdots 7- >$. Only the 5- state is

missing. This state cannot be observed in the beta decay of ^{140}Ba, and if it

is unmixed, the (2J+1) rule predicts that its normalized intensity should be 26.1.

Level 2   has a normalized intensity of 21.2. Rather than propose that this

decreased intensity is due to configuration mixing, it seems more likely that

states 1 and 2, in addition to the unobserved state at 43 keV, are inadequately

decomposed by the least squares analysis. From arguments presented in paragraph

(9), there are 8.7 too many units of normalized intensity in level 1. Of these,

4.9 units can be accounted for if level 2 has 26.1 units of intensity. An addi-

tional 4.6 units would be accounted for if the mixing of the 1- states deduced in

paragraph (10) is correct. Thus within experimental accuracy, we have accounted

for the intensity within the first grouplet of peaks by assuming/the 5- state is
                                                            that

unmixed and that the intensity of the 2- and 1- states in this grouplet can be

predicted from a knowledge of the relative intensities of the 162 kev 2- state

and the 467 keV 1- state. Since we have assigned the value $\alpha = 1$ for this

state, we expect not to observe the second 5- state in the (d,p) experiment.

(12) Peaks 10 - 14 are five intense, well-resolved peaks having $\ell = 1$

angular distributions and a mean energy of 687 keV. From the systematics of

neighboring isotonic odd-A nuclei, one expects that the $3p_{3/2}$ neutron orbital

should appear at ~700 keV in excitation. If we assume that we can neglect

vibrational states, then there should be eight states produced from the con-

figurations $|1g_{7/2}(p)3p_{3/2}(n); J\pi = 2-\cdots\cdot5->$ and $|2d_{5/2}(p)3p_{3/2}(n);$

$J\pi = 1-\cdots\cdot4->$. To first order, the states having spins 2, 3, and 4 may

be close enough in energy so that they can be appreciably mixed. Of course,

the $|1g_{7/2}(p)3p_{3/2}(n); J\pi = 5->$ state would be pure and should be the most

intense. But the method of analysis used in paragraphs(1)-(11)fails. After

summing the total $\ell = 1$ intensity of these five peaks, we find that peak 14,

the most intense of this group, is six units too small in relative intensity

to be the 5- state predicted by the (2J+1) rule. This suggests that here

phonon admixtures are appreciable. This is not surprising since Fulmer et al.[25]

found appreciable phonon mixing for the $3p_{3/2}$ state in ^{141}Ce. It is pertinent

that in ^{141}Ce, a nucleus with only one more proton, Fulmer et al.[25] find the

$3p_{3/2}$ strength shared between levels at 660 keV and 1120 keV and that the mean

energies of our first two groups (levels 10 - 14 and levels 18 - 22) that have

$\ell = 1$ angular distributions are 687 keV and 1077 keV. Fulmer et al.[25] see their

first excited state which/ an $\ell = 3$ angular distribution at 1500 keV. We observe

a sequence of levels that/ $\ell = 3$ angular distributions between 1400 and 1600 keV

which we therefore attribute to states having a large single particle $2f_{5/2}$ com-

ponent in their state vector. Fulmer et al.[25] observe their first $\ell = 1$ state

attributable to the $3p_{1/2}$ single particle state at 1730 keV. We observe a

sequence of states having $\ell = 1$ angular distributions between 1702 and 1795 keV.

It becomes very complex to discuss these states in terms of even a simple

odd-odd quasi-particle and phonon model because the state vector is then a linear

combination of the basis vectors $|\bar{j}_p\bar{j}_n J; pR;IM>$ where $\bar{j}_p$ and $\bar{j}_n$ are the quantum

numbers of the quasi-protons and neutrons which couple to angular momentum J .

The letter p represents the number of phonons coupled to angular momentum R, and

J and R are coupled to I.   Even if we restrict our analysis to states with at most

one phonon (pR = 00 and 12) and with $\bar{J}_p$ = $1g_{7/2}$ or $2d_{5/2}$ and $\bar{j}_n$ = $2f_{7/2}$ or $3p_{3/2}$,

there are 17 basis vectors having that spin 5 and negative parity.   At least five

of these will be close enough in zero[th] order to couple extensively with the

$|(1g_{7/2}3p_{3/2})5;00;5>$ component which has the total $3p_{3/2}$ strength for spin 5 states.

This complexity in the nuclear structure makes it impossible to use simple relation-

ships such as the (2J+1) rule and angular distributions to deduce detailed informa-

tion about the nature of the states or even as measure of their spin.

VI.   CONCLUSION

We have observed 70 levels below 1.858 MeV in the nucleus ^{140}La by (d,p)

reaction spectroscopy and have characterized 43 of them by specifying their ℓ

values as deduced from angular distributions.   Of the 14 lowest levels expected

from the two configurations $|1g_{7/2}(p)2f_{7/2}(n); J\pi = 0-,\cdots,7->$ and

$|2d_{5/2}(p)2f_{7/2}(n); J\pi = 1-,\cdots, 6->$, we have characterized 11 with respect to

their energy position, spin, parity, and the absolute value of the amplitudes in

the state vectors with the assumption that configurations other than the two

mentioned above are not important.   In addition, the (d,p) intensity of the

observed 4-, 5-, and 6- states suggest that they are not appreciably mixed and

therefore the three unobserved states which also have these spins should be

observed in the (d,p) experiment with very small intensity.   Below 600 keV we

have not been able to interpret the two weak levels 4b and 4c.   However, as

shown in Table 2, only one of these peaks may be real.   It is most likely the

unassigned 4-, 5-, or 6- state and is populated either through a weak $lg_{7/2}$ proton component or a second order process in the (d,p) reaction. Any attempt to extend these simple interpretations to levels above 600 keV seems doomed because of the strong phonon particle coupling.

^{140}La is one of the first non-magic vibrational odd-odd nuclei to be carefully studied. The results suggest, at least qualitatively, the validity of the odd-odd quasi-particle model but above 500 keV careful consideration of the particle phonon interaction must be included in any description even in this simple case where there are only 83 neutrons.

VII. ACKNOWLEDGEMENTS

Footnotes and References

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Table 1. A summary of experiments.

Target No.	Angle deg	Exposure (μ C)	Resolution (keV)	Cross sec/track (μb/sr)	Q-Value (keV)
1	25	10,000	13.1	0.20	2939.7
3	35	6,000	12.4	0.56	2936.4
3	45	7,500	12.8	0.45	2939.1
3	55	6,000	13.9	0.54	2939.1
3	65	6,000	12.1	0.58	2938.5
3	75	12,000	12.8	0.29	2937.6
4	85	9,000	14.3	0.13	2921.1
6	105	8,000	12.1	0.32	2937.8

Comment to Table 2

[†] For the significance of these standard deviations, the reader is referred to the paragraph on errors in section IV. Since we cannot make a good estimate of such errors as the energy calibration error at this time, we prefer not to increase arbitrarily the standard deviation to include them, in order not to mask such important errors as an improper number of components in the fitting of a group of peaks. Large and erratic differences compared to the standard deviation between our and other values should however not automatically be interpreted in this sense. For instance impurities may also alter the results, especially in the case of small peaks. We believe the standard deviation in intensities is in general a good estimate of the true error. However in some cases an improper number of components, impurities and the approximate fitting shape may be the cause of large non-statistical errors.

[‡] It appears from the discussion in section V, that there is an unobserved peak at 43 keV which has a non-negligible intensity. The inclusion of this component would, of course, modify the energies and intensities of the close lying peaks.

[*] A background has been subtracted from this peak.

[**] It is possible that the two levels 4a and 4b have only been artificially decomposed and that they represent only one level at about 102 keV.

[***] The appearance of impurity peaks near this level at several angles makes the uncertainty of the values appreciably larger than the quoted standard deviations.

WA: The energy value is a weighted value.

1) $5Si^{29}$ component at 45°.

2) $9F^{20}$ at 35° (30 μb).

3) $5Si^{29}$ at 85°.

4) $9F^{20}$ at 45° (30 μb).

5) G. S. O^{19} at 25° (100 μb). $9F^{20}$ at 55°. $5Si^{29}$ at 105°.

6) $5Si^{29}$ at 105°.

7) G. S. 0^{19} at 35° (20 µb).

8) $7Si^{29}$ at 25° (10 µb).

9) $9Si^{29}$ at 25° (300 µb).

10) $9Si^{29}$ at 35° (170 µb).

Table 2. Level energies (keV) and differential cross sections (Microbarns/sr).

The standard deviation is given beneath each value.[†]

Level	Energy	Differential Cross Section								Comments
		25°	35°	45°	55°	65°	75°	85°	105°	
GS	0.0	52	134	147	171	194	163	114	96	
		6	9	9	13	15	11	7	11	
1	30.6	43	85	220	149	227	189	147	114	‡
	0.2	54	47	56	82	84	54	88	46	
2	37.5	81	265	215	345	243	195	169	157	‡
	0.4	47	43	41	59	57	40	95	64	
3	49.2	111	290	448	395	378	325	251	230	‡
	0.3	10	17	31	27	50	28	14	13	
4	63.2	70	152	299	277	264	228	199	156	
	0.2	6	9	19	22	18	13	15	11	
4a	92.8	4	4	9	13	11	3	32	5	**
	1.5	1	2	3	4	5	2	4	1	
4b	106.3	5	12	20	13	9	16	30	14	**
	0.7	1	2	2	4	4	3	3	2	
5	161.6	25	44	89	77	71	62	60	43	***
	0.3	2	4	8	7	6	4	5	4	
6	284.2	123	315	477	492	447	387	341	234	
	0.4	8	20	27	30	25	20	17	22	
7	319.2	14	21	40	31	40	35	38	32	
	0.7	1	3	4	4	3	5	3	4	

Table 2.   (continued)

Level	Energy	25°	35°	45°	55°	65°	75°	85°	105°	Comments
				Differential Cross Section						Comments
8	466.6		22	34	35	31	26	20	16	WA
	1.0		3	2	3	3	2	4	3	
9	578.6		20	39	19	16	14	21	6	***
	1.4		3	6	5	3	2	2	3	
10	601.6	423*	369	423	431	417	363	263	148	WA 1
	0.6	30	25	30	30	25	20	20	14	
11	658.3	374*		488	471	445	373	238	191	
	0.5	30		30	31	26	22	16	13	
12	711.6	257*		228	268	200	162	108	85	
	0.7	25		15	19	14	11	7	7	
13	744.5	184*	188*	191	157	153	117	95	70	
	0.7	20	20	14	12	11	9	6	5	
14	771.7	513*	499*	660	557	492	476	330	237	
	0.6	60	40	38	35	28	26	18	15	
15	794.2	58*	75*	31	35	43	31	68	14	
	0.8	20	10	8	4	5	3	5	2	
16	912.6	40*	75*		33	36	34	23	22	
	0.8	15	20		4	3	4	3	2	
17	930.3	18*	29*		4	8	4	11	8	
	0.8	10	10		1	1	2	2	3	
18	1035.8	47*	54	60	32	41	42	22	17	
	0.6	10	6	6	4	5	5	2	2	

Table 2. (continued)

Level	Energy	Differential Cross Section								Comments
		25°	35°	45°	55°	65°	75°	85°	105°	
19	1056.9	248	349	339	370	351	326	228	154	2
	0.8	20	23	24	23	21	20	13	9	
20	1076.9	23	33	28	17	14	21	24	5	
	1.4	3	5	4	4	4	5	2	1	
21	1102.4	124	147	157	161	151	149	111	62	
	0.9	10	13	11	10	11	14	7	6	
22	1118.2	70	80	79	79*	75	55	75	27	3
	0.9	8	8	7	15	7	5	5	5	
23	1137.0	80	108	108	75*	75	55	74	35	WA
	1.0	8	9	8	15	9	13	7	5	
24	1149.9	33*	29	43	67*	26	37	24	29	
	1.4	10	5	6	15	4	14	4	5	
25	1169.1	33*	36	19		8	6	12	3	WA
	1.0	10	4	4		3	1	4	2	
26	1191.8	40*	92	115		87	79	65	58	
	0.8	20	8	8		8	5	4	5	
27	1212.0		28	60		33	30	38	16	4
	1.0		5	7		5	4	3	3	
28	1227.1		26	21		5	5	10	4	
	1.7		5	8		3	3	2	2	
29	1245.6		33	24		29	25	24	23	
	0.6		5	3		4	2	3	3	

Table 2. (continued)

Level	Energy	25°	35°	45°	55°	65°	75°	85°	105°	Comments
30	1262.4		22	31	15*	17	19	19		
	0.6		5	4	10	3	3	2	7	
31	1279.9		25*	27	36*	7	10	13	2	
	0.8		10	3	15	2	3	2		
32	1295.4		38*	48	59*	55	53	38	33	
	1.0		10	5	15	5	5	3	4	
33	1312.5		21*	21	19*	14	14	18	17	WA
	1.4		8	2	10	3	3	2	3	
34	1328.0			13	12	7		11	3	
	2.2			3	7	2		3	2	
35	1343.0				103*	71	70	66	60	
	1.3		111		10	17	11	7	12	
36	1352.2	40*		7	33*	43	38	25	19	WA
	1.0	20			15	16	10	6	2	
37	1370.2	42*		26	43*	27	21	23	20	
	0.9	10		3	8	4	3	4	2	
38	1388.0	105*		18	26	10	2	7	43	5
	1.5	20		3	4	3	1	2	29	
39	1403.3	18*		14	24	23	17	15	25	6
	0.6	10		3	7	4	3	4	27	
40	1418.4	49*		79	139	89	107	73	63	
	0.9	15		6	11	13	13	7	6	

Table 2. (continued)

Level	Energy	25°	35°	45°	55°	65°	75°	85°	105°	Comments
41	1431.5	43*		104	113	127	78	107	109	
	0.5	15		20	9	14	19	9	8	
42	1444.0	17*		56*	71	63	61	49	44	
	1.0	10		25	6	14	26	7	4	
43	1461.1	41*	48*	90*	80	84*	78	67	60	
	0.8	20	20	15	15	9	6	7	5	
44	1479.2	40*	43*	45*	88	113*	57	51	44	7
	0.9	15	20	20	10	20	8	5	5	
45	1493.0		43*	46*	65		36	40	40	
	1.4	18*	20	20	9		10	4	5	
46	1508.0	10	68*		55		25	32	24	
	2.2		30		11		13	8	4	
47	1519.3	23*	48*		74		38	44		WA
	0.9	10	20		8		4	13		
48	1529.2	30*	24*				70	37	74	WA
	0.6	15	10				5	18	7	
49	1554.6	32*	44*		66		64	55	52	WA
	0.6	10	15		19		7	4	5	
50	1568.9	21*	39*		42		40	54	41	
	0.7	10	15		25		11	5	5	
51	1583.6	8*	11*		62		27	15		
	2.6	5	5		19		13	4		

Table 2. (continued)

Level	Energy	Differential Cross Section								Comments
		25°	35°	45°	55°	65°	75°	85°	105°	
52	1600.1	45*	81*	86*	37	92*	62	53	39	
	0.9	10	10	30	19	25	5	5	5	
53	1616.6	23*	77*	51*	92	35*	28	25	27	
	1.1	10	10	20	10	20	4	12	4	
54	1630.2	36*	48*	64*	45	85*	77	44	55	
	1.0	10	10	20	8	20	7	8	6	
55	1643.6	31*	37	57*	60*	56*	43	42	35	8
	1.1	7	8	20	8	20	5	6	4	
56	1657.4	22*	42	66*	31*	35*	30	34	27	WA
	1.1	5	5	25	8	7	3	4	3	
57	1672.7	24*	35	39*	64*	33*	35	26	11	
	1.1	6	6	25	20	10	5	3	5	
58	1685.2	48	63	74*	51*	89*	48	51	39	
	0.8	6	7	25	15	10	6	4	6	
59	1702.2	43	50	61*	99*	81*	43	48	32	
	0.8	4	5	10		10	5	5	4	
60	1718.1		117	127		91	118	90	48	
	0.8	102	10	12		28	11	7	16	
61	1730.1	8	63	95		109	53	66	47	
	1.6		35	37		30	20	8	5	
62	1742.1	373	43	97		117	64	49	59	9
	1.2	23	37	15		10	19	7	5	

Table 3.   Optical Model Parameters.

	"d" potential	"p" potential
Depth of real potential V_S (MeV)	73	57
Nucleus and charge radius r_{OS}, R_C (F)	1.26	1.25
Diffuseness of real potential a_S (F)	0.87	0.65
Depth of Surface part of imaginary potential W_D (MeV)	12	14
Nuclear radius of imaginary potential r_{OI} (F)	1.37	1.25
Diffuseness of imaginary potential a_I (F)	0.7	0.47

Table 4a. Normalized cross sections of the peaks GS, 1, 2, 3, 4, 5, 6, 7 8 and 9.
Norm: GS + 1 + 2 + 3 + 4   = > 100
Angular distribution: $\ell = 3$ (see Fig. 4a)
The standard deviation is given beneath each value.

Level	Energy	Normalized Differential Cross Section								Average
		25°	35°	45°	55°	65°	75°	85°	105°	
GS	0.0	15	15	11	13	15	15	13	13	13.6
		2	1	1	1	1	1	1	2	0.5
1	30.6	12	9	16	11	17	17	17	15	14.4
	0.2	15	5	4	6	6	5	10	6	2
2	37.5	23	29	16	26	19	18	19	21	21.2
	0.4	13	5	3	4	4	4	11	9	2
3	49.2	31	31	34	30	29	30	29	31	30.4
	0.3	3	2	2	2	4	3	2	2	0.6
4	63.2	20	16	23	21	20	21	23	21	20.5
	0.2	2	1	1	2	1	1	2	1	0.7
5	161.6	7.0	4.7	6.7	5.7	5.4	5.7	6.8	5.7	6.0
	0.3	.6	.4	.6	.5	.4	.4	.5	.6	0.3
6	284.2	34	34	36	37	34	35	39	31	35.7
	0.4	2	2	2	2	2	2	2	3	0.6
7	319.2	3.9	2.3	3.0	2.3	3.0	3.2	4.3	4.2	3.3
	0.7	0.3	0.3	0.3	0.3	0.2	0.5	0.3	0.5	0.3
8	466.6		2.4	2.6	2.7	2.3	2.4	2.3	2.3	2.40
	1.0		0.3	0.2	0.2	0.3	0.2	0.4	0.3	0.1
9	578.6		2.1	2.9	1.4	1.2	1.3	2.4	0.8	1.7
	1.4		0.3	0.5	0.4	0.2	0.2	0.2	0.4	.7

Table 4b. Normalized cross sections of the peaks 10, 11, 12, 13, and 14.
            Norm: 10 + 13 + 14   => 100
            Angular distribution: $\ell = 1$ (see Fig. 4b)
            The standard deviation is given beneath each value.

Level	Energy	Normalized Differential Cross Section								Average
		25°	35°	45°	55°	65°	75°	85°	105°	
10	601.6	38*	35	33	38	39	38	38	33	36.4
	0.6	3	2	2	3	2	2	3	3	0.9
11	658.3	33*		38	41	42	39	35	42	38.5
	0.5	3		2	3	2	2	2	3	1.3
12	711.6	23*		18	23	19	17	16	19	19.1
	0.7	2		1	2	1	1	1	2	1.0
13	744.5	16*	18*	15	14	14	12	14	15	14.8
	0.7	2	2	1	1	1	1	1	1	0.6
14	711.7	46*	47*	52	49	46	50	48	52	48.6
	0.6	5	6	3	3	3	3	3	3	0.8

*A background has been subtracted from this peak.

Table 4c. Normalized cross sections of the peaks GS. 1. 2, 3, 4, 5, 6. and 8.
          · Norm: 18 + 19 + 20 + 21 + 22 => 100
           Angular distribution: $\ell = 1$ (See Figures 4c and 4d)
           The probable error is given beneath each value.

Level	Energy	Normalized Differential Cross Section								Average
		25°	35°	45°	55°	65°	75°	85°	105°	
18	1035.8	9*	8	9	5	7	7	5	6	7.0
	0.6	2	1	1	1	1	1	1	1	0.6
19	1056.9	48	53	51	56	56	55	50	58	53.3
	0.8	4	4	4	4	3	3	3	3	1.2
20	1076.9	4.5	5.0	4.2	2.6	2.2	3.5	5.2	1.9	3.6
	1.4	.4	.8	.6	.6	.6	.8	.4	.4	.4
21	1102.4	24	22	24	24	24	25	24	23	23.9
	0.9	2	2	2	2	2	2	2	2	0.3
22	1118.2	14	12	12	12*	12	9	16	10	12.3
				2						
	0.9	2	1	1	2	1	1	1	2	0.7

*
 A background has been subtracted from this peak.

-35-

Table 5. Configuration Analysis.

1 Level Nr.	2 Energy (keV)	3 Normal. Intens.	4 Intens. $\frac{(2J+1)}{Rule}$*	5 Spin	6 Experimental State Vector α	7 $|\beta|$	8 Calculated Intens.	9 Rel. Experiment. Intens.	10 Comments Section V
GS	0.0	13.6 0.5	0.47	3	0.90	0.43	0.38	0.38 0.02	2
1	30.6 0.2	14.4 2	0.33	2	0.69	0.72	0.16	0.40 0.06	9
2	37.5 0.4	21.2 2	0.73	5	1.0	~0	0.73 }1.02	0.59 0.06 } 0.99 ±0.04	11
2a	43	Unobserved	0.20	1	0.81	0.59	0.13	Unobserved	10
3	49.2 0.3	30.4 0.6	0.87	6	1.0	~0	0.87	0.85 0.03	5
4	63.2 0.2	20.5 0.8	0.60	4	1.0	~0	0.60	0.58 0.03	4
5	161.6 0.3	6.0 0.3	0.0	2	0.72	0.69	0.17	0.17 0.01	7
6	284.2 0.4	35.7 0.6	1.00	7	1.0		1.00	1.00 0.02	1
7	319.2 0.7	3.3 0.3	0.0	3	0.43	0.90	0.09	0.09 0.01	3
8	466.6 1.0	2.4 0.1	0.0	1	0.59	0.81	0.07	0.07 < 0.01	8
9	578.6 1.4	1.7 0.3	0.06	0	1.0		0.06	0.05 0.01	6

*It is assumed that for spin doublets the lower energy number belongs to the $1g_{7/2}$ proton configuration
Col. 3: From Table 4a
Col. 8 and 9: Intensity of peak 6 normalized to 1.0.
Col. 4: Intensity for pure $1g_{7/2}$ configuration

Figure Captions

Fig. 1. Levels in ^{140}La known from previous investigations.

Fig. 2. Typical proton spectrum for the reaction ^{139}La(d,p)^{140}La.

Fig. 3. Least-squares fit of the high energy part of the 25° proton spectrum

from the reaction ^{139}La(d,p)^{140}La.

Fig. 4. Angular distribution of several different proton groups from the reaction

^{139}La(d,p)^{140}La. Experimental data are represented by crosses (X) or by an

asterisk (*), when a background was subtracted, or by a zero (o) when an

impurity component was subtracted.   A zero surrounded by an asterisk

indicates that both subtractions have been performed.

a) Levels at 0, 30, 37, 49, and 63 keV, belonging to the $(1g_{7/2})_p (2f_{7/2})_n$

configuration.

b) Levels at 602, 745 and 772 keV.

c) Levels at 1036, 1057 and 1077 keV.

d) Levels at 1102 and 1118 keV.

e) Levels at 1343 and 1352 keV.

f) Levels at 1403, 1418, 1432 and 1444 keV.

g) Level at 1461 keV.

h) Levels at 1479, 1493, 1508, 1519 and 1529 keV.

i) Levels at 1555, 1568 and 1584 keV.

j) Levels at 1617, 1630 and 1644 keV.

k) Levels at 1657, 1672 and 1685 keV.

l) Levels at 1702 and 1718 keV.

m) Levels at 1778 and 1795 keV.

Fig. 5. Level scheme for ^{140}La from these experiments. Excitation energies

are in keV.

La^{140} Level scheme
Energies in KeV
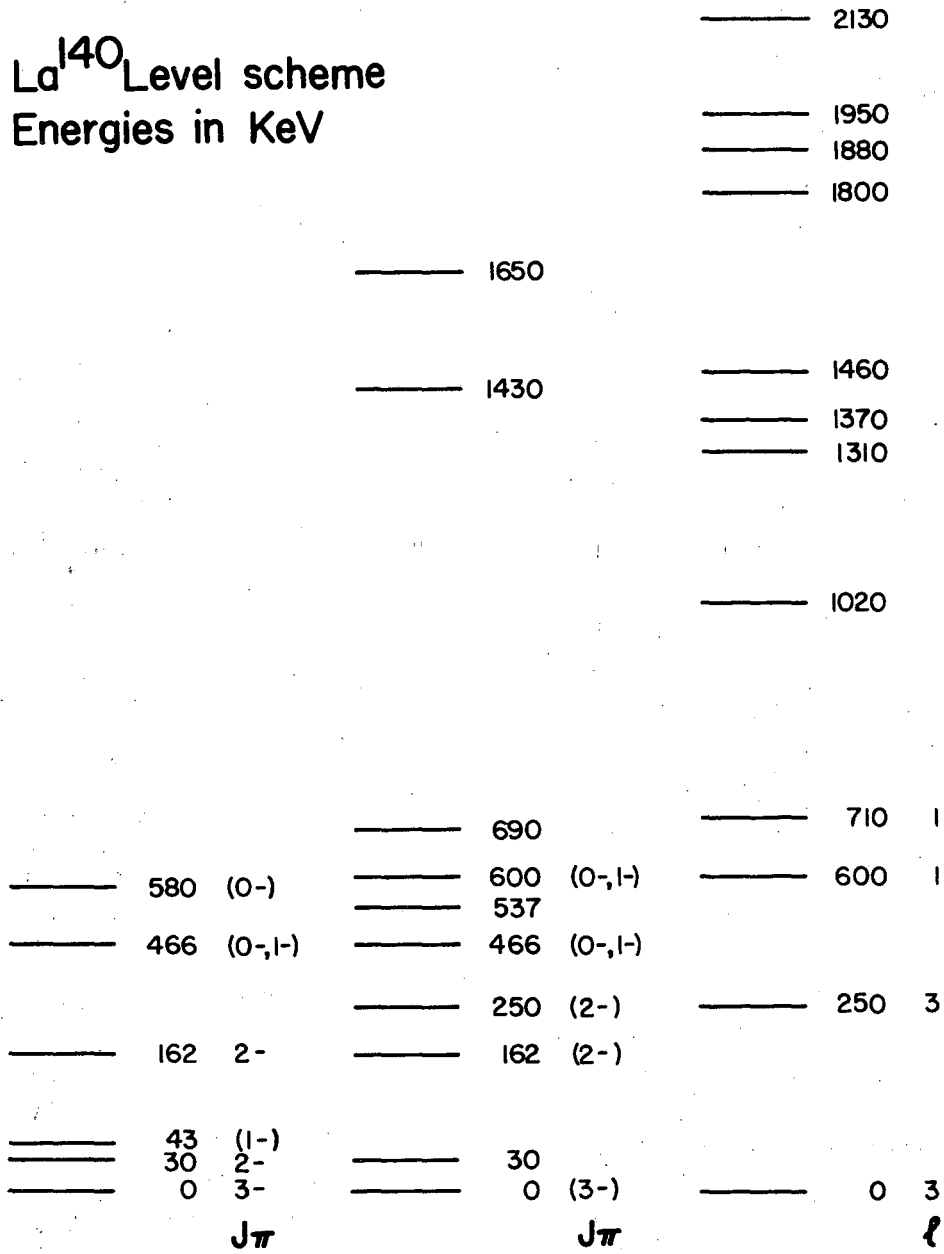
From ref. 8 and 9 (Decay Spectroscopy)		From ref. 11 (n,γ)		From ref. 12 (d,p)	
				2130	
				1950	
				1880	
				1800	
		1650			
1430				1460	
				1370	
				1310	
				1020	
		690		710	1
580	(0-)	600	(0-,1-)	600	1
		537			
466	(0-,1-)	466	(0-,1-)		
		250	(2-)	250	3
162	2-	162	(2-)		
43	(1-)				
30	2-	30			
0	3-	0	(3-)	0	3
	Jπ		Jπ		ℓ

MUB-10429

La-139 (d,p) La-140
Deuteron Energy: 10 MeV
Lab. Angle: 75°
Exposure: 12,000 μcoul.

Number of Protons Per 1/2mm Strip

Distance Along Plate — cm

MUB-9619

La^{139} (d,p) La^{140}
Lab. Angle : 25°
× Experimental Point
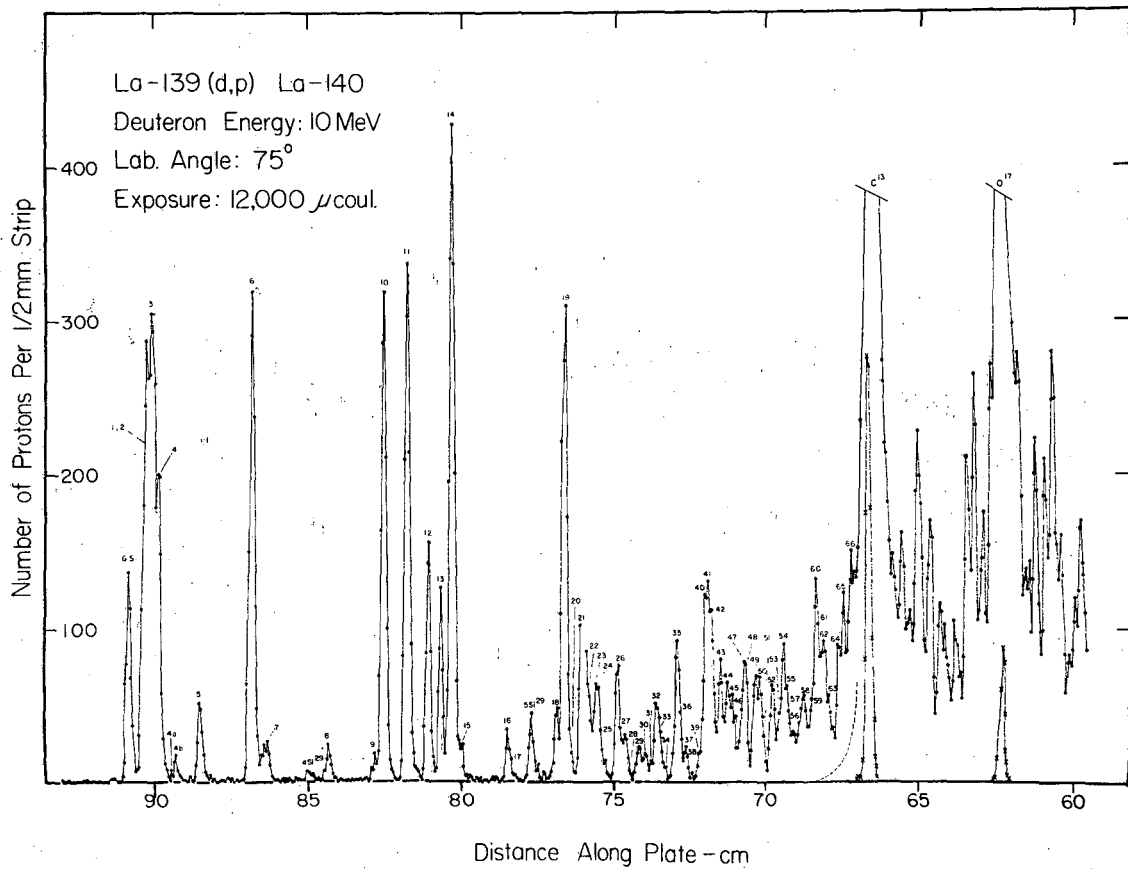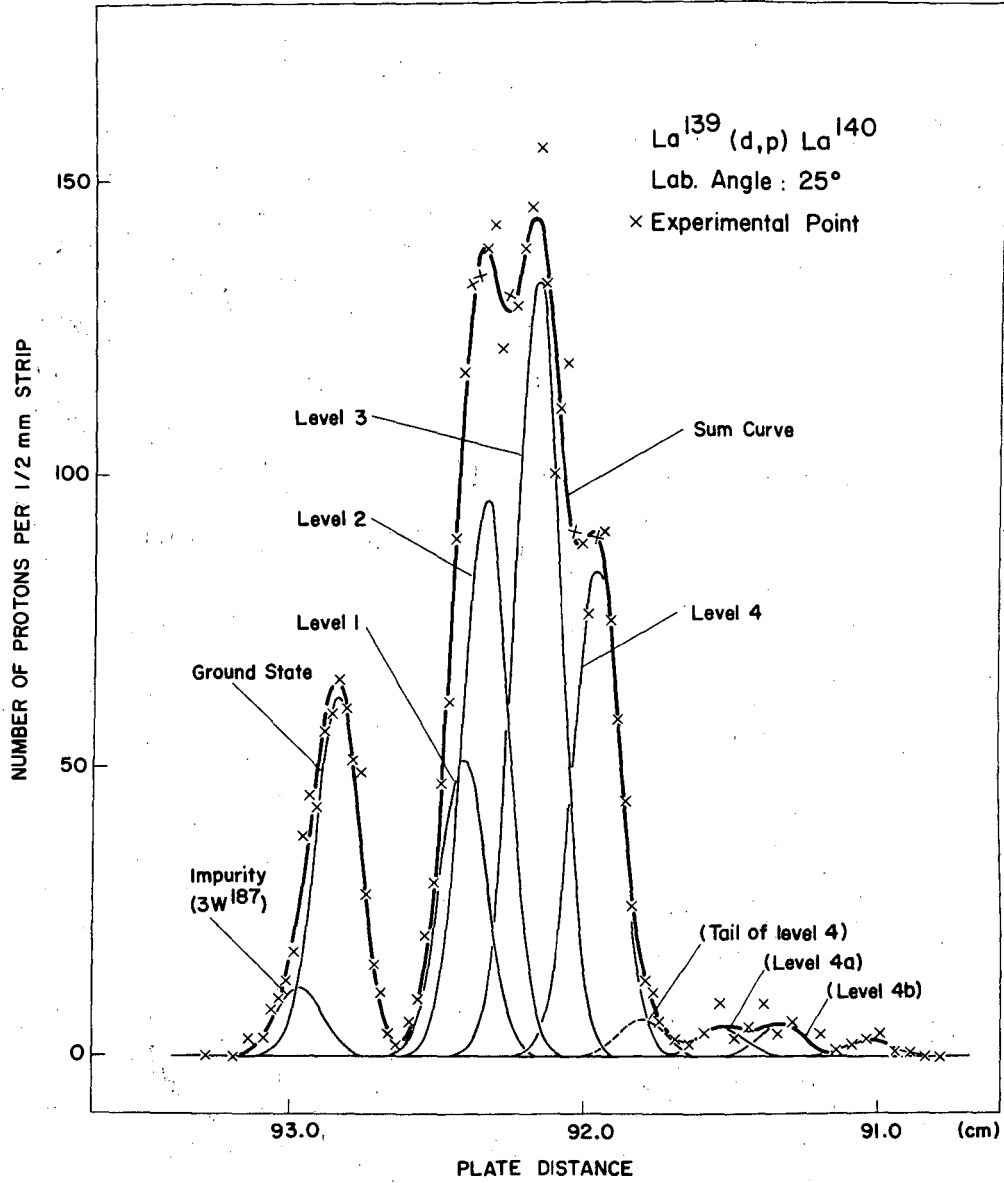
MUB-9620

La^{139} (d,p) La^{140}
Levels GS to 4
— DWBA $\ell=3$ Q=2.9 MeV
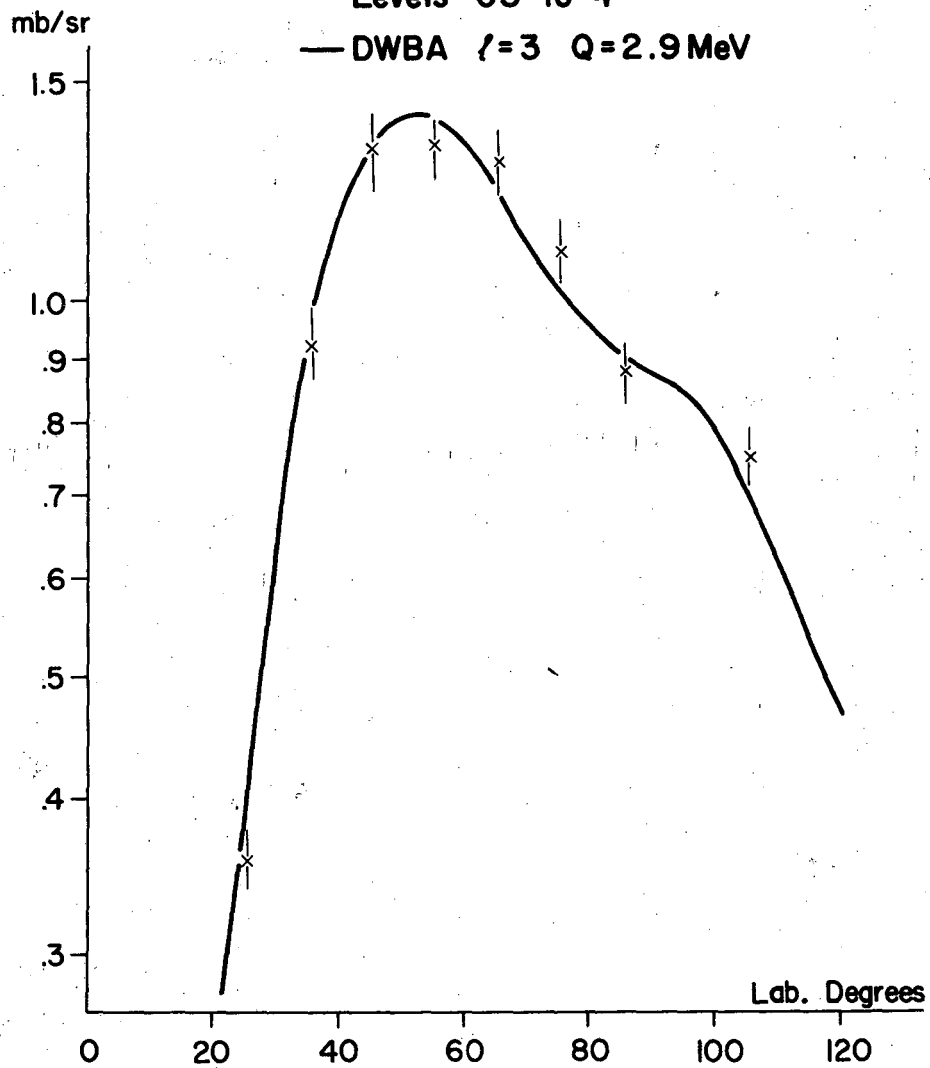
MUB-9621

La^{139} (d,p) La^{140}
Levels 10+13+14
— DWBA $\ell=1$ Q=2.2 MeV

mb/sr
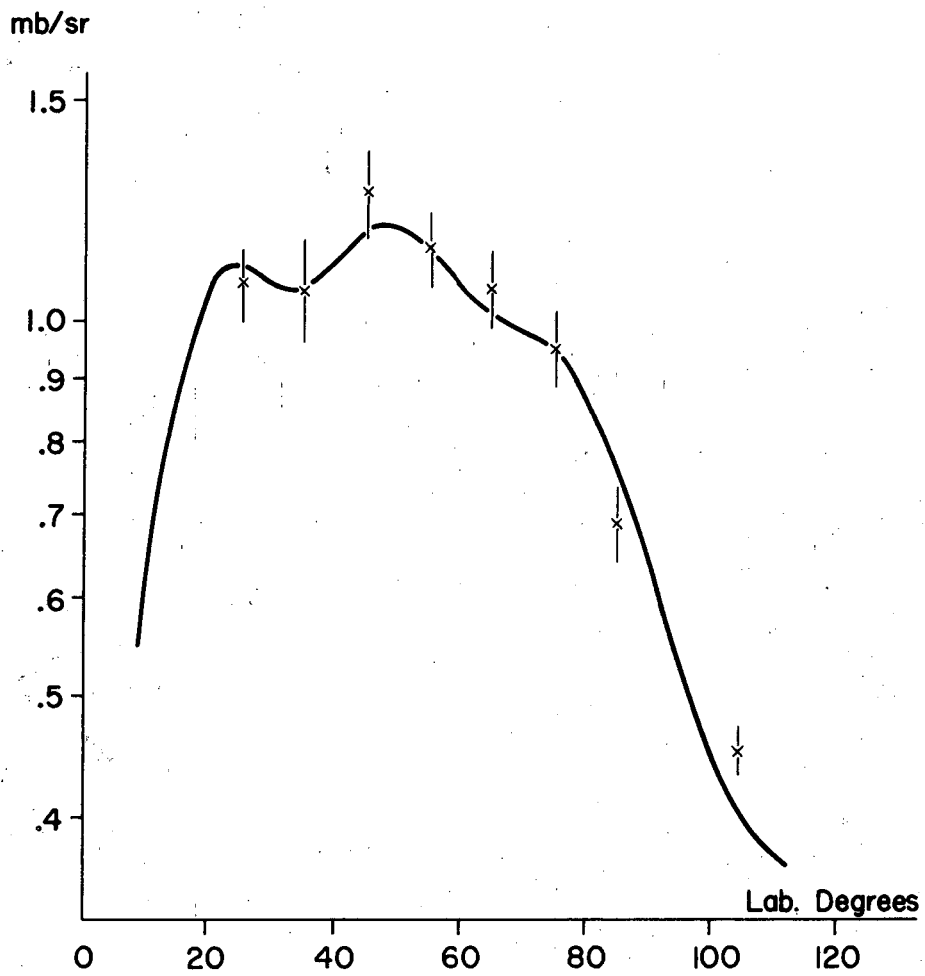
MUB-9622

La^{139} (d,p) La^{140}

Levels 18+19+20

— DWBA $\ell = 1$ Q = 1.8 MeV
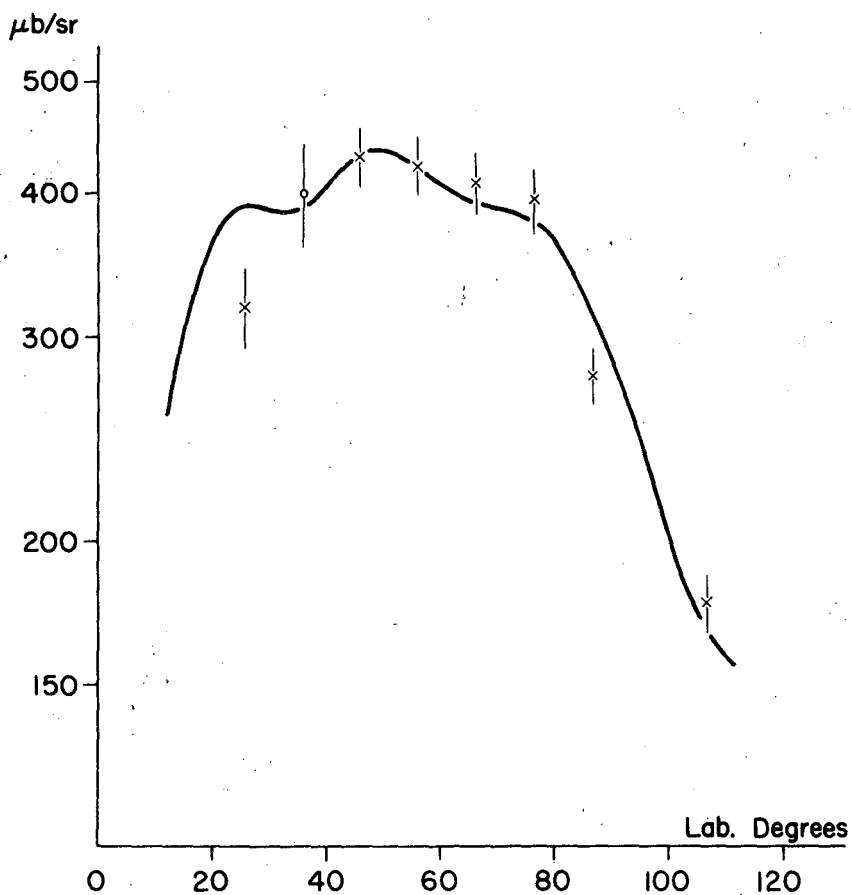
MUB-9608

La^{139} (d,p) La^{140}
Levels 21+22
— DWBA $\ell=1$ Q=1.8 MeV

MUB-9609
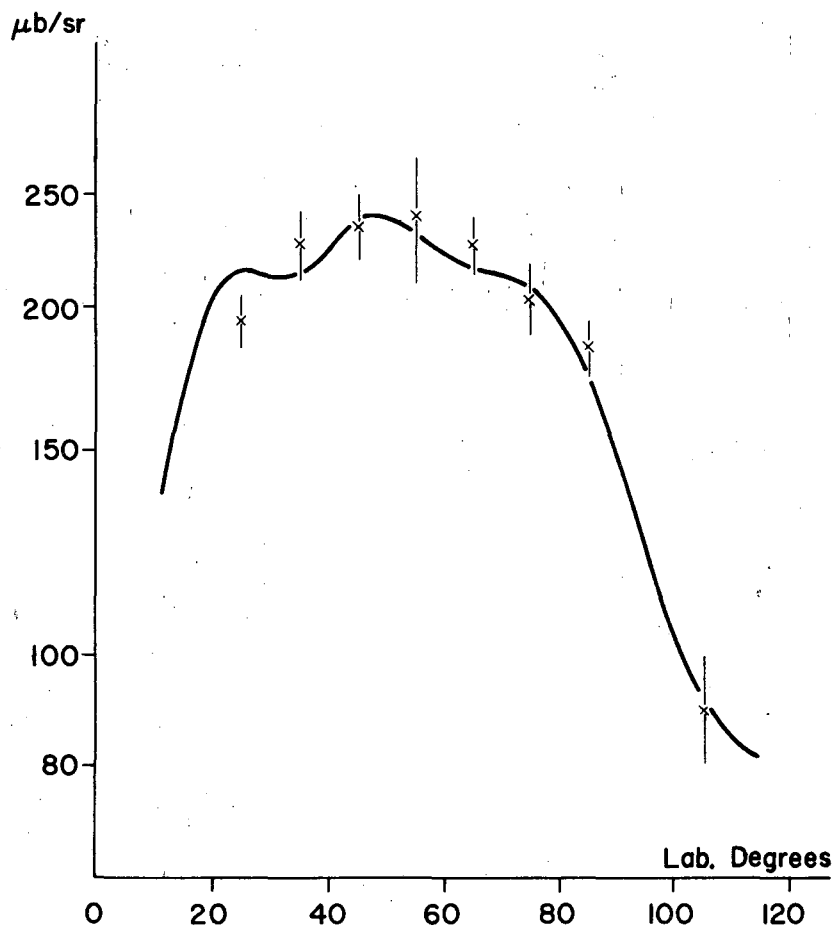
La^{139} (d,p) La^{140}
Levels 35+36
— DWBA $\ell=3$ Q=1.4 MeV
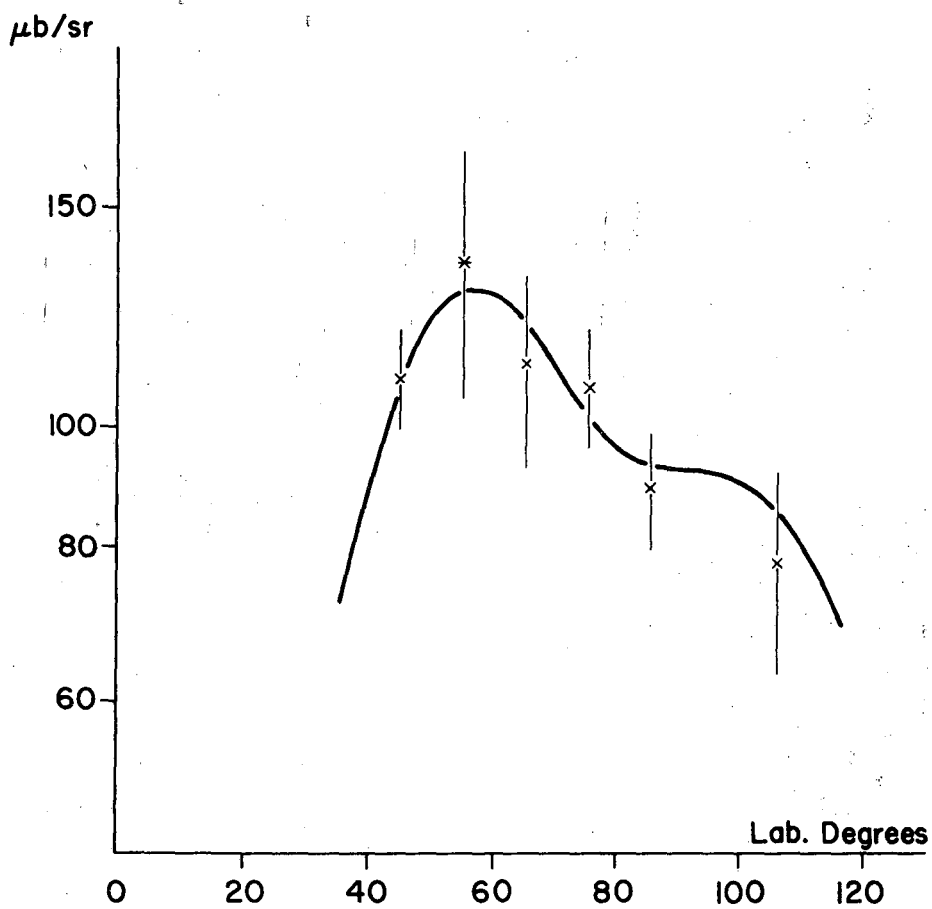
MUB-9610

La^{139} (d,p) La^{140}
Levels 39+40+41+42
— DWBA $\ell = 3$ Q = 1.4 MeV
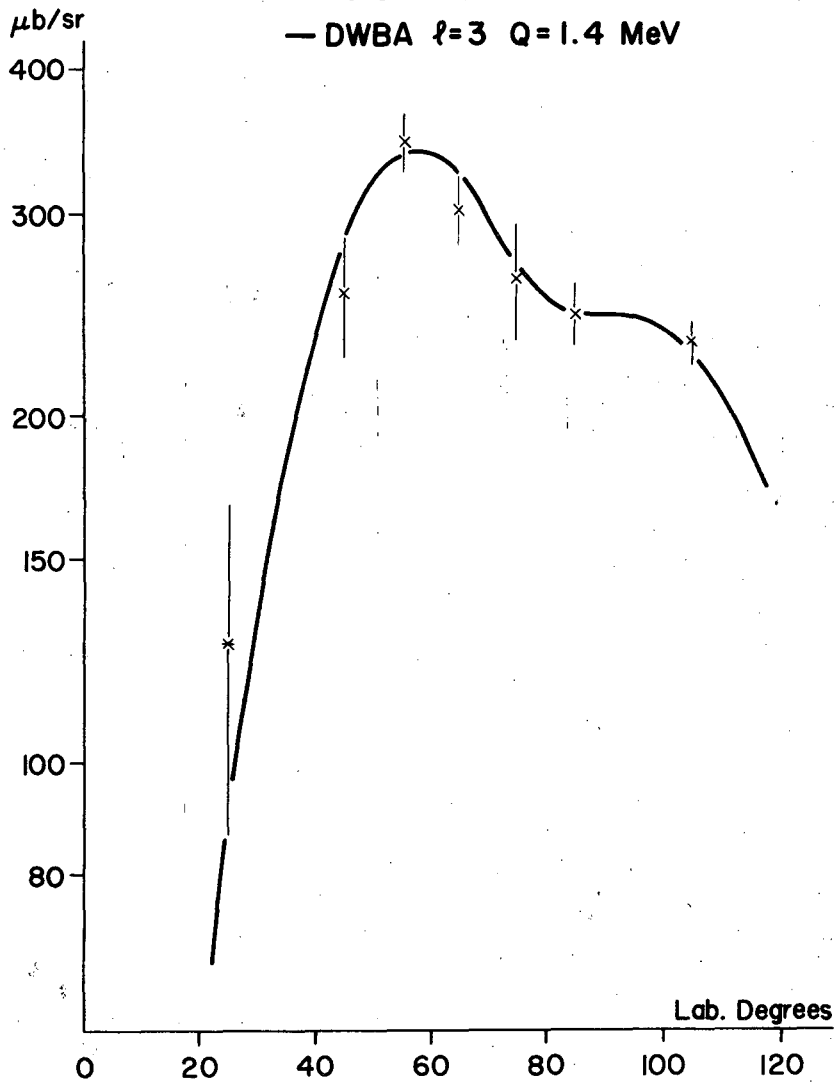
MUB-9611

La^{139} (d,p) La^{140}
Level 43
— DWBA $\ell = 3$ Q = 1.4 MeV

μb/sr
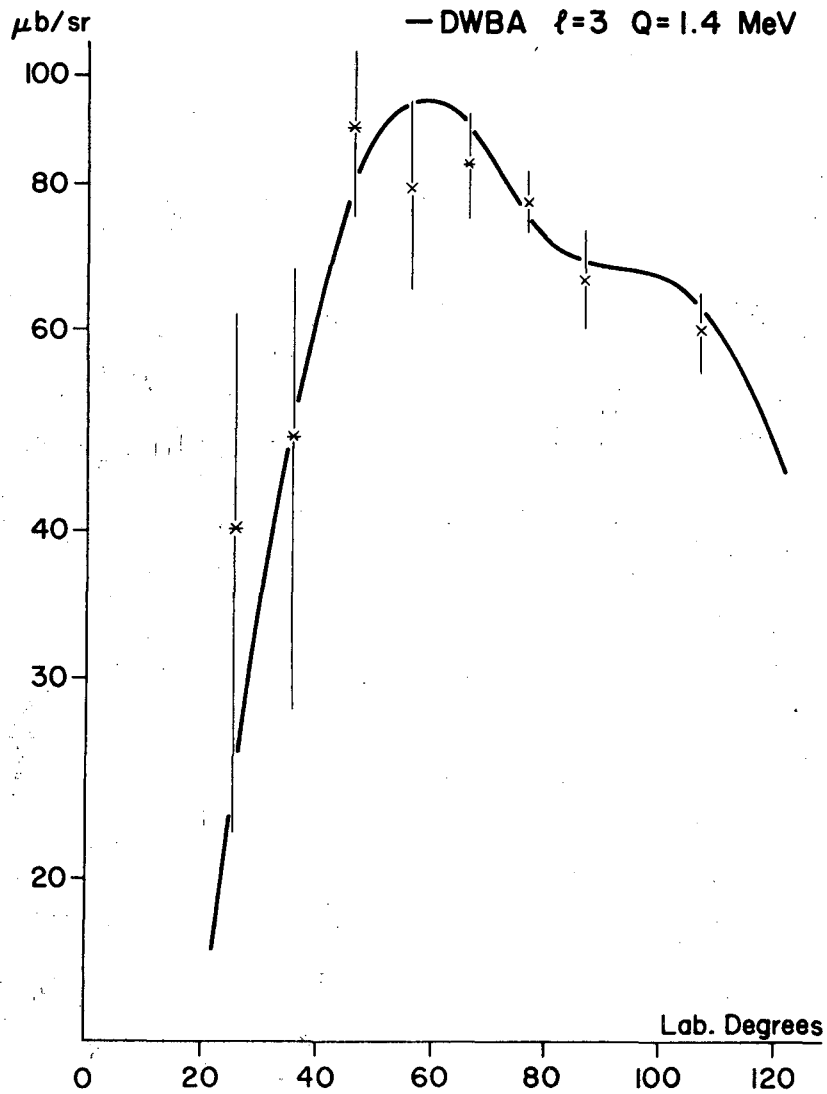
MUB-9612

La139 (d,p) La140
Levels 44+45+46+47+48
VoM ÷ DWBA ℓ=3 ΔQ=l.4 MeV
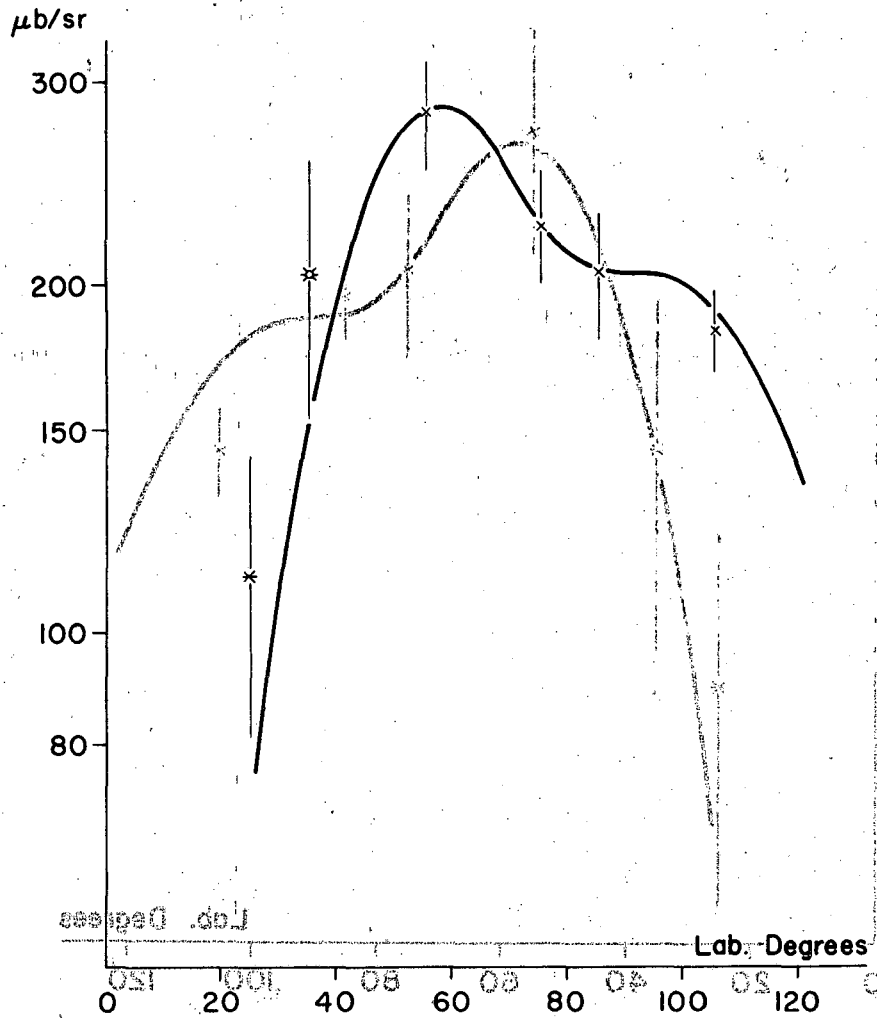
La^{139} (d,p) La^{140}

Levels 49+50+51

— DWBA $\ell=3$ Q=1.4 MeV
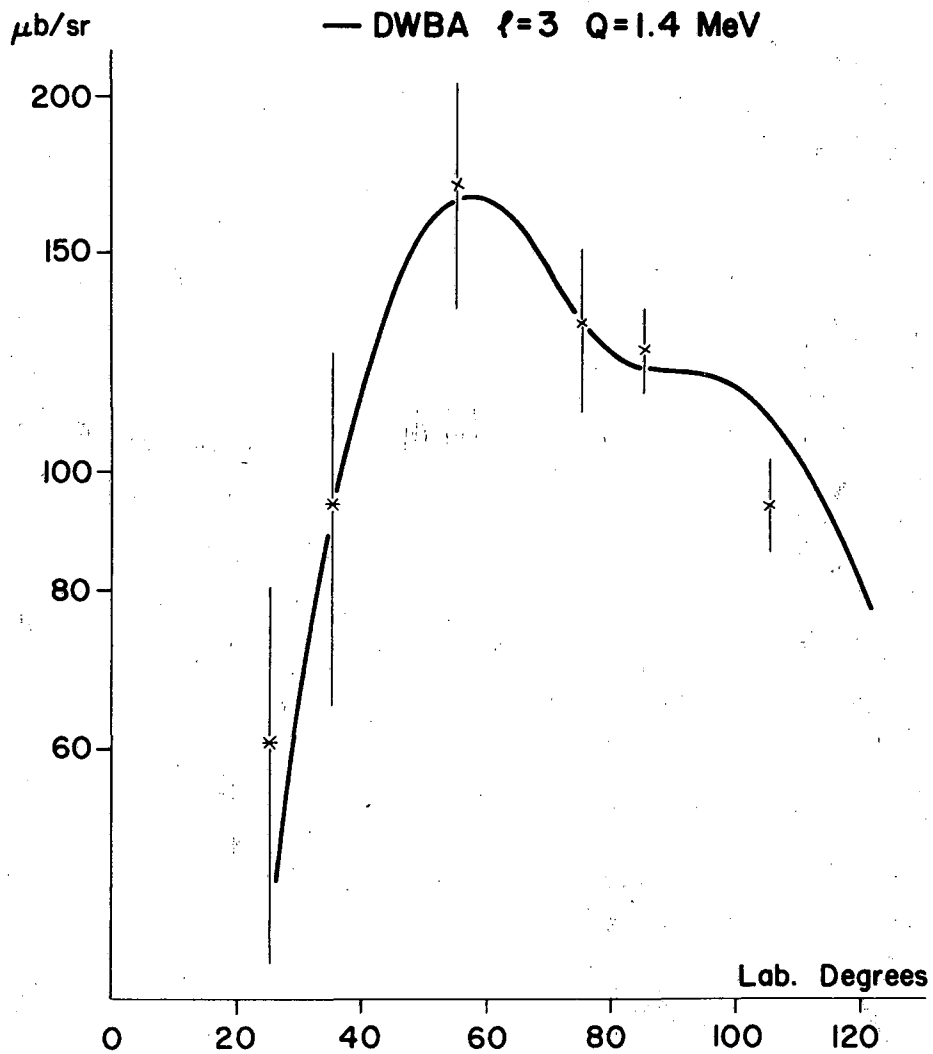
MUB-9614

La^{139} (d,p) La^{140}
Levels 53+54+55
— DWBA ℓ=3 Q=1.4 MeV
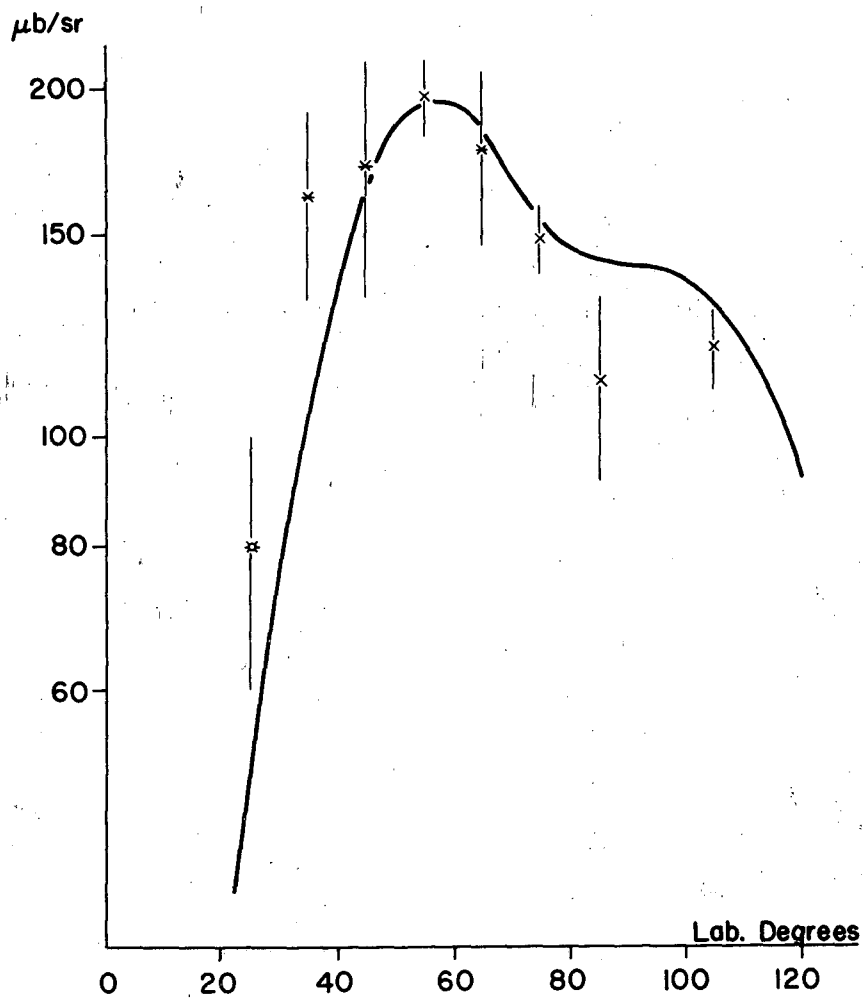
MUB-9615

La^{139} (d,p) La^{140}
Levels 56+57+58
—DWBA ℓ=1 Q=1.4 MeV

μb/ sr

200

150

100

80

60

Lab. Degrees

0   20   40   60   80   100   120
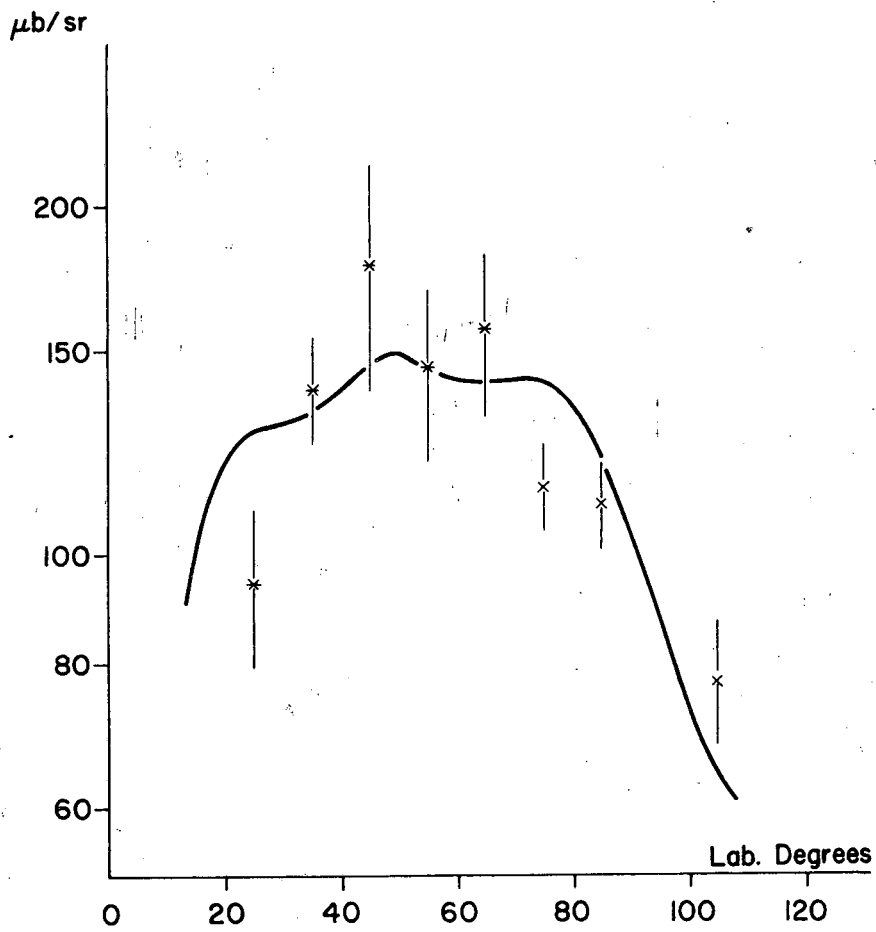
MUB-9616

La^{139} (d,p) La^{140}

Levels 59+60
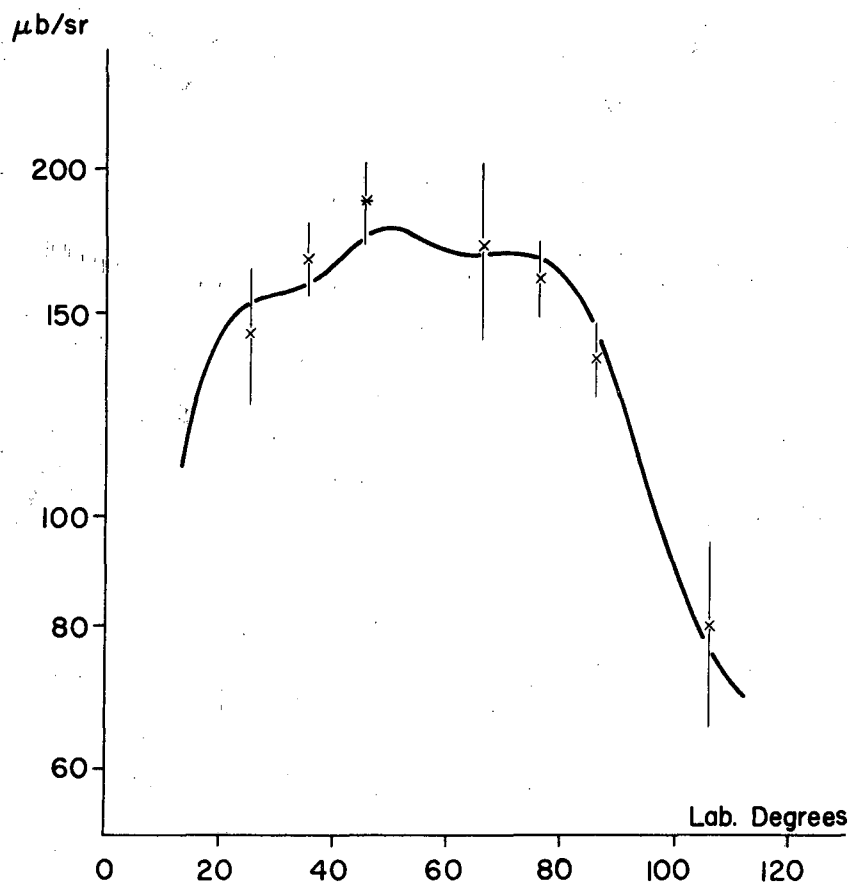
— DWBA $\ell = 1$ Q=1.4 MeV

MUB-9617

La^{139} (d,p) La^{140}
Levels 64+65
— DWBA ℓ=1 Q=1.4 MeV

MUB-9618

ℓ	Jπ		ℓ		ℓ
930			1493 3		1858
913			1479 3		1844
794			1461 3		1826
772 1			1444 3		1810
745 1			1432 3		1795 1
712 1			1418 3		1778 1
658 1			1403 3		1758
602 1			1388		1742
579 (3) 0-			1370		1730
467 3 1-			1352 (3)		1718 1
319 (3) 3-			1343 (3)		1702 1
284 3 7-			1328		1685 (1)
161 3 2-			1312		1673 (1)
106			1295		1657 (1)
93			1280		1644 (3)
63 3 4-			1262		1630 (3)
49 3 6-			1246		1617 (3)
37 3 5-			1227		1600
30 3 2-			1212		1584 3
0 3 3-			1192		1569 3
			1169		1555 3
			1149		1529 3
			1137		1519 3
			1118 1		1508 3
			1102 1		
			1077 1		
			1057 1		
			1036 1		

La^{140} - Level Scheme from this work
(Energies in KeV)