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Publication Date
1971-09-01

Submitted to Physics Letters B

LBL-227
Preprint c.2

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September 1971

AEC Contract No. W-7405-eng-48

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STRONG AND WEAK 0^+ EXCITATIONS IN THE $^{142}Ce(p,t)^{140}Ce$ AND $^{140}Ce(p,t)^{138}Ce$ REACTIONS*

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September 1971

The 0^+ level structure of ^{140}Ce and ^{138}Ce as revealed by the $^{142}Ce(p,t)$ and $^{140}Ce(p,t)$ reactions is reported. Comparisons are made to a model which mixes the anharmonic pair vibration with "two multipole-phonon" 0^+ excitations and "one-phonon" 0^+ proton configurations.

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During the past few years much theoretical and experimental work has been directed at the pair vibrational concept. In the region of closed neutron shells for $A \geqslant 90$, (p,t) experiments [1] have revealed frequent deviations from the uncoupled-harmonic (u.h.) pair vibrational (p.v.) model [2-4]. These deviations are apparent in the p.v. excitation energy and its transition strength relative to the neighboring N-2 ground state transition which it would equal in the u.h. model. However, recent theoretical calculations in the Zr (N = 50) region [5] have shown that these deviations can, in large part, be understood by

*Work performed under the auspices of the U. S. Atomic Energy Commission.

coupling the anharmonic p.v. to other nuclear states characterized by $J^{\Pi} = 0^{+}$. These states included quadrupole pair vibrations [3], two-multipole excitations such as $(2^{+} \otimes 2^{+})_{0^{+}}$, and admixtures of a 0^{+} proton two-quasiparticle configuration with the neutron p.v. The purpose of this letter is to test the coupled-anharmonic (c.a.) p.v. description at N = 82 by checking its consistency with the 0^{+} structure observed in the $^{142,140}Ce(p,t)$ experiments.

The reactions used a 30.3-MeV proton beam prepared by the Berkeley 88-inch cyclotron high resolution beam line [6]. Self-supporting metallic foils of ^{142}Ce (0.400 mg/cm^{2}) and ^{140}Ce (0.790 mg/cm^{2}) were prepared. The ^{142}Ce target had 10% ^{140}Ce impurity; uncertainties in the target thicknesses are ±15%. Reaction particles were detected in Si detectors and identified in a Goulding-Landis ΔE-E particle identifying system [7]. Resulting ^{140}Ce and ^{138}Ce spectra are shown in figs. 1(a) and 1(b). We had energy resolutions (FWHM) of 30 keV in ^{140}Ce and 55 keV in ^{138}Ce. We were able to identify 46 discrete peaks in ^{140}Ce and 22 peaks in ^{138}Ce. Differential cross-sections were extracted for most of these, but for the remainder of this discussion we will be concerned only with those states characterized by $J^{\Pi} = 0^{+}$.

The 0^{+} assignments are made on the basis of the familiar L = 0 (p,t) angular distributions. These angular distributions are given in figs. 2(a) and 2(b) for ^{140}Ce and ^{138}Ce, respectively. Five such states are found in ^{140}Ce at $E_x < 6.36$ MeV. The ground state and 3.23 MeV levels are most strongly populated. The latter state has been interpreted [8] as the anticipated p.v. state. The 1.90 MeV and 3.03 MeV states are weak, but the differential cross sections are reliably extracted. Extraction of the 5.57 MeV differential cross section in ^{140}Ce was hampered by background and a ^{138}Ce contaminant peak. The shape does suggest a 0^+ assignment for this state. Two 0^+ states in ^{138}Ce have been found at $E_x < 3.62$ MeV. The ground state is strongly populated while the 2.32 MeV 0^+ level is comparatively weak. The solid lines in fig. 2 are two-nucleon transfer DWBA calculations [9] which use structure amplitudes derived from wave functions that are to be described. Proton [10] and triton [11] optical model parameters are taken from the literature. The DWBA calculations are normalized to the 35° point (lab angle) of the ^{142}Ce(p,t)^{140}Ce (3.23 MeV) transition. Generally, the DWBA fits are good.

We now describe a coupling model which attempts to understand the deviations of harmonic theory from experimental results. The calculations are quite similar to those performed in the Zr case [5], and we summarize that work in relation to the Ce experiments. The collective boson wave functions used to describe the ground states (0_+ or 0_- in our notation) of neighboring nuclei and the p.v. (0_-0_+) are calculated by a boson expansion method [12,13] using the Tamm-Dancoff basis (TDA). The neutron Hamiltonian is of the form

$$H_{sp} + H_p = \sum_j \varepsilon_j N_j - \sum_{jj'} G_{jj'} P_j^+ P_{j'}$$

with

$$P_j^+ = \frac{1}{2} \sum_m a_{j\tilde{m}}^+ a_{jm}^+ \quad .$$

The residual pairing interaction is often represented by a constant matrix element $G_{jj'} = G$ that is inversely proportional to the nuclear mass. In order to extract pairing matrix elements that reproduce the experimental mass differences, which are corrected for effects other than pairing [22], we introduce different pairing force matrix elements for configurations below and above the closed shell [5,22]. Three parameters were adjusted, G_{11} for pairs in configurations above N = 82, G_{22} for pairs below N = 82 and finally G_{12} for interactions between a pair below and a pair above N = 82. Anharmonicities then correspond to all terms of the pairing force which are not taken into account in the TDA. Neutron pairing strengths G_{11} = 0.127, G_{22} = 0.197 and G_{12} = 0.155 MeV are found to fit the ground state mass differences of all stable Ce isotopes within experimental uncertainties. The method also yields predictions for non-collective 0^+ states. These latter states are calculated in harmonic approximation only [12], and these are represented in our notation as $(0'_\pm)$.

The residual quadrupole interaction may have a dramatic effect on the p.v. energy in the c.a. calculation [3]. Spin-parity 2^+ assignments in ^{138}Ce at 0.796 MeV and 1.510 MeV can be made from (p,t) angular distributions [8] and from a study of ^{138}Pr decay [14]. The ^{138}Pr decay study also revealed a 0^+ state at 1.477 MeV which if weakly populated in the (p,t) reaction would not have been resolved from the nearby 2^+ level in our experiment. The two-neutron hole 2^+ configuration corresponding to the 0.79 MeV level (2_- in our notation) in ^{138}Ce is expected to combine in the u.h. approximation with the two-neutron particle configuration corresponding to the 0.64 MeV 2^+ state (2_+) in ^{142}Ce. The result would be a J = 0 to 4 multiplet (2_-2_+) at E_x(u.h.) = 5.33 MeV in ^{140}Ce. In the c.a. theory a strong splitting between the (0_-0_+) and $(2_-2_+)_{0^+}$ states [15] accounts for the energy depression of the u.h. p.v.

The next step in the calculation involves the two multipole-phonon surface vibrations. One-phonon multipole vibrations, a 2^+ (1.59 MeV) and 3^- (2.46 MeV), have been seen in the ^{140}Ce(α,α') [17] and ^{140}Ce(p,p') [18] experiments. Thus one could expect 0^+ states in ^{140}Ce at 3.18 MeV with $(2^+ \times 2^+)_{0^+}$ configuration and at 4.92 MeV with $(3^- \times 3^-)_{0^+}$ configuration if the harmonic phonon model were accurate. A random-phase approximation (RPA) calculation analogous to ref. 5 is carried out in order to derive wave functions for the two-multipole phonon states. These wave functions do not have the coherence properties which could provide (p,t) transition strength of the observed magnitude, e.g. for the 3.03 MeV level in ^{140}Ce.

As a plausible explanation for the experimentally observed distribution of L = 0 strength we consider the admixture of the two-multipole surface vibrations mentioned above and the p.v. The mixing amplitudes are calculated [5] by diagonalizing the Hamiltonian

$$H = H_{sp} + H_p + H_2 + H_3 \quad ,$$

in an orthogonal basis constructed from the p.v. (0_-0_+), the two-multipole phonon states $(2^+)^2_{0^+}$ and $(3^-)^2_{0^+}$, the state $(2_-2_+)_{0^+}$, and four proton states described in the following paragraph. H_{sp} is the single-particle part derived from one-nucleon transfer experiments [19]. H_p is the pairing force of which the neutron part was described above, and H_λ (λ = 2,3) the separable multipole forces.

Another 0^+ state in ^{140}Ce which is sharing two-nucleon transfer strength is the 1.90 MeV state. This level may be analogous to the 1.76 MeV 0^+ state in ^{90}Zr, i.e., it appears to be a two-quasi-particle proton configuration orthogonal to the ^{140}Ce ground state. The 1.90 MeV state was observed with a weak spectroscopic factor in the ^{141}Pr(d,^{3}He)^{140}Ce experiment and was not seen in the ^{139}La(^{3}He,d)^{140}Ce reaction [20]. Four proton states of two quasi-particle nature appear below 6 MeV in an RPA diagonalization [21] of a proton pairing force of strength $G_p = 0.201$ MeV (the same as was used to define the superfluid proton basis for the RPA diagonalization of the 2^+ and 3^- states). They couple weakly to the $(2^+)^2_{0^+}$ and $(3^-)^2_{0^+}$ states and only in second order with the p.v. The proton quasi-particle states are all included in the admixture calculation outlined above. Reference 5 indicated that to be successful in describing the experimental transition strength to states of proton nature one may have to add proton-neutron pairing forces. The proton-neutron parts of the multipole forces by themselves do in the present case explain the distribution of (p,t) strength among low-lying ^{140}Ce states. However, the energy of the proton "one-phonon" state is predicted too high (possibly due to inadequacies in the proton s.p. energies), so the (p,t) strength acquired by coupling may be overestimated.

The 5.57 MeV level in ^{140}Ce has about the same additional energy compared to the p.v. as the 2.32 MeV level in ^{138}Ce has above its ground state, and the (p,t) transition strengths are equal. It therefore appears natural to associate the 5.57 MeV level with the configuration $(0'_-0_+)$ corresponding to the noncollective state $(0'_-)$ at 2.32 MeV in ^{138}Ce. The $(0'_-0_+)$ and $(2_-2_+)_{0^+}$ states are predicted in the c.a. theory to be very close in energy, and they therefore mix although their coupling matrix element is small. Their calculated, summed (p,t) strength exceeds the 0^+ strength actually observed in this excitation region. However, unresolved moderately weak L = 0 (p,t) strength between 6 and 7 MeV excitation energy could be present.

Experimental and theoretical results are summarized in fig. 3. The experimental (p,t) cross sections are normalized to the 3.23 MeV state which is associated with the p.v. in ^{140}Ce and the resulting relative strengths are given in large figures. This method of normalization is chosen in order to facilitate the comparison with the coupling calculation results which are normalized to the theoretical p.v. The calculated ground state cross-sections are then overestimated. Using a different set of optical model parameters still based on the average parameters of refs. 10 and 11, the A = 140 and A = 138 ground state cross sections reduced to 149 and 163 with a poorer fit to the angular distributions. In addition to optical model parameter ambiguities, other reasons for the over-estimated ground state cross sections could be slightly incorrect ratios of particle and hole (p,t) amplitudes or slightly incorrect amounts of pairing anharmonicities. Furthermore, the possible inadequacy of the Woods-Saxon form factors with fixed binding energy used in the DWBA calculations [9] should be kept in mind. We performed a separate calculation using harmonic oscillator form factors asymptotically matched to Hankel functions [23]. In this case the ratio of the ^{140}Ce (g.s.) cross section to the ^{140}Ce (3.23 MeV) cross section increases by 20% relative to the Woods-Saxon calculation. Similarly, the ratio of ^{138}Ce (g.s.) cross section to ^{140}Ce (3.23 MeV) cross section increases by 14%. Optical model parameters were held constant in this analysis.

To the right of experimental levels in fig. 3 known J^{Π} values are given. To the left of the calculated states are the J-values of the quanta of hole pairs (minus suffix), particle pairs (plus suffix) or "one-phonons" on which numerical suffices indicate a proton two-quasi-particle state. For ^{140}Ce both the u.h. and c.a. pictures are given. In the c.a. case the dashed line connecting a given state with a u.h. state intends to show the dominant configuration in the c.a. wave function. As an energy scale the (p,t) Q-value relative to that of the ^{142}Ce(p,t)^{140}Ce (g.s.) is used in order to emphasize the significant energy shift of the Q-value for the (0_-0_+) pair vibration state away from ^{138}Ce (g.s.) = (0_-) and of the ^{142}Ce (g.s.) = (0_+) away from ^{140}Ce (g.s.) = (0). Both Q-values are reproduced by theory.

Summarizing, the (p,t) reactions on the ^{142}Ce and ^{140}Ce isotopes has revealed, as in most previous cases for $A \geq 90$ [1], a $J^{\pi} = 0^+$ level structure that deviates significantly from harmonic p.v. theory. However the described model calculation seems able to explain the redistribution of (p,t) strength from the harmonic p.v. to a number of low-lying states, to give a plausible reason for the large energy shift of the p.v. and for the occurrence of two 0^+ levels in ^{140}Ce (p,t) below the p.v. The 5.57 MeV state is likely to represent the first finding of a pair-analogue of a noncollective state that was predicted in ref. 12.

We would like to thank P. D. Kunz for use of his two-nucleon transfer version of the code DWUCK, and C. Maples for the use of the program LORNA which was used to establish energy scales in our spectra.

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renormalized interaction for this matrix element would destroy the whole spectrum, whereas the remaining matrix elements could be taken with either force prescription without qualitative changes in spectrum or (p,t) cross sections.

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Figure Captions

Fig. 1. Spectra of $^{142,140}Ce(p,t)$ reactions taken at $E_p = 30.3$ MeV.

Fig. 2. Differential cross-sections for L = 0 transitions and DWBA calculations using the coupled-anharmonic theory. A single normalization factor is used.

Fig. 3. Summary of calculated and experimental energies and (p,t) cross sections compared at the peak near 35° for the selected states considered.

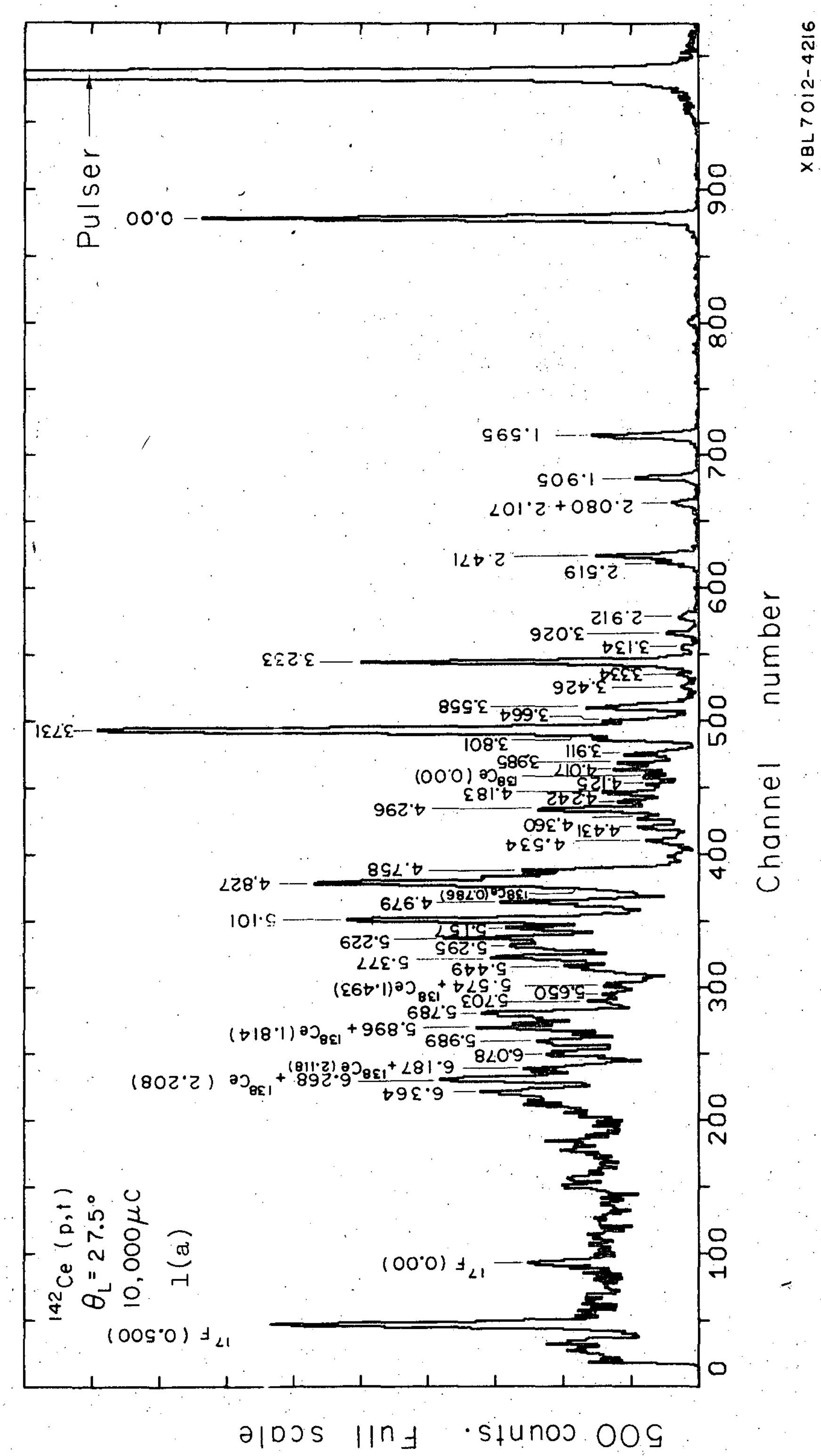
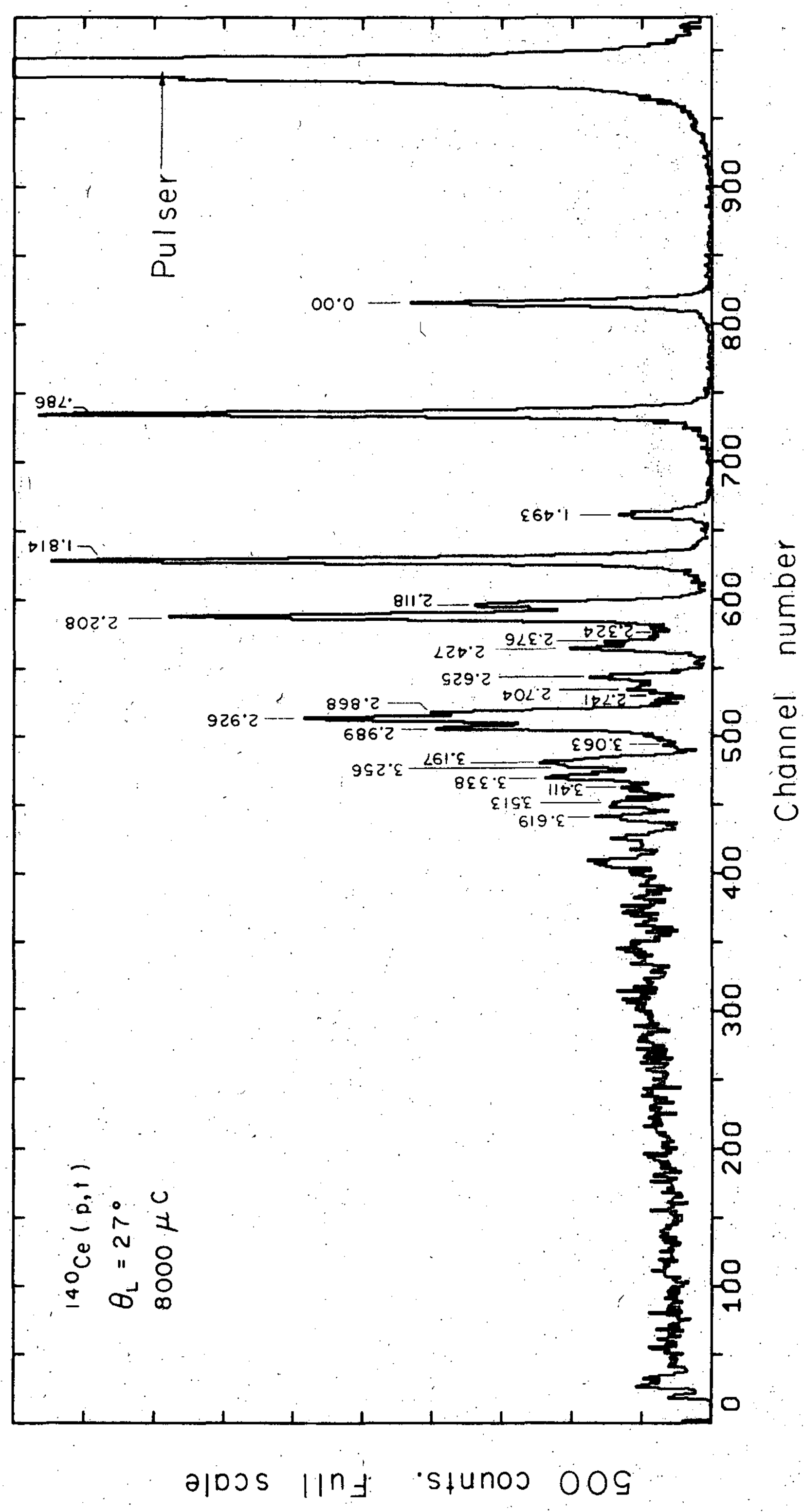
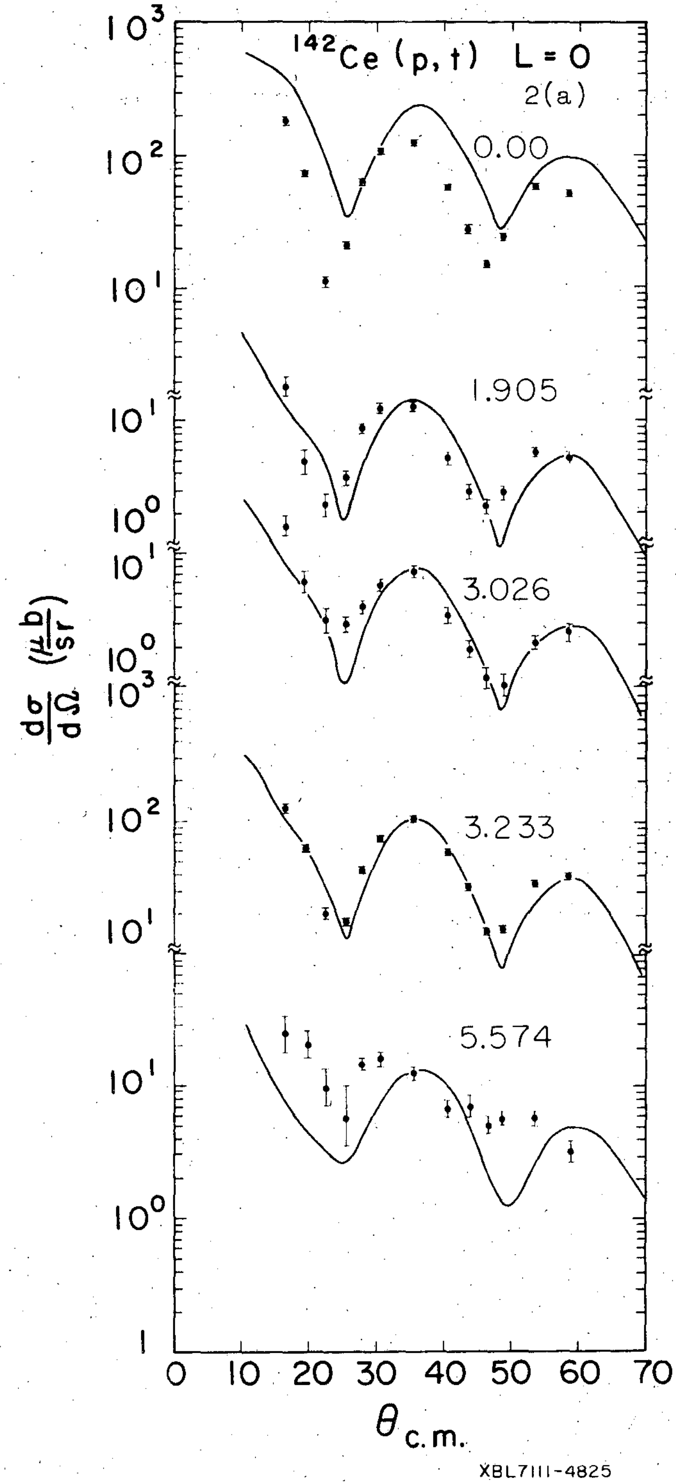

500 counts. Full scale
Channel number
^{142}Ce (p,t)
θ_L = 27.5°
10,000 μC
1(a)
^{17}F (0.500)
^{17}F (0.00)
6.364
6.268 + ^{138}Ce (2.208)
6.187 + ^{138}Ce (2.118)
6.078
5.989
5.896 + ^{138}Ce (1.814)
5.789
5.703
5.650
5.574 + ^{138}Ce (1.493)
5.449
5.377
5.295
5.229
5.157
5.101
4.979
^{138}Ce (0.786)
4.827
4.758
4.534
4.431
4.360
4.296
4.242
4.183
4.125
^{138}Ce (0.00)
4.017
3.985
3.911
3.801
3.731
3.664
3.558
3.426
3.334
3.233
3.134
3.026
2.912
2.519
2.471
2.080 + 2.107
1.905
1.595
0.00
Pulser
0 100 200 300 400 500 600 700 800 900
XBL 7012-4216

Fig. 1(a)



XBL7012-4215

Fig. 1(b)



^{142}Ce (p, t) L = 0
2(a)
0.00
1.905
3.026
3.233
5.574
10^3
10^2
10^1
10^0
1
0 10 20 30 40 50 60 70
$\frac{d\sigma}{d\Omega}$ ($\frac{\mu b}{sr}$)
$\theta_{c.m.}$
XBL711-4825

Fig. 2(a)

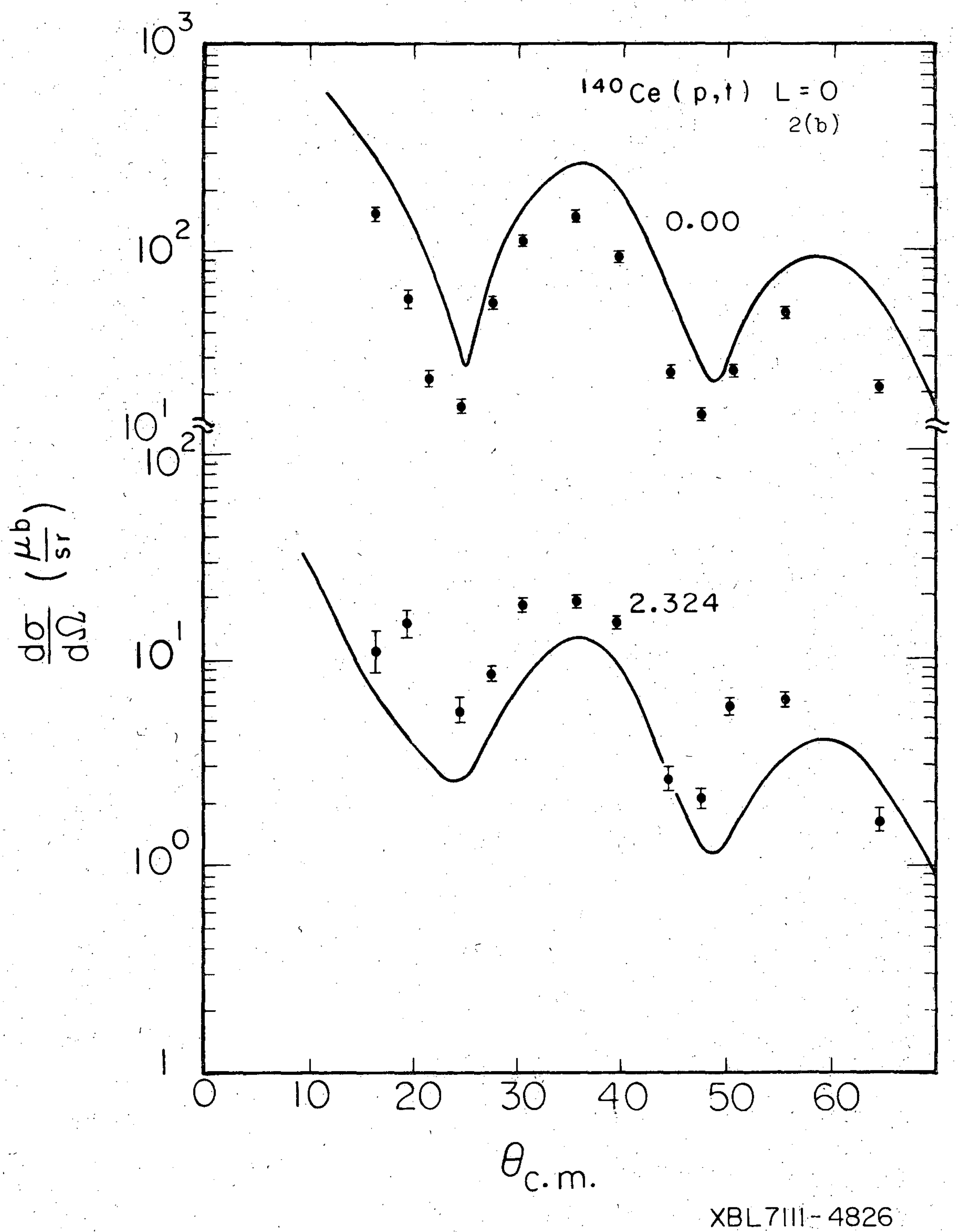

^{140}Ce (p,t) L = 0
2(b)
0.00
2.324
10^3
10^2
10^1
10^2
10^1
10^0
1
$\frac{d\sigma}{d\Omega}$ $(\frac{\mu b}{sr})$
0
10
20
30
40
50
60
$\theta_{c.m.}$
XBL7111-4826

Fig. 2(b)

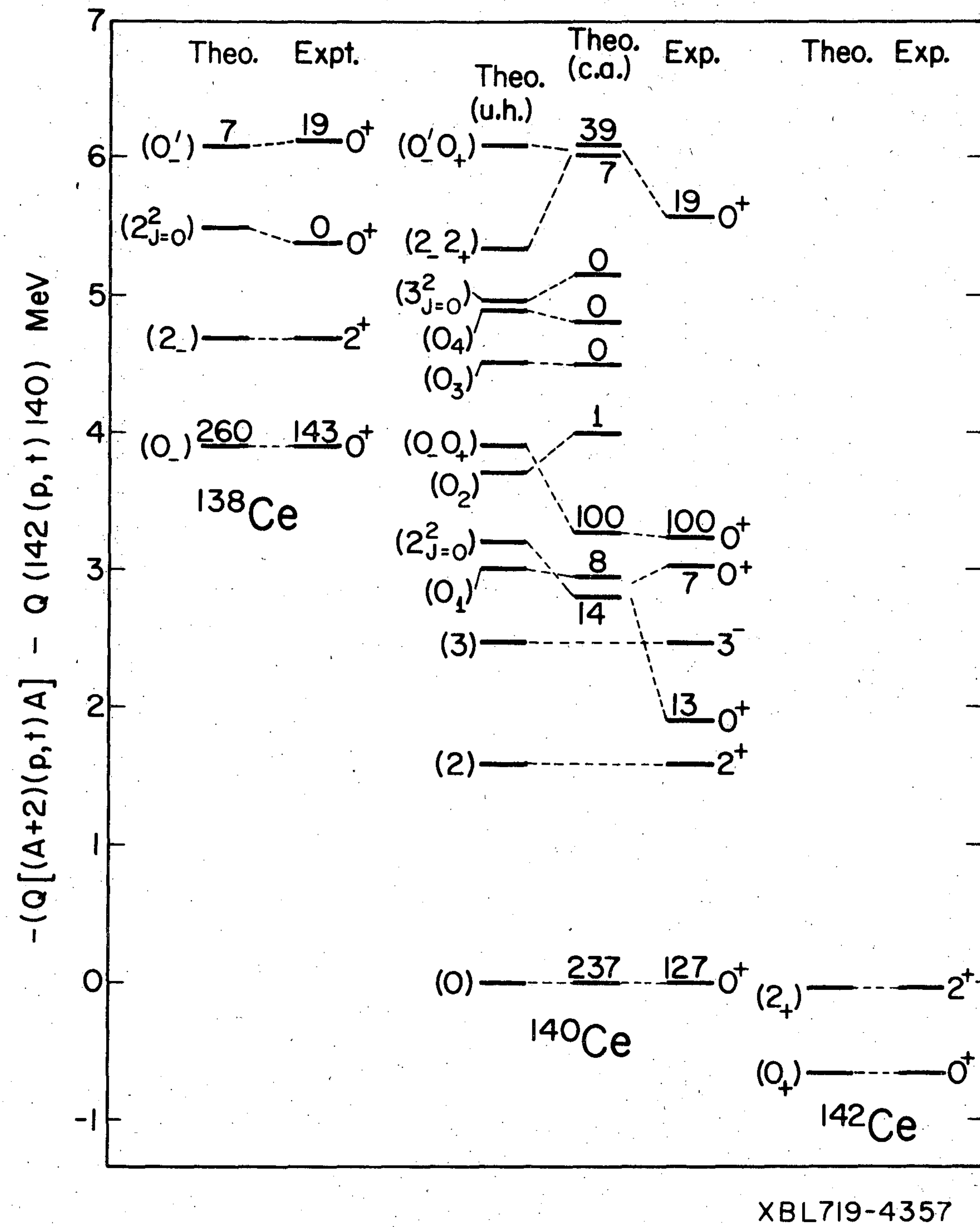

Theo. Expt.
Theo. (u.h.)
Theo. (c.a.)
Exp.
Theo. Exp.
-(Q[(A+2)(p,t)A] - Q(142(p,t)140) MeV
138Ce
140Ce
142Ce
XBL719-4357

Fig. 3