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THE FIRST 4^+ STATE OF ^{12}C AND A LEVEL AT 15.6 MeV*)

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Abstract:

Measurements of the $^{14}N(d,\alpha'\alpha)$ and of the $^{12}C(\alpha,\alpha')$ reactions confirm a broad level in ^{12}C at 15.6 MeV.
Analysis of α-particle inelastic angular distributions indicates that this level is the 4^+ member of the ground-state rotational band. Reconsideration of earlier experiments shows them to be consistent with a 3^- assignment for the level at 14.08 MeV previously thought to have 4^+.

Messungen der $^{14}N(d,\alpha'\alpha)$ und $^{12}C(\alpha,\alpha')$ Reaktionen bestätigen die Existenz eines breiten Niveaus in ^{12}C bei 15.6 MeV Anregungsenergie. Die Analyse der Winkelverteilungen der inelastischen α-Streuung deutet darauf hin, daß dieses Niveau das $J^\pi=4^+$ Mitglied des Grundzustands-Rotationsbandes ist. Für das Niveau bei 14.08 MeV, für das bisher 4^+ angenommen wurde, ergibt die Analyse eine neue Zuordnung von 3^-.

In the α-particle model ^{12}C is assembled from three α-particles bonded together in the form of an equilateral triangle. This configuration is an intrinsic state with an oblate deformation which should lead to a rotational band. The first two members of this rotational band are presumably the ground state and the first excited state. The position of the next member, the 4^+ state, would then be at 14.8 MeV excitation, assuming a constant moment of inertia. The reasons for expecting the 4^+ level in the neighborhood of the position predicted by the simple rotational model are strong. Nuclear structure calculations [2]) generally predict a 0^+ ground state, a 2^+ state with at least, crudely, the spacing predicted by the rotational model.

Calculations based on shell-model wave functions [3]) indicate that the cross section for a two-particle pick-up reaction leading from ^{14}N to the lowest 4^+ level of ^{12}C will be especially large. This is a useful signature which should be helpful in identifying the level.

There is a well-known level near the predicted position of the 4^+ state. This level is the 14.08 MeV level and it is prominent in the $^{14}N(d,\alpha)$ reaction [1, 4]). However, in these studies it was observed that there is another level at 15.6 MeV which is about equally strongly excited in the $^{14}N(d,\alpha)$ reaction as the one at 14.08 MeV. It is less obvious in the excitation function because it has a substantially larger width ($\approx$ 1.2 MeV vs. $\approx$ 300 keV). The observation of the level at 15.6 MeV substantially undermined the basis which existed for identifying the 14.08 MeV level as the lowest lying 4^+ level in ^{12}C.

There is information in the literature on angular correlations [6, 9]) and angular distributions [7]) which have relevance to the spin and parity assignment of the 14.08 MeV level. These data either do not point uniquely to a 4^+ assignment or are inconsistent with a 4^+ assignment [8]). This in brief has constituted the background of the work reported here.

To provide additional confirmation of the level at 15.6 MeV it was decided to investigate the $^{14}N(d,\alpha'\alpha)$ reaction [4]) in which one of the decay products of the ^{12}C states is detected in coincidence with the primary α-particle. Because the new level at 15.6 MeV is still below other thresholds it can only decay into three α-particles. It was therefore certain that the level previously detected in $^{14}N(d,\alpha)$ would also be apparent in this measurement. Where sequential decay via the ground state of ^{8}Be is the dominant decay mechanism, spin and parity assignments might be made by analysis of the angular correlation of the two α-particles.

The $^{12}C(\alpha,\alpha')$ reaction was also investigated because the 4^+ level as a member of the ground-state rotational band is expected to be prominent in this reaction as well. Furthermore analysis of α-particle inelastic angular distributions is a reliable way of determining spins and parities of natural-parity states [12]). It was expected therefore that the 4^+ level might be identified by means of this reaction.

The experimental methods used in the coincidence measurement were conventional in most details. The deuteron energy was 52 MeV. Two-dimensional pulse height spectra were taken with an energy resolution of 400 keV. Kinematical curves were calculated for the ^{8}Be ground state and for the ^{8}Be first excited state. Events lying within a pulse height equivalent of about 1.4 MeV of each of these curves were projected separately on the $E_{\alpha'}$ axis. Representative projections are given in fig. 1.

The data show the existence of the 15.6 MeV level.On the basis of consistency the error in position is estimated as ±120 keV and that in width as ±300 keV. This does not take into account any model dependence. In contrast with the nearby 14.08 MeV level there is no evidence for sequential decay of the 15.6 MeV level via the ground state of ^{8}Be. Monte Carlo calculations indicated that more extensive measurements of this type would allow spin and parity assignments only for levels which decay via the ^{8}Be ground state [4]). Since the 14.08 MeV level which does decay via the ground state was known to be prominent in α-particle inelastic scattering it was decided to pursue this line in order to assign spins and parities.

The measurements on the $^{12}C(\alpha,\alpha')$ reaction were made with the new striped detectors developed at this laboratory. These detectors are quite similar to the checkerboard detectors developed for use on project BOL [10]. The striped detectors differ from the checkerboard detectors in that there are stripes on only one side. On the opposite side is a single aluminium electrode from which the ΔE signal was taken. The E counter was a standard ion-implanted silicon detector. The striped detectors used in this experiment had five position stripes. The five bits of yes-no information were reduced to three bits for routing with a simple digital circuit. Six spectra were stored simultaneously corresponding to position stripes one through five plus a spectrum of invalid events [5].

Fig. 2 shows the cross section integrated between 15° and 55° c.m., as a function of the ^{12}C excitation energy. The 15.6 MeV level shows up clearly enough in this integrated spectrum, though not so clearly as it does in some of the individual spectra. The solid curve represents a fit to a function containing Breit-Wigner terms plus background [4].

Angular distributions for several states are shown in fig. 3. The solid curves are DWBA calculations for the ℓ-transfer which qualitatively gives the best fits. The optical potential used is the six-parameter potential given by Hauser et al. [13] with slight modifications to give a better fit to the ground-state angular distribution. The changes presumably reflect the fact that the bombarding energy was 90 MeV instead of 104 MeV. A discrepancy of 0.3° in the angle calibration would produce a change in parameters of about the same magnitude.

The angular distribution for the 14.08 MeV state disagrees with the DWBA prediction for 4^+ and agrees qualitatively with the prediction for 3^-. The observed angular distribution is very similar to that of the 9.64 level, which is known to have 3^-. Evidently with increasing excitation energy the first minimum in the DWBA curves isshifted to larger angles, whereas the further maxima are well fitted. Theearlier data which have a bearing on the spin and parity of the 14.08 MeV level support the new assignment of 3^-. The attempt by Satchler [8] to fit the 46 MeV proton inelastic scattering data of Peterson et al. [7] for a 4^+ assignment was not successful. For proton inelastic scattering the angular distributions for the 14.08 and 9.64 MeV states are also very similar.

The angular distribution for the 9.64 MeV state is well fitted for the 3^- assumption.

The $^{12}C(^{12}C,^{12}C',\alpha)$ angular correlation measurement of Garvey et al. [6]) which is cited as evidence for the 4^+ assignment actually gives slightly better agreement with the angular correlation computed for 3^-.

The evidence is strong that 3^- is the correct spin and parity assignment for the 14.08 MeV level in ^{12}C.

The 15.6 MeV level would now appear to be the first 4^+ level in ^{12}C and the third member of the ground-state rotational band. It is strongly excited in $^{14}N(d,\alpha')$, as expected, and the α-particle inelastic angular distribution agrees best with this assumption. There are three reasons for some caution. For the 15.6 MeV level the extraction of an angular distribution depends on a fitting procedure in which the excitation function is fitted with Breit-Wigner and background terms. This procecure could lead to errors which are difficult to estimate. The angular distribution is rather unstructured so that the qualitative difference between the predictions for 4^+ and for a higher spin is not so marked, and finally there is no nearby 4^+ level which allows direct comparison of the angular distributions.

There still remains the argument that the 4^+ level is expected in the neighborhood of 15 MeV and that the 15.6 MeV level is the only known level having characteristics consistent with those of the expected level and therefore must be the expected level. This argument has its obvious weaknesses. Similar arguments could have been used in the past to favour a 4^+ assignment for the 14.08 MeV level.

We assume, however, that the cross section for inelastic scattering to the 15.6 MeV level is large enough for it to have normal parity, that higher spins are not physically reasonable and that we would have been able to distinguish a state with lower spin. While the evidence for a 4^+ assignment to the 15.6 MeV level is not as strong as that favouring a 3^- assignment for the 14.08 MeV level, it is consistent and we believe it to be strong enough to be accepted.

With the lowest 4^+ level of ^{12}C at 15.6 MeV the ratio $R_4=E_4/E_2$ is 3.52. For almost all nuclei R_4 is less than the rigid rotator value of 3.33 which is approached from below in the case of highly deformed rare earth nuclei [11]). Known exceptions to the rule are ^8Be, ^{254}Fm and now ^{12}C. By Scharff-Goldhaber and Goldhaber [11]) it has been suggested that the instability of the 4^+ state against fission may play a role. This could also be true for ^{12}C.

Another possibility is that α-clustering is responsible. Calculations [2]) by Yakawa and Yoshida and by Friedrich and Weiguny which are based on the α-particle model predict a decreasing nuclear deformation with increasing spin and $R_4 > 3.33$.

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Figure Captions

Fig. 1 Coincidence spectra for two different decay channels summed across the kinematic curve and projected onto the $E_{\alpha'}$ axis. The lines in the bottom spectrum correspond to the levels at 12.72 and 14.08 MeV.

Fig. 2 The $^{12}C(\alpha,\alpha')$ spectrum integrated over the angular range of 15^{o} - 50^{o}. The differential cross section is plotted as a function of the excitation energy.

Fig. 3 Angular distributions for excited states in ^{12}C from the $^{12}C(\alpha,\alpha')$ reaction compared with DWBA calculations (solid curves).

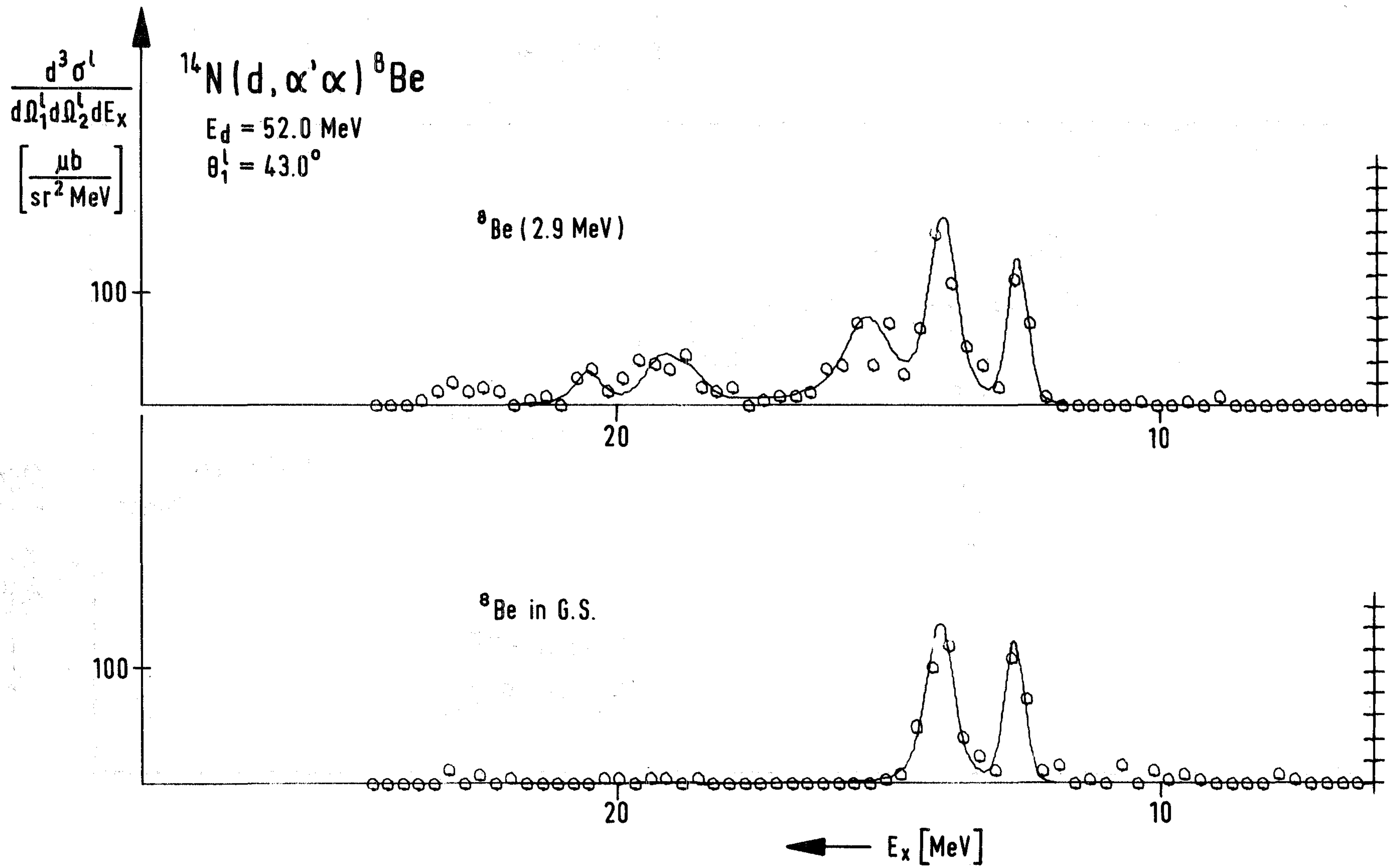

$\frac{d^3\sigma^l}{d\Omega_1^l d\Omega_2^l dE_x}$ $\left[\frac{\mu b}{sr^2 MeV}\right]$
$^{14}N(d,\alpha'\alpha)^8Be$
$E_d = 52.0$ MeV
$\theta_1^l = 43.0°$
^8Be (2.9 MeV)
100
20
10
^8Be in G.S.
100
20
10
E_x [MeV]

Fig. 1

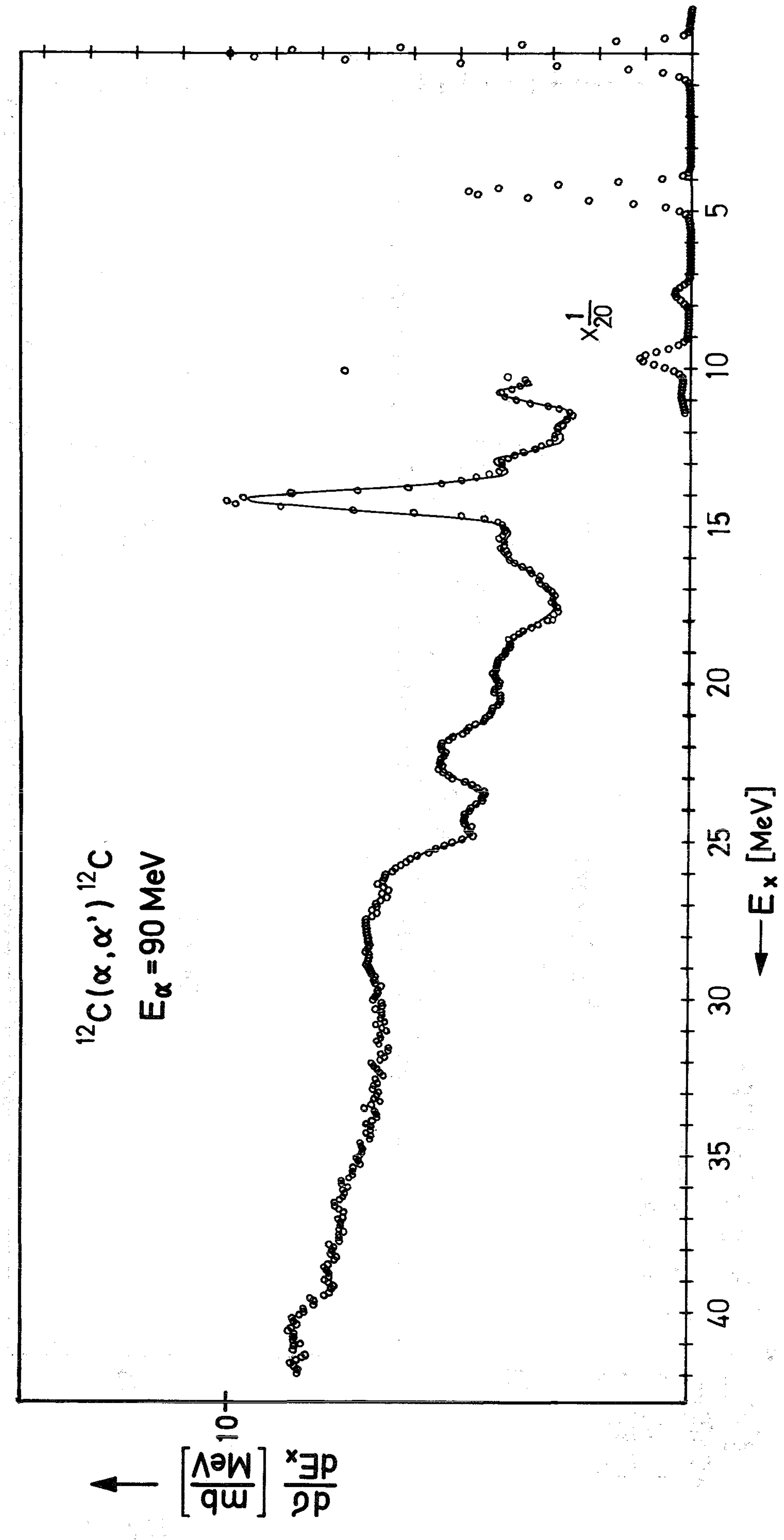
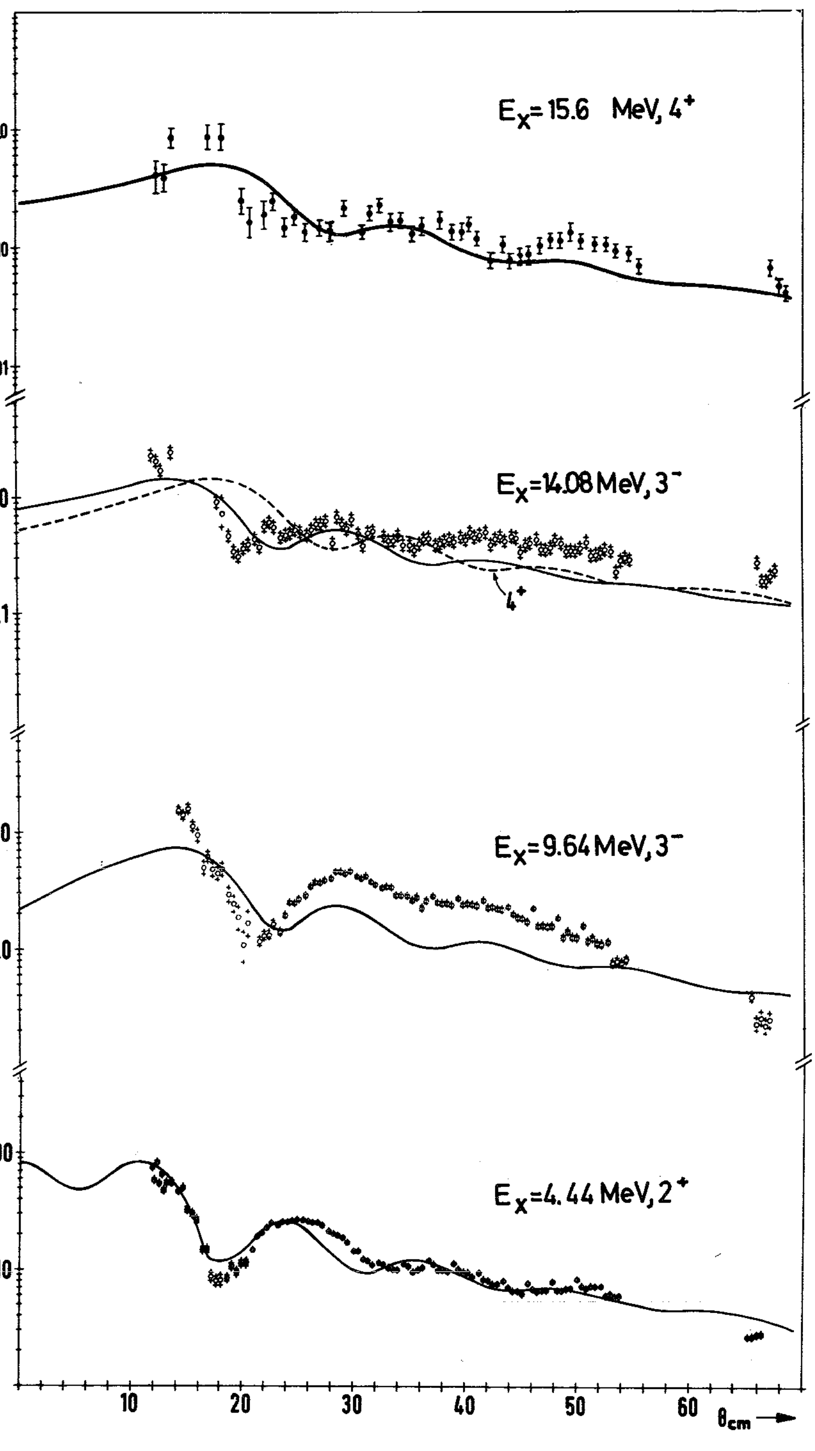

$^{12}C(\alpha,\alpha')\,^{12}C$
$E_\alpha = 90$ MeV
$\times\frac{1}{20}$
5
10
15
20
25
30
35
40
E_x [MeV]
10
$\frac{d\sigma}{dE_x}\left[\frac{mb}{MeV}\right]$

Fig. 2



E_x= 15.6 MeV, 4^+
E_x=14.08 MeV, 3^-
4^+
E_x=9.64 MeV, 3^-
E_x=4.44 MeV, 2^+
$\frac{d\sigma}{d\Omega_{cm}}\left[\frac{mb}{sr}\right]$
θ_{cm}

Fig. 3