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Proton nuclear reaction cross sections in carbon and the $^{12}C(p, p'3\alpha)$ reaction mechanism at 13 MeV

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Abstract. The mechanism of the $^{12}C(p, p'3\alpha)$ reaction at 13 MeV is found to involve the ground state of ^{8}Be and the ground state of ^{9}B in 24% of the events, and the ^{8}Be ground state alone in 51% of the events. The remaining 25% of the events show no clear evidence of levels in intermediate nuclei. The cross section for this reaction is 154 mb.

1. Introduction

This article describes three results which have been obtained from a cloud chamber study of the reactions of 13 MeV protons with carbon. Our technique for measuring the total reaction cross section does not involve the large uncertainties of previous measurements at low energies. We are also able to measure the cross section for the $^{12}C(p, p'3\alpha)$ reaction, for which there are no previous measurements reported in the literature. Further we discuss the mechanism of the $^{12}C(p, p'3\alpha)$ reaction, and we note that the only reported work in this field has been at rather higher energies.

The total reaction cross section in carbon, and in a wide range of other elements, has been measured by Igo and Wilkins (1963). They use an attenuation technique which yields accurate basic measurements, but involves large corrections for both elastic and inelastic scattering. Meyer and Hintz (1960) have made measurements, again at 10 MeV by simply determining the cross section for charged particle production, without distinguishing between different charged particles. The results of the present experiment show that they would fail to detect many of the low energy α particles produced. Pollock and Schrank (1965) have measured the total cross section at 16·4 MeV, and there have been a range of other measurements at higher energies (Burge 1959, Giles and Burge 1964, Gooding 1959, Makino *et al* 1964, 1965).

The mechanism of the $^{12}C(p, p'3\alpha)$ reaction has been studied by Need (1955) at 29 MeV using a cloud chamber, and by Vasilyev *et al* (1963) at 15 to 29 MeV using nuclear emulsions. Both groups find evidence for a sequential process, proceeding through levels in ^{8}Be and through levels in ^{12}C or ^{9}B. Maxson (1962) has measured the cross section for the (p, α) reaction to the ground state of ^{9}B using protons of 15 and 18·6 MeV. This reaction is, of course, the first stage in the $(p, p'3\alpha)$ reaction, the ground state of ^{9}B being unstable to proton emission.

2. Experimental technique

The experimental technique has been fully described by MacLeod and Reid (1965) and later modifications by Chapman and MacLeod (1967).

Two thin proportional counters are set in front of the cloud chamber, counting the number of incident protons. A thick scintillator is set in the back wall of the chamber, and the chamber is triggered when a proton passes through the proportional counters but fails to record in the scintillator.

This counter system shows close similarities to that of Igo and Wilkins (1963) referred to above, but the great benefit in our experiment is that the trigger is only accepted as a nuclear reaction if the reaction is observed in the cloud chamber photograph. There is therefore no need to correct for elastic scattering in the gas, or for reactions and scatters in the windows etc. The gas filling in the cloud chamber was methane. The unwanted proton scatters in the hydrogen are easily identified on the photographs and are discarded at the analysis stage.

3. Analysis

The reaction $^{12}C(p, p'3\alpha)$ is of special interest in the study of reaction mechanisms because of the large number of decay modes available to it. These are shown in table 1.

From the cloud chamber photographs the events were classified into four groups according to their appearance on the film.

Table 1

(*a*) $p + {}^{12}C \rightarrow p' + 3\alpha$
(*b*) $p + {}^{12}C \rightarrow p' + {}^{12}C^* \rightarrow p' + 3\alpha$
(*c*) $p + {}^{12}C \rightarrow p' + {}^{12}C^* \rightarrow p' + \alpha + {}^{8}Be^* \rightarrow p' + 3\alpha$
(*d*) $p + {}^{12}C \rightarrow \alpha + {}^{9}B^* \rightarrow p' + 3\alpha$
(*e*) $p + {}^{12}C \rightarrow \alpha + {}^{9}B^* \rightarrow p' + \alpha + {}^{8}Be^* \rightarrow p' + 3\alpha$
(*f*) $p + {}^{12}C \rightarrow \alpha + {}^{9}B^* \rightarrow 2\alpha + {}^{5}Li^* \rightarrow p' + 3\alpha$
(*g*) $p + {}^{12}C \rightarrow p' + \alpha + {}^{8}Be^* \rightarrow p' + 3\alpha$
(*h*) $p + {}^{12}C \rightarrow 2\alpha + {}^{5}Li^* \rightarrow p' + 3\alpha$
(*i*) $p + {}^{12}C \rightarrow {}^{5}Li^* + {}^{8}Be^* \rightarrow p' + 3\alpha$

3.1. Type I

The incident proton was seen to be scattered and a short heavy-recoil track was observed at the point of interaction. These events were classified as elastic or inelastic scatters in carbon.

3.2. Type II

At the point of interaction two heavily ionizing tracks were seen to originate, one being in general very short and the other a few centimetres in length. These events were assumed to be $(p, p'3\alpha)$ reactions in which the proton had extremely low energy, and two of the α particles were emitted in the same direction causing them to appear as one. Kinematic calculations were applied to see if this assumption was valid for each event of this type.

3.3. Type III

In this case three tracks were seen to originate at the point of interaction. Two of these were very short and more heavily ionizing than the other which generally left the illuminated region of the chamber. These events were again assumed to be $^{12}C(p, p'3\alpha)$ in which two of the α particles were emitted in the same direction and therefore appeared as one. Again this was confirmed by kinematic calculations.

3.4. Type IV

In this type of reaction, four tracks originated at the point of interaction, three of these being short and more heavily ionizing than the fourth which sometimes left the illuminated region of the chamber. These events were obviously $^{12}C(p, p'3\alpha)$.

We now note that types II, III and IV are all $^{12}C(p, p'3\alpha)$ reactions. However, in the presentation of our results we keep these types separate, and it will become clear that the differences in appearance were brought about by the differences in the reaction mechanism.

4. Results

4.1. Type II events

Only 23 such events were observed. Figure 1(*a*) shows the Q values obtained assuming the mechanism $p + {}^{12}C \rightarrow \alpha_1 + {}^9B^*$. The α particle used is always the most energetic. Figure 1(*b*) shows a similar plot of the Q values obtained for the intermediate stage ${}^8Be \rightarrow \alpha_2 + \alpha_3$. The arrows on these plots show the positions of the ground states of the two nuclei ^9B and ^8Be.

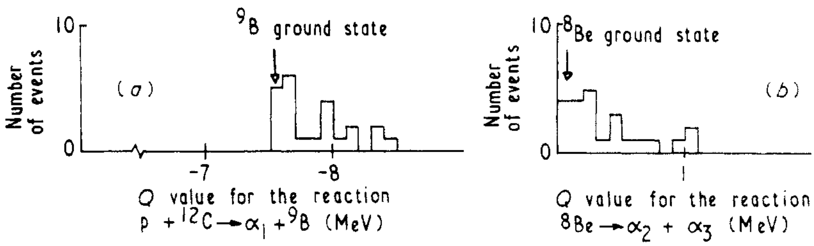

Figure 1. Results of type II events.

4.2. Type III events

A total of 133 events of this type were observed. Figure 2 is the triangle plot for the reaction. Since three of the product particles are identical, each event contributes three points to this plot. The histograms shown are the projections of the plotted points on the axes, and the arrows indicate the positions of the known levels of ^5Li and ^8Be. The boundary line of the triangle is that for the mean incident energy, and the points above this line are due to events in the front of the cloud chamber, where the incident proton energy is higher.

4.3. Type IV events

A total of 123 events of this type were observed and figure 3 is the triangle plot for these events. The corresponding histograms are again plotted.

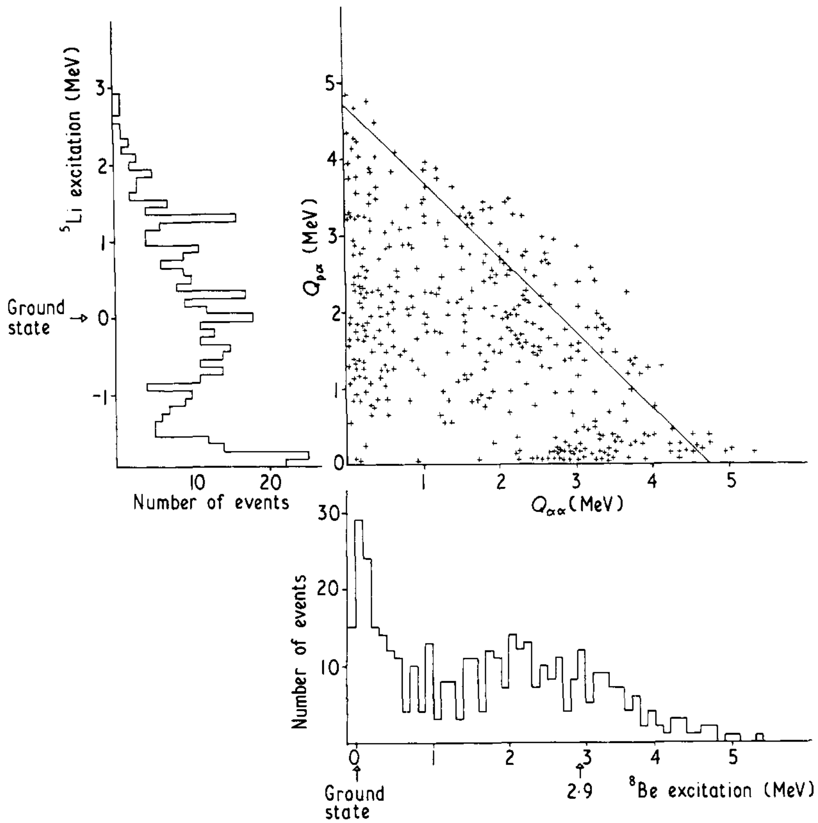

Figure 2. Triangle plot for type III events.

4.4. Cross sections

The total number of ^{12}C(p, p'3α) events is 279 and this corresponds to a cross section of 154 mb, as shown in table 2. The inelastic scattering cross sections to the first three levels in ^{12}C are taken from the work of Peele (1957) since our classification of these levels could be confused with elastic scattering. With the higher levels in ^{12}C, the scattered proton always stopped in the cloud chamber, so ranging gave the level involved, and we therefore quote our own results. The total reaction cross section can therefore be evaluated and is found to be 446 mb.

5. Discussion

5.1. Type II events

In view of the peaking observed in figure 1 at the ground state of ^{9}B and ^{8}Be, it was decided that all these events should be classed as mechanism (*e*) in table 1.

5.2. Type III events

In figure 2 we observe a large clustering of events in the region $0 \leqslant Q_{\alpha\alpha} \leqslant 0{\cdot}7$ MeV,

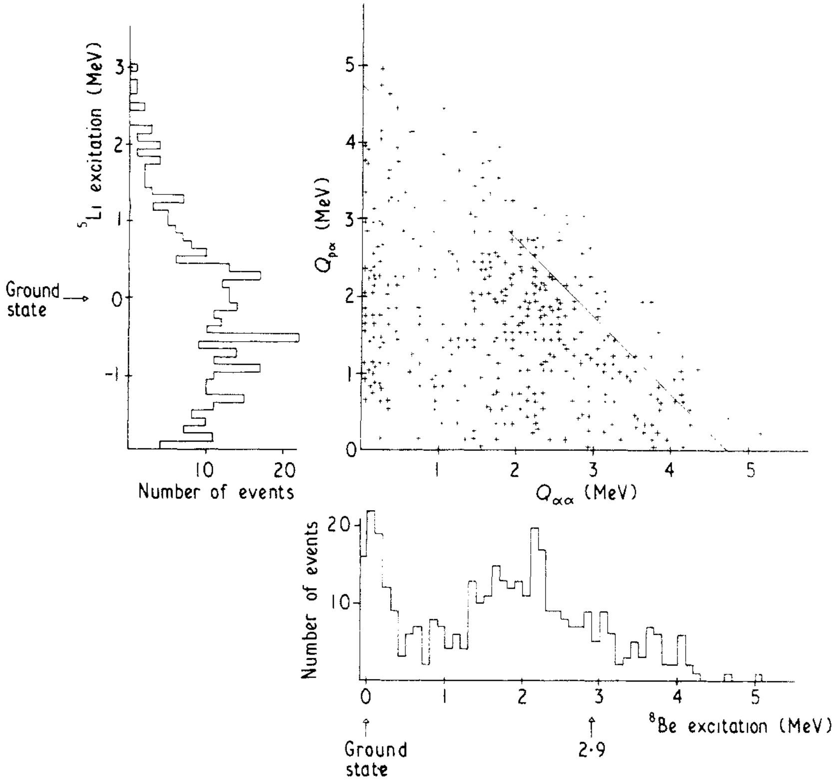

Figure 3. Triangle plot for type IV events.

Table 2. $^{12}C+p$ cross sections at $13{\cdot}2\pm0{\cdot}6$ MeV

Reaction	Level in residual nucleus (MeV)	Cross section (mb)
(p, p′γ)	4·43	$230{\cdot}0\pm11{\cdot}5$†
	7·66	$4{\cdot}7\pm0{\cdot}3$†
	9·63	$51{\cdot}0\pm7{\cdot}7$†
	10·10	$2{\cdot}8\pm1{\cdot}2$
	10·83	$1{\cdot}1\pm0{\cdot}8$
	11·10	$2{\cdot}8\pm1{\cdot}2$
(p, p′3α)		$154{\cdot}0\pm9{\cdot}2$
		$\sigma_T = 446{\cdot}4\pm16{\cdot}6$

† From Peele (1957).

and we therefore classify the 112 events in this cluster as showing the presence of the ^{8}Be ground state. Now in these events two of the α particles, α_i and α_j, have been accounted for, and so any ^{5}Li state can yield only the α_k particle. When this is looked for no ^{5}Li levels are observed and so the decay of these 112 events is by mechanisms (*c*), (*e*) or (*g*).

For these 112 events we can now study the $^{12}C(p, p'\alpha)^{8}Be$ reaction using the Dalitz plot shown in figure 4. The closed line defines the kinematic area for the mean energy of the experiment, but events at the front and back of the chamber may lie outside this area. We observe 31 events in a peak corresponding to the ground state of ^{9}B and therefore classify these events as mechanism (*e*). No other peaks are observed on either axis.

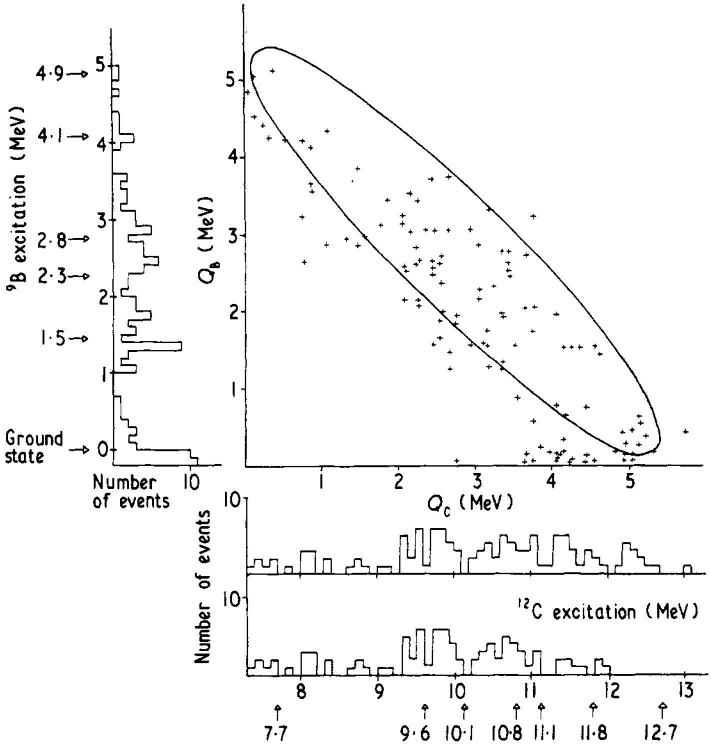

Figure 4. Dalitz plot for type III events which display the ground state of ^{8}Be. The ^{9}B excitation (formed from $^{8}Be + p$) is plotted against the ^{12}C excitation (formed from $^{8}Be + \alpha$).

Figure 5 shows a further investigation of the remaining type III events. There is no evidence for participation of any of these intermediate nuclei and so the classification is as shown in table 3.

5.3. *Type IV events*

Figure 3 indicates that the ground state of ^{8}Be is again participating in the reaction. The 74 events with $0 \leqslant Q_{\alpha\alpha} \leqslant 0{\cdot}5$ MeV were assigned as decaying via this level. From the Dalitz plot in figure 6 for these 74 events, we see that 12 decay through the ground state of ^{9}B, and there is no conclusive evidence for other levels in ^{9}B or ^{12}C.

The remaining 49 events which do not go through the ^{8}Be ground state are studied in figure 7. Again one can say conclusively that there is no participation of ^{8}Be or ^{5}Li

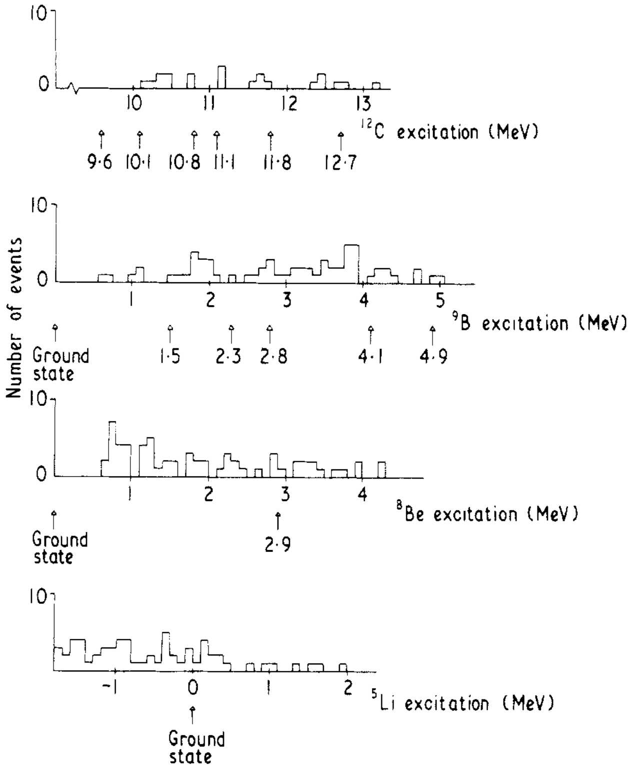

Figure 5. Excitation of ^{12}C, ^{9}B, ^{8}Be and ^{5}Li for type III events which do not show the ground state of ^{8}Be.

Table 3. Results of type III events

Reaction mechanism	Number of events
(*a*)	21
(*e*)	31
(*c*), (*g*), (*e*) (not ground state of ^{9}B)	81

levels, and there is no definite evidence for levels in ^{12}C or ^{9}B. The mechanisms are therefore as shown in table 4.

5.4. *Total cross section*

The most striking feature of the total cross section is that 30 % of it is made up from the (p, p'3α) cross section. This of course results from the absence of other modes of decay.

Maxson's result of 43 ± 8 mb for the (p, α) reaction to the ground state is in agreement with our result of 36 ± 4 mb for transitions to the ground state of ^{9}B, but our results indicate that this is only a small part of the cross section for four body break-up.

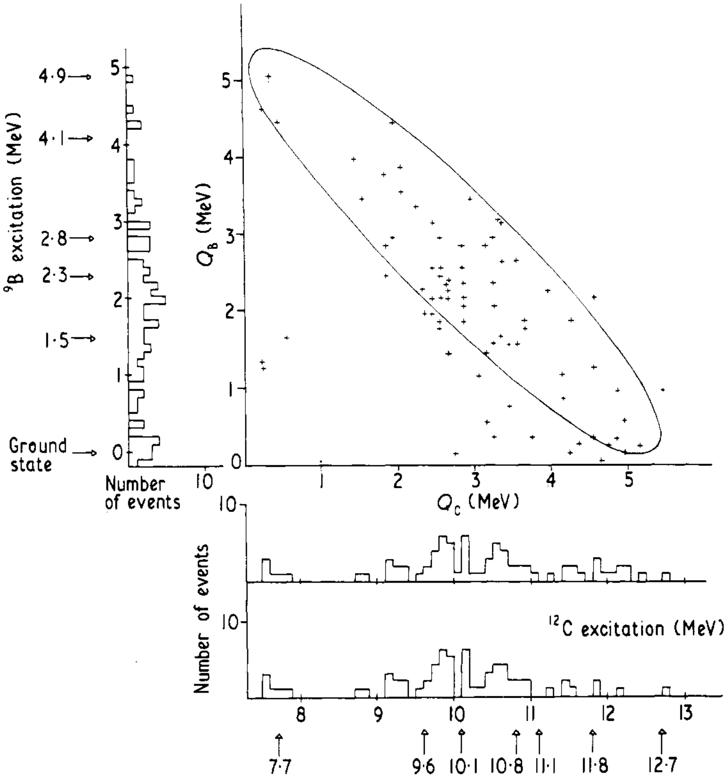

Figure 6. Dalitz plot for type IV events which display the ground state of ^{8}Be. The ^{9}B excitation (formed from ^{8}Be+p) is plotted against the ^{12}C excitation (formed from ^{8}Be+α).

The total cross section measured here is about 10% higher than theoretical predictions using the optical model, but there is no reason to think that the optical model is satisfactory in the present case, where the density of levels in the compound nucleus is low.

In figure 8 we show a comparison of the total cross section in carbon, with that in nitrogen, oxygen and neon, as measured by the same technique (MacLeod and Reid 1966, Chapman and MacLeod 1967). The line drawn is a least squares fit to the carbon nitrogen and neon results, based on the continuum theory. The oxygen result was clearly anomalously low, and it was not used in this fit. The gradient of the line gives a value for the radius parameter r_0 as $1{\cdot}12 \pm 0{\cdot}09$ fm.

6. Conclusion

Table 5 summarizes the results for the mechanism of the ^{12}C(p, p′3α) reaction. We note the absence of excited states of ^{8}Be and ^{9}B, and of any levels in ^{5}Li, as would be expected at a low energy of 13 MeV, but the absence of evidence for levels in ^{12}C could be due to our failure to resolve them.

The measurement of the cross section for the ^{12}C(p, p′3α) reaction is particularly important in view of the large number of low energy particles emitted. These particles

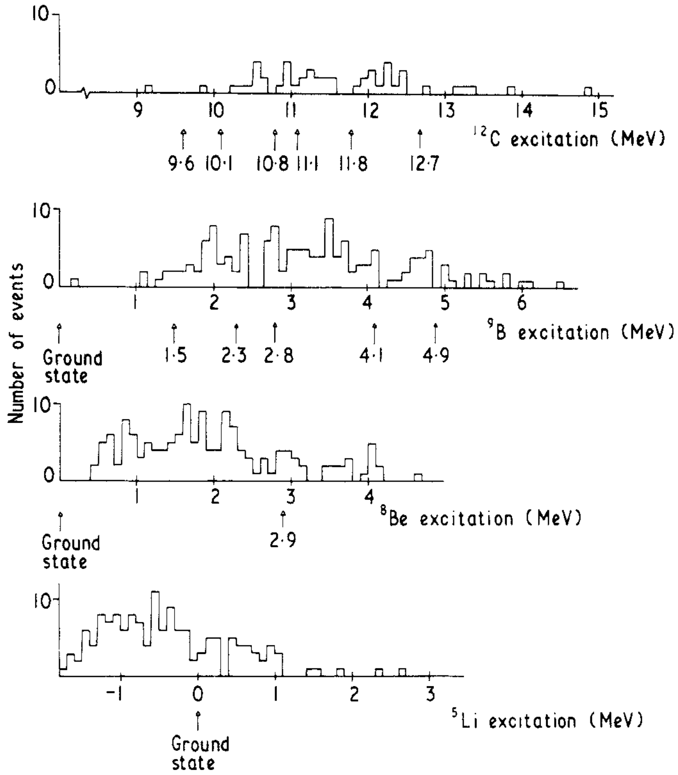

Figure 7. Excitations of ^{12}C, ^{9}B, ^{8}Be and ^{5}Li for type IV events which do not show the ground state of ^{8}Be.

Table 4. Results of type IV events

Reaction mechanism	Number of events
(*a*)	49
(*e*)	12
(*c*), (*g*), (*e*) (not ground state of ^{9}B)	62

Table 5. The mechanism of the reaction $p + {}^{12}C \rightarrow p' + 3\alpha$

Decay scheme	Number of events	Percentage of events
(*a*)	70	25
(*e*) (ground state of ^{9}B and ^{8}Be)	66	24
(*c*), (*g*), (*e*) (not ground state of ^{9}B)	143	51
(*b*), (*d*), (*f*), (*h*), (*i*)	0	0

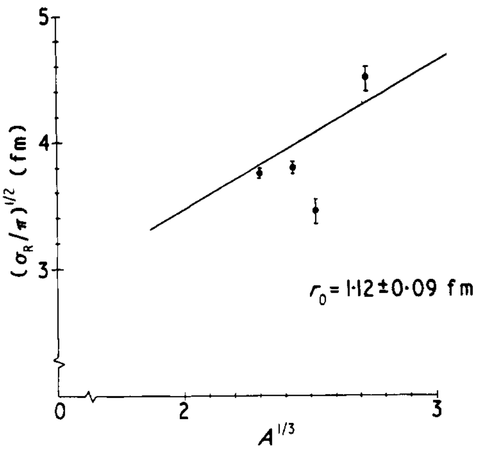

Figure 8. Variation of cross section with mass number.

would not be observed in counters, or in nuclear emulsions which have much higher stopping power.

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