KERNFORSCHUNGSZENTRUM

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Institut für Experimentelle Kernphysik

Investigation of the T=O Negative Parity Excited States in ^{4}He

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Investigation of the T=0 Negative Parity Excited States in ^4He

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Abstract:

Using inelastic scattering of 52 MeV deuterons and 104 MeV alpha-particles, excited states in ^4He were investigated. These reactions selectively only excite T=0 levels. The results are consistent with the assignments from a phase shift analysis of T(p,p)T and $^3He(n,n)^3He$ data. Making assumptions about the reaction mechanism, positions and widths for two states are extracted.

Spectroscopic investigations in ^4He are of particular interest because one deals with a doubly magic nucleus with a high degree of symmetry. This facilitates theoretical calculations and recently such have been carried out by de Shalit and Walecka (1), by Kramer and Moshinsky (2) and by Barrett (3). Because of the symmetry to first order, some of the components of the nuclear forces do not contribute to the splittings of the excited states, and so one is able to distinguish between the contributions of the different force components.

Let us consider the A=4 system. Prof. Meyerhof has just given an excellent survey (4). Figure 1 summarizes the information available when we started this investigation (5,6). For a more up to date version see fig. 15 in ref. (4). There are the two well known excited states, the narrow 0^+, T=0 level near 20 MeV, and a broad state at about 21-22 MeV. To fit the n-^3He scattering data by a phase shift analysis as done by Tombrello (7), Barrett and coworkers (8) one needs a state of spin and parity of 2^- in this region.

As is well known all these states are unstable against particle emission, with thresholds given in fig. 1. The excited states can have a width of up to several MeV on account of the particle emission unstability.
Now let us first see from theoretical aspects what states one can expect to find in the region of up to about 30 MeV excitation. In the shell model the lowest exited states of ^4He are one phonon excitations into the lp-shell. It has been shown that seven such states are possible, namely the four T=1 states analogous to ^4Li which one expects at the excitation energies given in the fig. 1 minus the small Coulomb energy difference, and further a T=0, 0^-, 1^-, 2^- triplet. There will also be ld and 2s two-phonon states with positive parity. As these states are expected to lie above the p-states. I will exclude them from the following discussion.

Obviously the experimental situation is rather complex as one can excite 8 states with considerable widths in an energy interval of about 10 MeV. Additionally one has to cope with a background arising from reactions with more than two particles in the exit channel.

With the help of selective reactions one can reduce the number of states excited. Deuterons and alpha particles have T=0, and so, assuming no isospin mixing, in the inelastic scattering of alpha particles and deuterons off ^{4}He one can only excite T=0 states. In the case of alpha particles there are further restrictions, because in the entrance channel we have two identical spin zero bosons. As the total wave function has to be symmetrical with respect to exchange of the two alpha particles, the relative and hence the total angular momentum in the entrance channel can only be 0^+, 2^+, 4^+ etc. As total spin and parity have to be conserved, the 0^- state cannot be excited in inelastic alpha scattering. Further the 2^- cannot be excited, if the entrance channel spin is equal to zero. This means that in inelastic scattering the 2^- state will probably be more weakly excited than the 1^- state.

We have used the 104 MeV alpha and the 52 MeV deuteron beam of the Karlsruhe Isochronous Cyclotron to investigate the inelastic ^{4}He(α, α') and ^{4}He(d,d') scattering. In fig. 2 an alpha spectrum taken at 20^o in the laboratory system is shown. Plotted is the relative intensity versus energy. The elastic peak is far off to the right.

One sees a continuous distribution with a broad maximum and two bumps on the high energy side.

The solid line represents an arbitrarily normalized phase space distribution (9) for the t-p and the n-^{3}He break up of the alpha particle. The experimental resolution has been folded in. The intensities for these two channels have been taken to be equal. A deviation from this assumption will significantly only effect the points near 20 MeV. As discussed later, for the analysis we subtract the background from the spectra, divide by the phase space distribution and change the energy variable to excitation energy in ^{4}He. The resulting curves are shown in fig. 4 .
The alpha-curve shows three regions of enhanced intensity; the lowest corresponds to the 20 MeV 0^+, T=0 state. There is a second peak with maximum at 21.9 MeV, and a broad distribution peaking at 28 MeV excitation. As the 0^- state cannot be excited in inelastic alpha-scattering, only the 2^- and 1^-, T=0 states come into consideration. Our results check very well with Meyerhofs assignments of a 2^-, T=0 state at 22.4 MeV and a 1^-, T=0 state at 28.3 MeV based on a phase shift analysis. To the broad distribution near 28 MeV, higher excited states, as well as the d,d and other phase space distributions can contribute. The 2^- state is reasonably isolated.

The ^{4}He(d,d') spectrum for $\Theta_{lab} = 25^0$ is shown in fig. 3, and the corresponding analysed curve in fig. 4. The 0^+ state is expected at the position indicated. In none of the spectra taken at different angles does it show up with appreciable intensity. Here we have a much more prominent peak at 20.7 MeV. In this case the 0^-, T=0 state can additionally be excited. Meyerhof places this state at 21.4 MeV. At the end of this paper a decomposition of this peak into a 0^- and a 2^- resonance is attempted.

Both reactions were measured at several forward angles. The spectra are quite similar to the ones shown and their features change only gradually with angle. The energy calibration was carried out by measuring the elastically scattered particles at two angles chosen such that they fell into the region of interest in the above spectrum. The uncertainties in the primary energy and the scattering angle enter only in second order and make the energy calibration of the above spectra uncertain by ± 200 keV.

In what follows we attempt an analysis to see how the spectra can be explained and to extract values for the resonance parameters. These numbers should be treated with all due caution on account of the theoretical uncertainties and the approximations. Let me very briefly discuss the reaction mechanism. We assume the process to be sequential. In inelastic scattering an excited alpha-particle is formed which then decays. When only one particle is detected, the differential cross section leading to three particles in the final state is given by (see ref. 9 for instance):

$$\frac{d^2\sigma}{d\Omega_1 dE_1} = \sum_c |M_c|^2 \cdot \rho_c(E_1) \qquad (1)$$

Where the sum is over the different breakup channels c, $\rho_c(E_1)$ is the phase space factor, and all constants are absorbed into the matrix element M. We then take M to be given by the sum of a matrix element M_{stat}, representing the statistical decay and describing the pure phase space distribution and a term M_{seq} describing the sequential decay. We further assume that the matrix element M_{seq} can be factored (10) into a term U not dependent on the relative energy E of the unobserved particles, which describes the scattering in the absence of final state interaction and an enhancement factor D which describes the final state interaction between the two unobserved particles and which reflects resonances between them. For the interaction between n and ^{3}He (see ref. 11

for instance) a general form of the matrix element is then

$$\left|M_{seq}\right|^2 = U^2 \cdot \sum_l \left[C_l(E) + \sum_n \frac{\frac{1}{2}\Gamma_{ln}B_{ln}(E) + (E-E_{ln})A_{ln}(E)}{(E-E_{ln})^2 + \frac{1}{4}\Gamma_{ln}^2}\right] \quad (2)$$

where the sums are over angular momenta l and the poles n. E_{ln} and Γ_{ln} are real constants determined by the position of the poles, E we take to be the relative energy, and A_{ln}, B_{ln}, C_l are in general smooth functions of E. C_l represents the potential scattering, and the A_{ln} represent the interference terms between the resonance and the potential scattering as well as the fact that in our case the Γ_{ln} are not small in comparison with E_{ln}. Now the decay into T,p is also possible and this case is more complex on account of the Coulomb interaction. As the total width determines the analytic form of the denominator, we shall assume a single resonance term to represent both n, ^{3}He and p,T channels. As these two channels are charge symmetric, this should be a reasonable approximation below the d,d threshold. Looking at the spectra one can tell that apart from the resonances both spectra are quite well represented by the phase space distribution, so there does not appear to be any drastic energy dependance beyond that of the phase space distribution. So we shall take the A_n, B_n, C to be constant, and each resonance to be represented by a single term in equation (2). The entire matrix element $|M|^2$ contains two constant terms arising from $\left|M_{stat}\right|^2$ and C, and the energy dependent term from formula (2). In this approximation part of the interference term is neglected. In the following the subscripts refer to the two resonances for which an analysis is carried out.

To get a "spectrum" proportional to $\left|M\right|^2$ we subtract the experimental background from the spectra and divide by the phase space. The resulting curves are shown in fig. 4, plotted as a function of E referred to the ground state of

^{4}He, and corrected for the change in variable. As expected this afflicts the points near 20 MeV with large statistical errors. For the inelastic alpha-curve an analysis minimizing X^2 of the middle peak yields E_2 = 21.9 MeV, Γ_2 = 1.6 MeV. $A_2 \approx 0$. Γ_2 still has the experimental resolution folded in. To eliminate it to first order $\Gamma_2' = \sqrt{\Gamma_2^2 - R^2}$ = 1.2 MeV, where R is the experimental resolution. For the deuteron curve, using E_2 and Γ_2' from the alpha-data and making a fit minimizing X^2 with a constant and two resonance terms, we get E_1 = 20.7MeV, Γ_1' = 1.4 MeV, and $A_1 = A_2 \approx 0$.
As I mentioned before these numbers should be treated with caution, on account of the uncertainties of the theoretical interpretation and the various approximations. As one expects only a single resonance to contribute in the inelastic alpha spectrum, those parameters are more reliable.

References:

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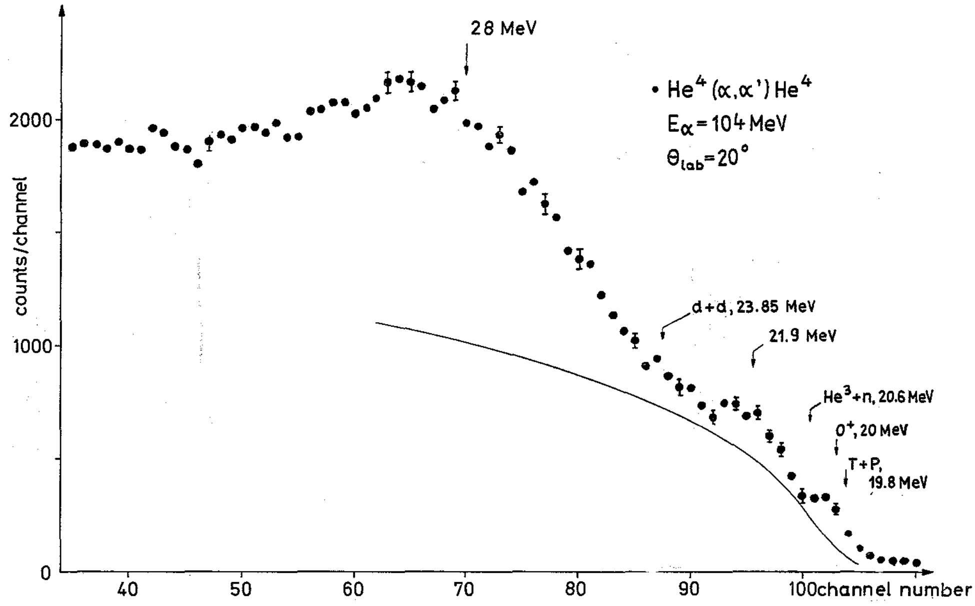
Figure Captions:

Fig. 1:
Energy level diagram of the A=4 system

Fig. 2:
Spectrum of inelastically scattered alpha-particles at the laboratory angle of 20^{o}

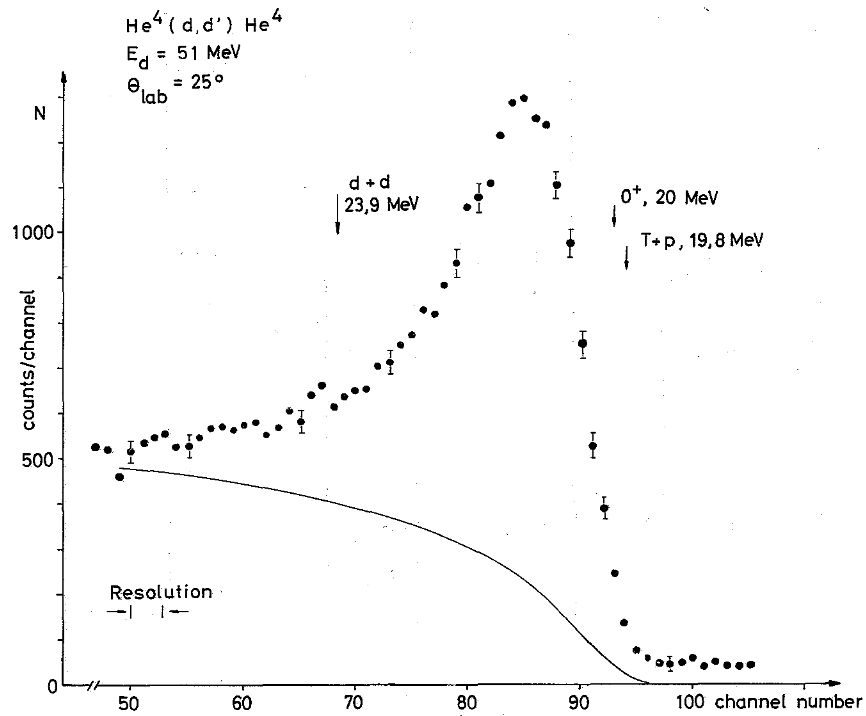
Fig. 3:
Spectrum of inelastically scattered deuterons at the laboratory angle of 25^{o}

Fig. 4:
Differential cross sections divided by phase space distribution as function of excitation energy in ^{4}He



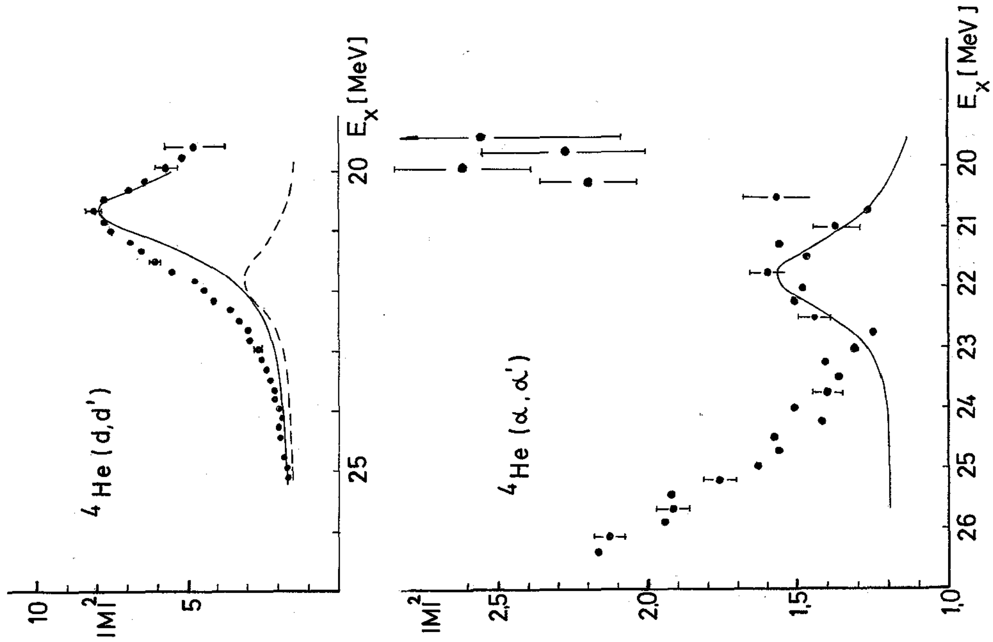
28 MeV
• $He^4(\alpha,\alpha')He^4$
E_α=104 MeV
Θ_{lab}=20°
counts/channel
2000
1000
0
d+d, 23.85 MeV
21.9 MeV
He^3+n, 20.6 MeV
0^+, 20 MeV
T+P,
19.8 MeV
40
50
60
70
80
90
100channel number

fig. 2



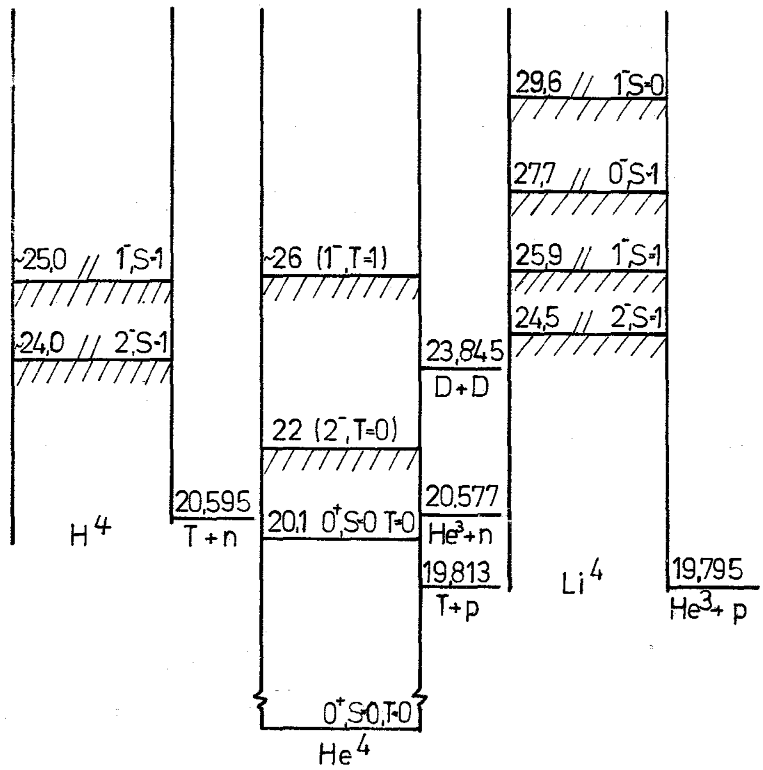
$He^4(d,d')He^4$
E_d = 51 MeV
Θ_{lab} = 25°
N
counts/channel
1000
500
0
d+d
23,9 MeV
0^+, 20 MeV
T+p, 19,8 MeV
Resolution
50
60
70
80
90
100 channel number

fig. 3



^{4}He (d,d')
^{4}He (α,α')
$|M|^2$
E_x [MeV]

fig. 4



~25,0 // 1⁻S-1
~24,0 // 2⁻S-1
H^4
20,595
T + n
~26 (1⁻,T=1)
22 (2⁻,T=0)
20,1 0⁺S-0 T=0
0⁺S-0,T-0
He^4
23,845
D + D
20,577
He^3+n
19,813
T+p
29,6 // 1⁻S-0
27,7 // 0⁻S-1
25,9 // 1⁻S-1
24,5 // 2⁻S-1
Li^4
19,795
He^3+ p

fig. 1