Title

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DISCLAIMER

OBSERVATION OF HIGH-LYING LEVELS IN ^{8}Be FROM ALPHA-ALPHA ELASTIC SCATTERING*

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Abstract:

The elastic scattering of alpha particles from helium-4 has been measured in the energy range between 30 and 70 MeV. A phase-shift analysis was used to investigate the even-spin, positive-parity levels in ^{8}Be in the region between 15 and 35 MeV of excitation. New 0^+ and 4^+ levels have been located near 20.3 MeV and 25.6 MeV respectively. The positions of five 2^+ levels and an additional 4^+ level are compared to previous work and to theoretical predictions based on the intermediate-coupling shell model.

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Below an excitation energy of 16 MeV, the level structure of ^{8}Be is well-understood[1,2] in terms of states predominantly of a two-alpha-particle configuration. Above 16 MeV the level structure rapidly becomes more complex as other configurations for these states (e.g. p+^{7}Li, n+^{7}Be, and d+^{6}Li) become important. Those states of ^{8}Be which have both even spin and parity can decay into the 2α channel, and this selectivity is extremely useful in identifying levels of ^{8}Be that lie above the ^{7}Li + p threshold. Although multi-level

R- and S-matrix analyses of $^{7}Li(p,\alpha)^{4}He$ (Ref. 3) and $^{6}Li(d,\alpha)^{4}He$ (Ref. 4) data have provided some level assignments between excitation energies of 19 and 26 MeV in ^{8}Be, these assignments are not unique. However, any state with a significant alpha-particle width will appear as a resonance in α-α elastic scattering, which permits immediate assignment of spin and parity from a determination of the resonant partial wave. Earlier studies of the elastic scattering provided some information on ^{8}Be states above 16 MeV;[5] however, it was clear that more detailed measurements were required in order to remove ambiguities in the phase-shift analysis. We report here new results which are already apparent from a phase-shift analysis of more extensive elastic scattering measurements.

The present measurements were performed with alpha-particle beams from the Berkeley 88-inch cyclotron using a beam analysis system[6] which provided a high resolution beam ($\Delta E/E \approx 0.02\%$) of accurately-known[7] energy (±0.03%). Measurements were taken at about 100 energies between 30 and 70 MeV (spanning a region of excitation in ^{8}Be between 15 and 35 MeV). An array of seven detectors was used to obtain cross sections at 21 center-of-mass angles between 16° and 96°. The ^{4}He gas target with a thin (7500 Å) nickel entrance foil was operated at a pressure of 0.1 atm. The relative errors are typically less than ±2%, while the absolute normalization of the cross section is accurate to better than 4%.

A standard χ^2 minimization search routine was employed to determine phase shifts including $\ell = 8$ at the higher energies. A small $\ell = 6$ phase shift ($\approx 2°$) was required at the lowest energies. Continuity of the phase shifts as a function of energy was required for an acceptable solution. This criterion was particularly useful in regions where the level structure was most complex, e.g. near E_α = 40 MeV where three resonances overlap. Numerous attempts to locate alternate solutions were unsuccessful. Phase shifts corresponding to the only acceptable solution are presented in Fig. 1 as functions of the alpha-particle laboratory energy, E_α. The $^7Li(p,\alpha)$ and $^6Li(d,\alpha)$ reaction thresholds occur at E_α = 34.7 and 44.7 MeV respectively.

The $\ell = 0$ phase shift decreases monotonically between 30 and 38 MeV in a manner similar to Darriulat's previous work,[5] but the present values are 5-10° more positive. The resonant behavior centered around E_α = 40.7 MeV corresponds to a new 0^+ level in ^8Be near 20.3 MeV with a level width of less than 1 MeV. Since the resonant part of δ_0 passes through 0° at the resonance energy, the elasticity, Γ_α/Γ, is less than 1/2 (Ref. 9). The existence of a 0^+ level in this region of excitation has been predicted by intermediate-coupling shell model calculations.[10,11] Although the most recent multi-level analysis[3] of the $^7Li(p,\alpha)^4He$ reaction requires 0^+ levels at 19.7 and 21.8 MeV, the α-particle reduced widths obtained are so small that the calculated α-α, $\ell = 0$ phase shift does not show any trace of resonant behavior. This is in contradiction with our present result. Above E_α = 43 MeV there is no evidence for additional 0^+ levels. We observe a smooth decrease of δ_0 while η_0 decreases as absorption into the open reaction channels becomes more significant.

Five 2^+ levels are apparent in the $\ell = 2$ phase shifts shown in Fig. 1. The elastic resonances ($\Gamma_\alpha = \Gamma$) near 16.6 and 16.9 MeV excitation correspond to the isospin-mixed[2] doublet previously identified by Shield _et al._[5] The position of the next 2^+ level at 20.2 MeV excitation is also consistent with previous work.[3-5] The two remaining 2^+ levels near 22.2 and 25.2 MeV excitation have been located previously by the multi-level analyses. Additional evidence for the 2^+ spin assignments has come from studies of the $^6Li(\vec{d},\alpha)^4He$ reaction with polarized deuterons.[12] The phase shift behavior for the 25.2 MeV level shows it to have a small partial width for α-particles.

Two levels are prominent in an examination of the $\ell = 4$ phase shifts. The rapid rise of δ_4 at $E_\alpha = 40$ MeV corresponds to a 4^+ level near 19.8 MeV excitation in ^8Be. Since the resonant part of δ_4 goes thru $\pi/2$ and $\eta_4 \approx 0.92$ at the position of the resonance, $\Gamma_\alpha/\Gamma \approx 0.96$. The total width Γ, and hence Γ_α, is less than 1 MeV, which is at least a factor of 20 smaller than that corresponding to an α-particle reduced width equal to the Wigner limit. Hence, unless some other parentages (e.g. $^6Li + d$) are unexpectedly large,[10] the f-wave nucleon <u>reduced widths</u> for this state are not as small as suggested,[3] but the nucleon <u>partial widths</u> are small because of the small f-wave penetration factors. The broad 4^+ resonance near $E_\alpha = 51.3$ MeV corresponds to a new level in ^8Be near 25.6 MeV excitation. We find no evidence for an additional 4^+ state at 27.5 MeV with a width of approximately 1 MeV as was previously assigned by Clark <u>et al.</u>[13] on the basis of the behavior of the coefficients of Legendre polynomial fits to $^6Li(d,\alpha)^4He$ cross-section angular distributions.

The behavior of the $\ell = 6$ phase shift is also shown in Fig. 1. The gradual increase in δ_6 from about 2° at 30 MeV to about 30° at 70 MeV is in reasonable agreement with previous work,[8] and it corresponds to an attractive interaction in this energy range.

In order to compare our results with those of previous studies, Fig. 2 contrasts our level scheme derived from the α-α phase shifts with schemes based on analyses of the $^7Li(p,\alpha)^4He$ reaction[3] and the $^6Li(d,\alpha)^4He$ reaction.[4] Since, for the present discussion, this comparison is intended to be qualitative in nature, an indication of the widths of the various reported levels has been omitted. For the level scheme based on the $^6Li(d,\alpha)^4He$ reaction, three combinations (each consisting of three levels) which produce acceptable results have been joined by a vertical dashed line.[14] In addition we include some predictions based on intermediate-coupling shell model calculations fitted to the observed properties of nuclei with masses in the range A = 6-9.

The 2^+ states at 16.6 and 16.9 MeV are seen to correspond closely with the shell-model prediction of two levels at 16.8 MeV (J = 0, T = 0) and 16.9 MeV (0,1). The isospin mixing of these levels has been discussed by Barker.[2] The new 0^+ state near 20.3 MeV may be identified with the lowest 0^+ state predicted to lie at 19.8 MeV[10] or at 23.6 MeV.[11] Other levels can be matched to the three observed 2^+ levels and to the 4^+ levels observed at 19.8 and 25.6 MeV, but more detailed comparisons must await a more formal extraction of level parameters, which is in progress. These results will be reported in a future publication.

The comparison with the results of multi-level fits to the $^7Li(p,\alpha)^4He$ and $^6Li(d,\alpha)^4He$ reactions is less satisfactory. It seems clear that, due to the non-zero spin in the entrance channel and the resulting large number of parameters which can be varied, the multi-level analyses of these reaction data are at present unable to produce reliable level assignments. It is of particular interest now to investigate whether the present assignments based on elastic scattering measurements will be able to explain adequately the reaction data.

The contributions to this work of the entire 88-inch cyclotron operating crew are greatly appreciated.

FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Nuclear phase shifts, δ_ℓ, and inelastic parameters, η_ℓ, derived from α-α elastic scattering, for the ℓ = 0, 2, 4, and 6 partial waves. The S-matrix element is $S_\ell = \eta_\ell \exp(2i\delta_\ell)$. The excitation energy in ^{8}Be is $E_\alpha/2 - 0.091$ MeV.

Fig. 2. Comparison of level positions for the even-spin, positive parity states in ^{8}Be between 15 and 30 MeV excitation. (a) ^{6}Li(d,α)^{4}He, Refs. 4 and 13. The (2, 0, 2) sequence is from Freeman and Mani, the (2, 4, 2) and (0, 4, 2) from Tsan et al., and the 4^+ level at 27.5 is from Clark et al. (b) ^{7}Li(p,α)^{4}He, Ref. 3. (c) Present work, α-α elastic scattering. (d) T = 0 levels from shell-model calculations by Barker[10] (left) and Kumar[11] (right).

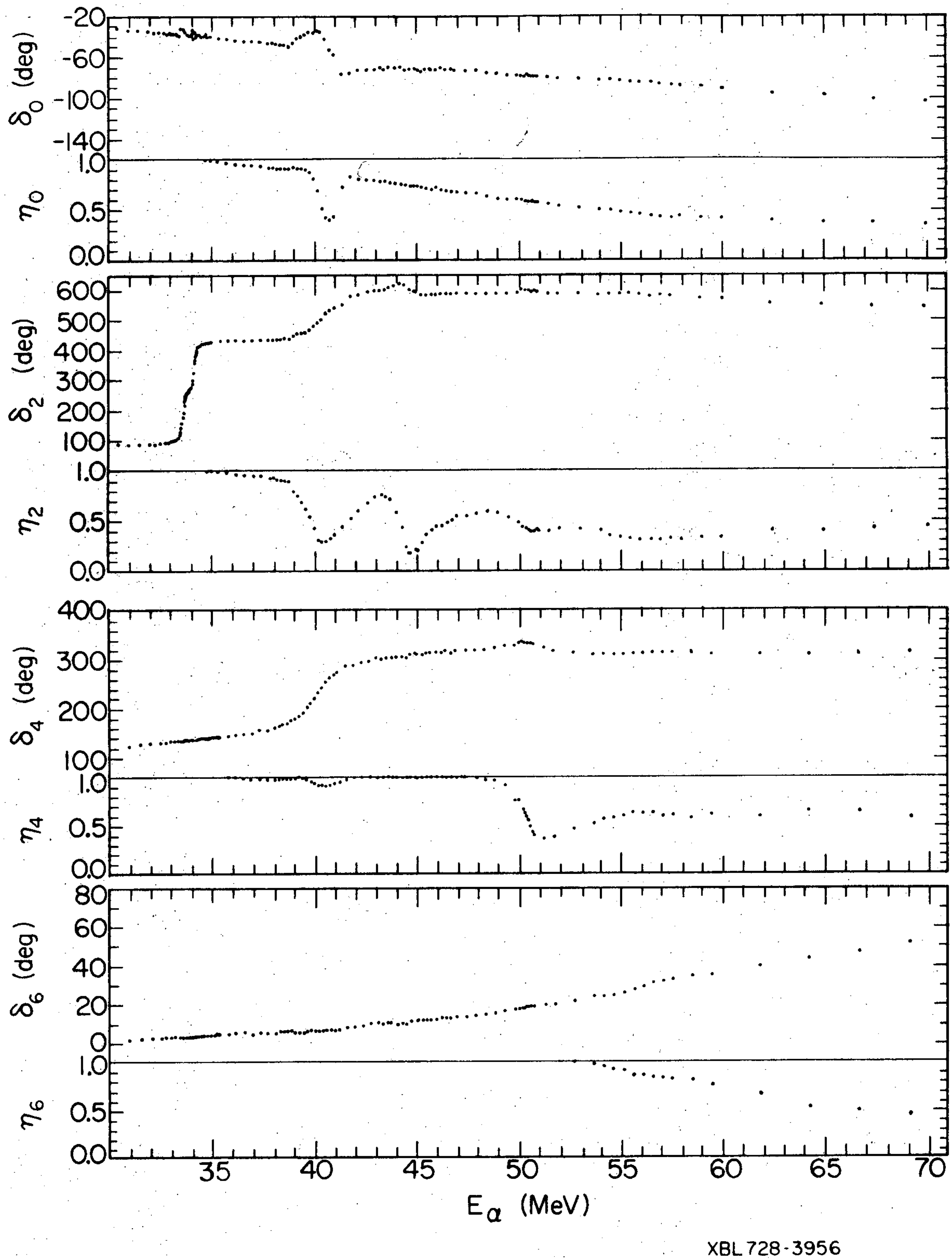
δ0 (deg)
-20
-60
-100
-140
η0
1.0
0.5
0.0
δ2 (deg)
600
500
400
300
200
100
η2
1.0
0.5
0.0
δ4 (deg)
400
300
200
100
η4
1.0
0.5
0.0
δ6 (deg)
80
60
40
20
0
η6
1.0
0.5
0.0
35
40
45
50
55
60
65
70
Eα (MeV)
XBL 728-3956

Fig. 1

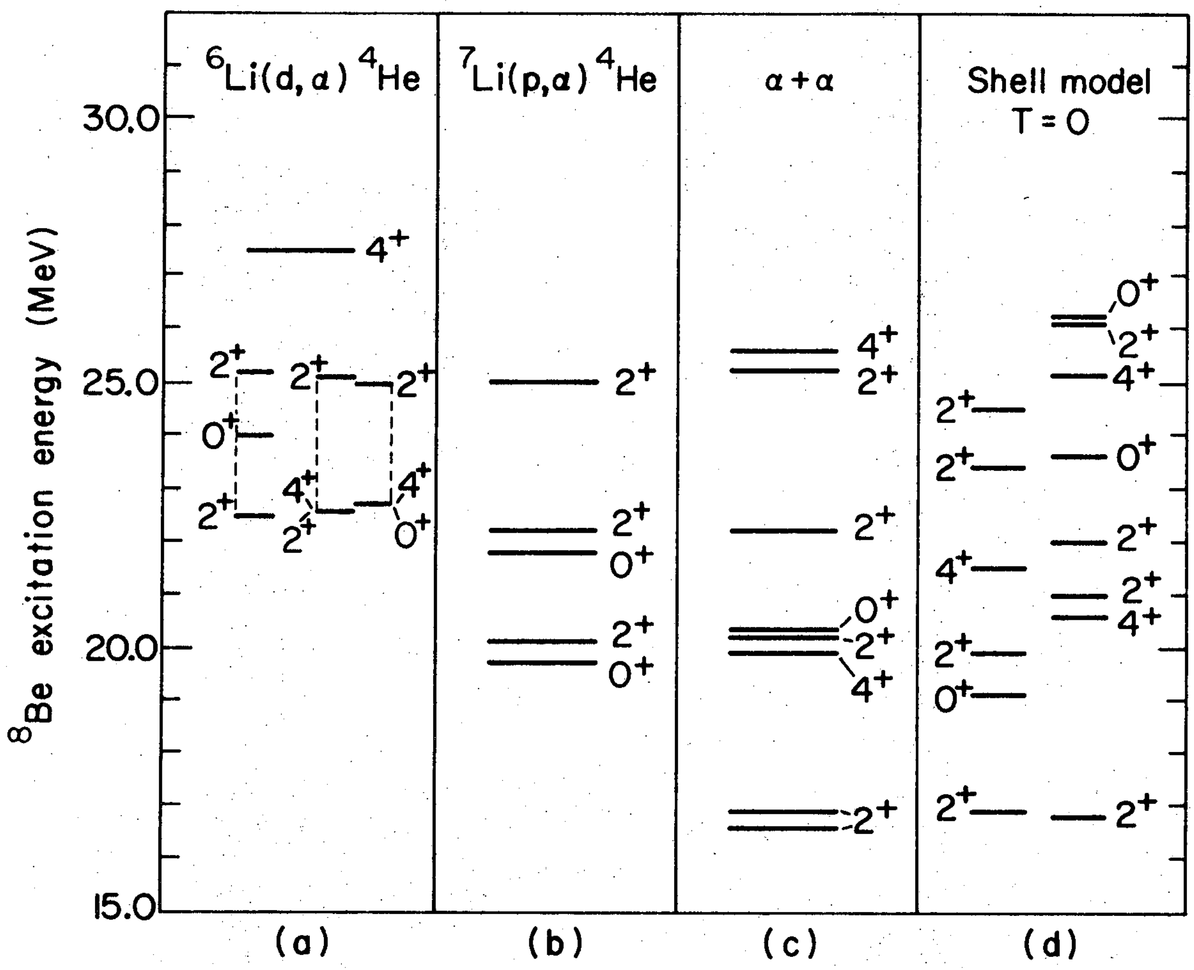
^{8}Be excitation energy (MeV)
30.0
25.0
20.0
15.0
^{6}Li(d,α)^{4}He
^{7}Li(p,α)^{4}He
α+α
Shell model
T=0
4+
2+
0+
(a)
(b)
(c)
(d)
XBL728-3955

Fig. 2