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May 1964

ELASTIC ALPHA-HELIUM SCATTERING UP TO 120 MeV*

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The elastic scattering of low-energy alpha-particles by helium has shown after analysis in terms of phase shifts that the nucleus Be^8 has a series of states, of spins 0^+, 2^+ and 4^+, at center-of-mass energies of 0.094 MeV, 2.9 MeV and 11.7 MeV respectively. These states all have widths comparable with the Wigner limit. There have been many attempts to explain the existence of these states and the energy dependence of the phase shifts by means of a two-body α-α potential. The phenomenological potentials which have been constructed to fit the scattering data contain a repulsive core surrounded by an attractive well. However, detailed investigations[1,2] have shown that the parameters must be ℓ-dependent. Effective potentials which were derived[3,4] by approximate methods from nucleon-nucleon forces exhibit the same features.

Using the Berkeley 88 inch cyclotron we have extended the elastic scattering measurements up to a bombarding energy of 120 MeV (60 MeV in the Be^8 center-of-mass system). We find evidence for 6^+ and 8^+ states which like the lower states occur at excitation energies roughly proportional to $J(J + 1)$. In addition, the new data enables us to define the effective α-α interaction potential move precisely than has hitherto been possible.

We have measured the differential cross-section as a function of the center-of-mass angle between 10° and 90° at seven energies between 53 Mev and 120 MeV. The relative values of the cross-sections at each energy are uncertain to 1 or 2% and the uncertainty in the absolute cross-section is also 1 or 2%.

We have fitted these differential cross-sections with an expansion using complex phase shifts $\delta_\ell = \mathrm{Re}\,(\delta_\ell) + i\,\mathrm{Im}\,(\delta_\ell)$ where the imaginary part takes into account the effect of nuclear reactions. The real parts of the phase shifts obtained in this analysis are shown in Fig. 1, together with those obtained at lower energies.[5,6] All of the phase shifts show a smooth and simple behavior except for the rapid flucturations near 40 MeV. These fluctuations are not fully understood and are currently the subject of a careful experimental investigation.[7] Since they are confined to a narrow energy range in the region of the threshold for nuclear reactions we have assumed that they are not important in the general consideration of the α-α interaction and have limited our discussion to the smooth energy variations.

We have obtained fits to the phase shifts with a potential of the form

$$V(r) = U_1 \left(1 + \exp\left[(r-r_1)/a_1\right]\right)^{-1} - U_2 \left(1 + \exp\left[(r-r_2)/a_2\right]\right)^{-1}$$

$$-i\,W \left(1 + \exp\left[(r-r_3)/a_3\right]\right)^{-1} + V_c(r)$$

where the first three terms, each with a Saxon-Woods form, represent a repulsive core, an attractive outer region and an absorptive potential to allow for reactions. The last term is the Coulomb potential due to a uniformly-charged sphere of radius r_c.

We found that the real parts of the phase shifts are very insensitive to the parameters r_c, W, r_3, a_3 and U_1. Hence, these were fixed in the following way: $r_c = 2F$; $W = 5$ MeV for $E > 40$ MeV and zero for $E < 40$ Mev; $r_3 = r_2$; $a_3 = a_2$; $V_1 = 150$ MeV $+ U_2$. The value for W was chosen to reproduce approximately the imaginary parts of the phase shifts. We were then left with five free parameters: r_1, a_1, U_2, r_2 and a_2. It should be noted that with appropriate values for these parameters it is possible to make the potential approach the shapes used by Margenau[8] or Haefner[9] or those predicted from nucleon-nucleon forces.

An attempt to fit the phase shifts as a function of energy using an ℓ-independent potential failed. We found that the higher angular momenta required a more attractive outer region. For instance, no potential could be found which would generate a g-wave phase shift just above resonance which was higher than that for the d-wave, as is observed experimentally. We have therefore used independent potentials for the individual partial waves. The best fits to the phase shifts are shown in Fig. 1 and the corresponding potentials in Fig. 2. The potentials become progressively less well-defined at small radii with increasing ℓ. At 120 MeV the repulsive core has very little effect on the g-wave and does not affect the higher angular momenta at all.

We have attempted to analyse the i- and k-waves in terms of single-level dispersion theory. It is not possible to fit the energy dependence of these or the lower phase shifts over any extensive energy range with a single value of the hard-sphere radius. The fits obtained with three different hard-sphere radii are listed in Table 1 and illustrated in Fig. 3. In order to compare all the excited states of Be^8 observed in α-α scattering we have chosen the same hard-sphere radius (4.5 F) for all the states and have plotted the excitation energy and reduced width as a function of $J(J+1)$ in Fig. 4. These quantities appear to be nearly linearly dependent on the argument.

A more detailed account of this work will be given elsewhere.

REFERENCES AND FOOTNOTES

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[†] Nato Fellow on leave from C. E. N. Saclay, France.

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Table I. Some of the sets of parameters obtained by fitting the i- and k-resonances with the single level dispersion relation. The notation used is that of reference 10. The fits are illustrated in Figure 3.

L	a (F)	$\gamma_{\lambda L}^2$ (MeV)	$E_{\lambda L}$ (MeV)	E_{res} (MeV)	$\Gamma_{\lambda L}$ (MeV)	$\frac{2\mu a^2}{3\hbar^2}\gamma_{\lambda L}^2$
6 (a)	3.5	2.3	33.5	36.8	11.4	0.88
6 (b)	4.5	2.4	25.3	27.7	16.7	1.52
6(c)	4.5	3.3	26.5	29.5	25.2	2.09
6	5.0	2.0	23.2	24.8	16.6	1.52
8 (d)	4.5	6.5	51.2	57	73	4.11

FIGURE CAPTIONS

Figure 1, The real parts of the phase shifts plotted as a function of the bombarding energy. The phase shifts below 53.4 MeV are obtained from references 5 and 6. The solid curves are fits using the potentials shown in Figure 2.

Figure 2. The real parts of the potentials used to fit the phase shifts, shown with and without the centrifugal barrier added.

Figure 3. Single-level dispersion theory fits to the $\ell = 6$ and $\ell = 8$ partial waves using the parameters listed in Table 1.

Figure 4. The excitation energies E_{res} and reduced widths $\gamma^2_{\lambda L}$ for the 0^+, 2^+, 4^+, 6^+ and 8^+ states in Be^8, obtained using a hard-sphere radius of 4.5 fermis. The two values shown for the 6^+ state are for solutions (b) and (c) of Figure 3 and Table 1. The parameters for the first three states are taken from references 10, 11 and 12.

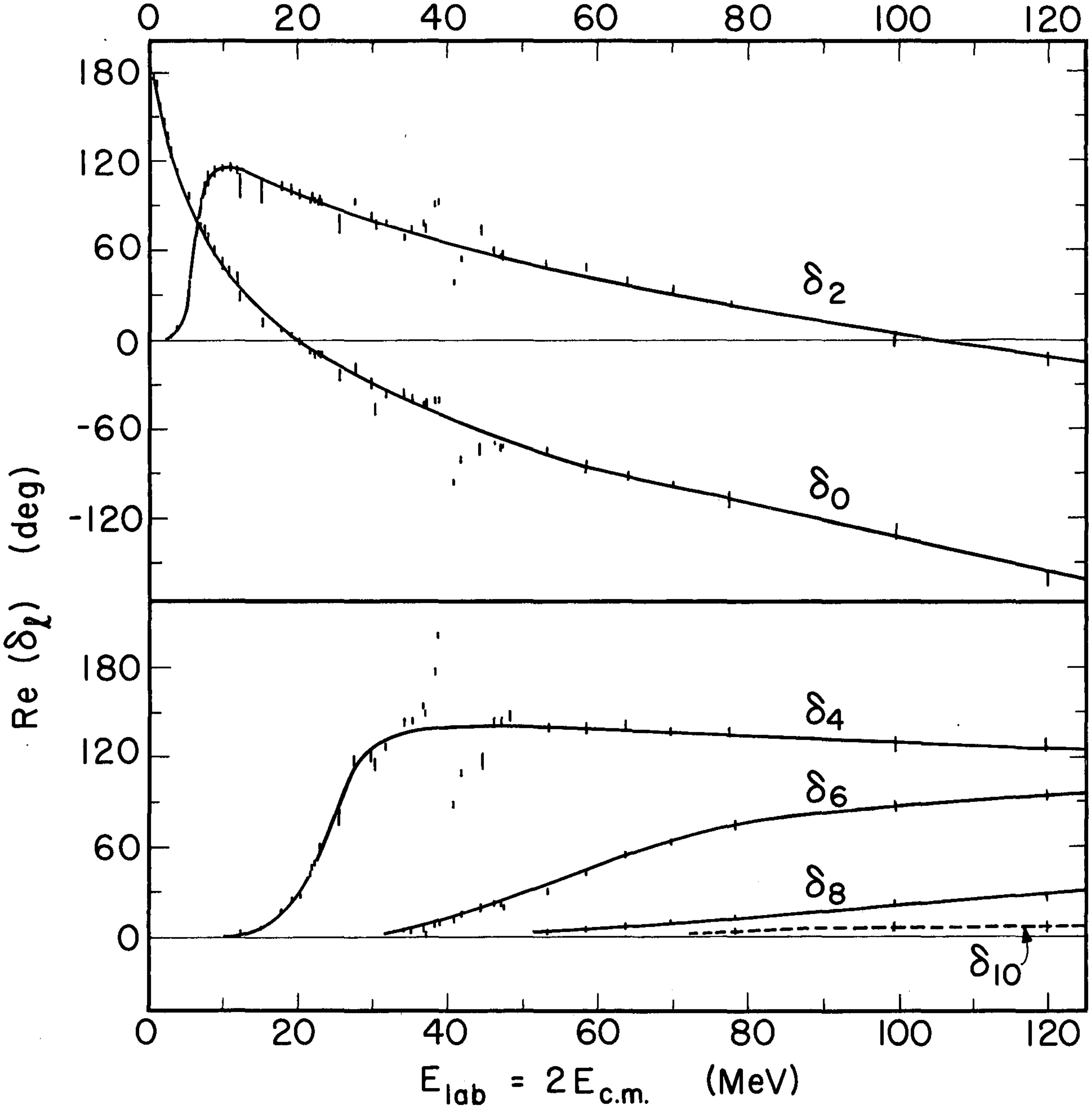

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Fig. 1

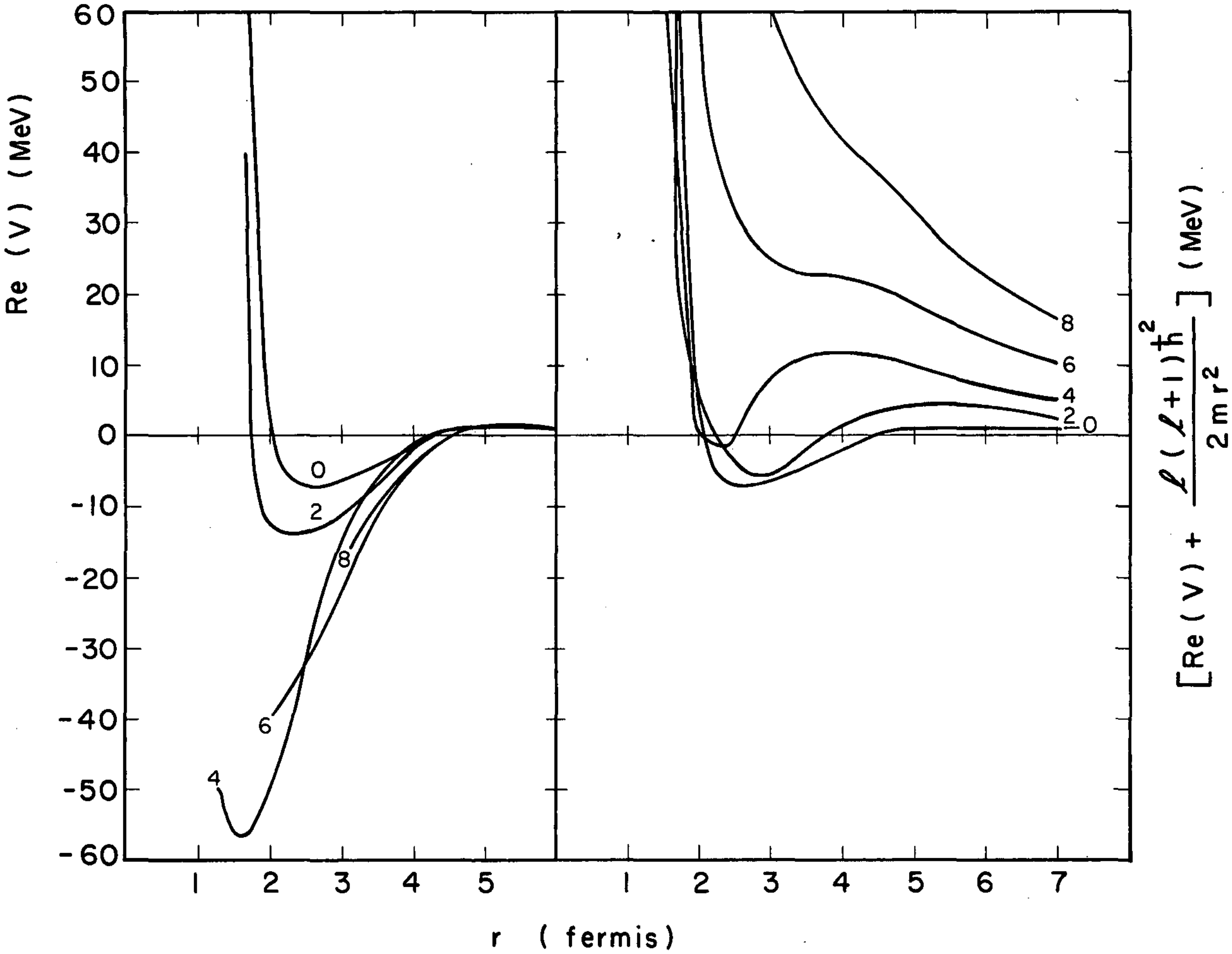

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Fig. 2

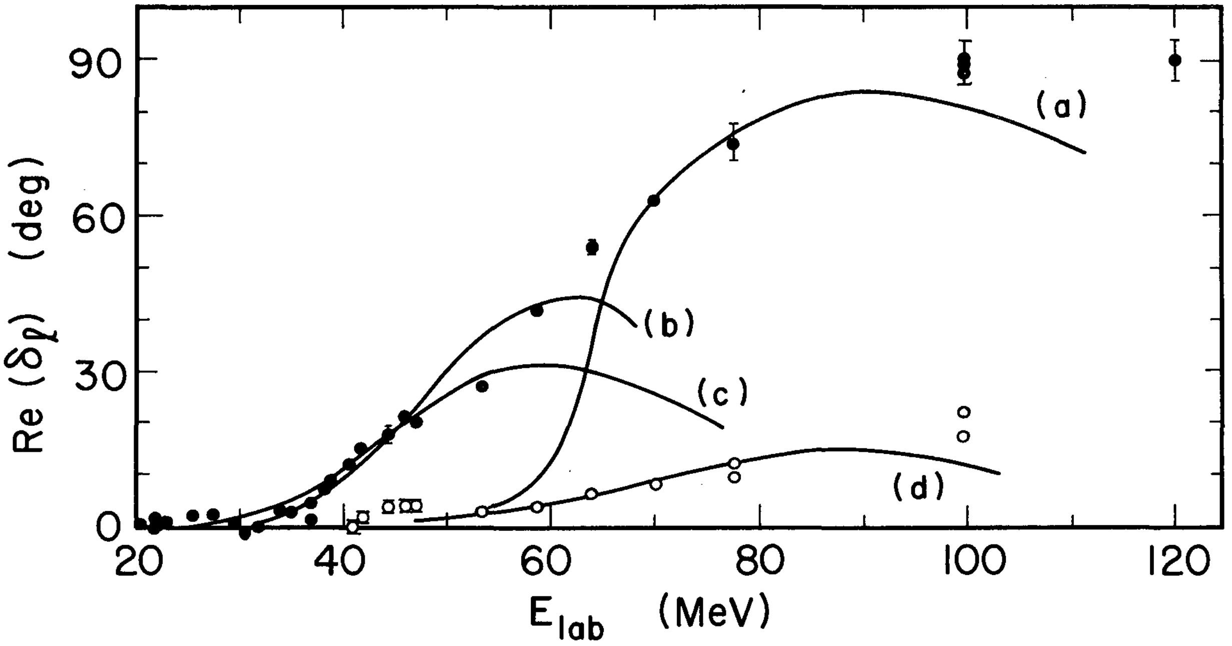

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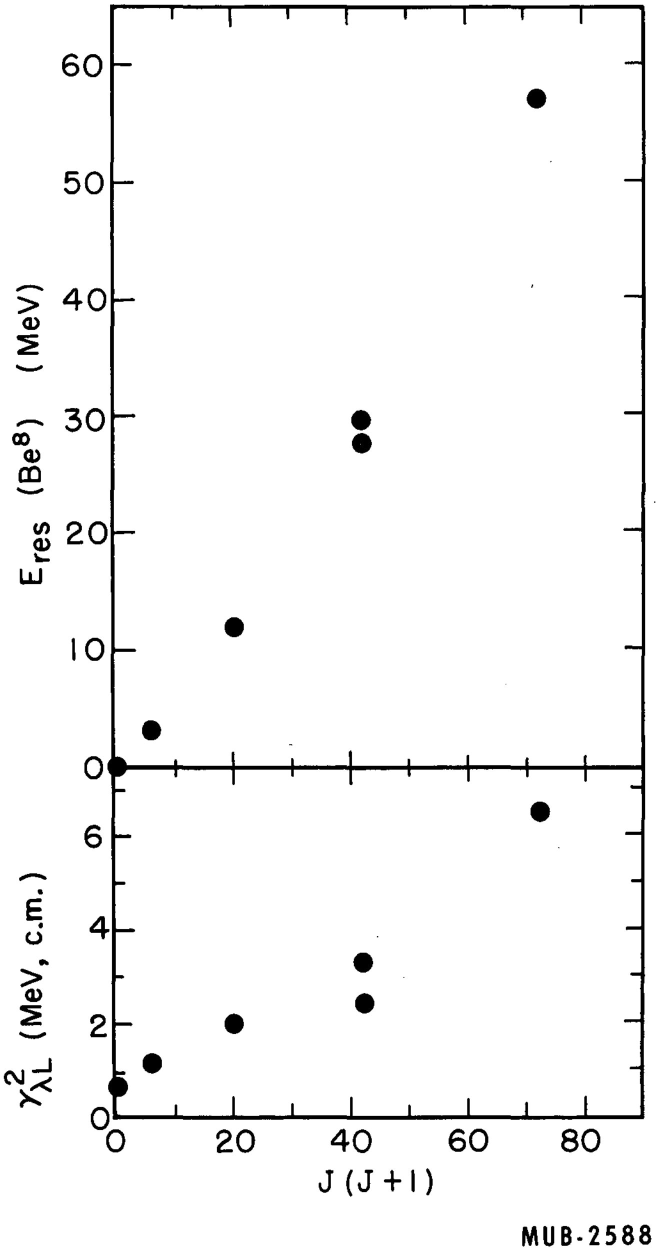
Fig. 3



E_{res} (Be^8) (MeV)
0
10
20
30
40
50
60
$\gamma^2_{\lambda L}$ (MeV, c.m.)
0
2
4
6
0
20
40
60
80
J (J+1)
MUB-2588

Fig. 4

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