Target Dependence in Breakup Reactions

Neil Curtis

This report outlines some of the preliminary results of an experiment performed at ANU in June 1996. The aim of this experiment was to search for the breakup of ^{24}Mg, ^{28}Si and ^{32}S from carbon, lithium, oxygen and beryllium targets. This was in an attempt to help establish the reaction mechanism populating the breakup states seen previously in the ^{12}C(^{24}Mg,^{12}C ^{12}C)^{12}C, ^{12}C(^{24}Mg,^{12}C ^{16}O)^{8}Be and ^{12}C(^{24}Mg,^{16}O ^{16}O)^{4}He channels.

The experiment was performed using a 170 MeV ^{24}Mg beam and targets of 380 μg/cm^2 carbon, 300 μg/cm^2 lithium oxide (Li_2O) and 350 μg/cm^2 beryllium (^{9}Be). Additional calibration beams of 54.4 MeV and 85.0 MeV ^{12}C and 63.8 MeV and 91.8 MeV ^{16}O were used. The breakup fragments were detected by two gas-silicon-scintillator hybrid telescopes, this being the first time that these detectors have been used in an experiment. The telescopes were placed at arm angles of 16°/16° for the majority of the running, and at a distance of 170 mm from the target (as measured from the front face of the silicon strip detectors). The gas ΔE detectors were held at 60 torr of propane, and 3.5 μm mylar windows were used.

The ^{12}C + ^{12}C Breakup of ^{24}Mg

In Figure 1 the reconstructed total and excitation energy spectra are shown for the ^{12}C(^{24}Mg,^{12}C ^{12}C)^{12}C reaction. Both of these spectra agree well with previous results. The Q_{ggg} peak in the total energy spectrum lies at a measured energy of (155.06 $\pm$ 0.01) MeV, the predicted position being 155.07 MeV (using the average of the energy lost in the target calculated by the codes DEDX [1] and TARGET [2]). The excitation energy spectrum is in good agreement with that obtained in a previous experiment by Curtis *et al.* [3], and when overlaid upon this earlier data agrees to within one channel (100 keV). Both the total energy and excitation energy spectra therefore indicate that the energy and position calibrations and the ΔE reconstruction have been performed correctly in the sort code used to analyse the data. Data were taken from the carbon target to allow the above check with previous results to be made.

The value of the double differential cross-section obtained for this reaction channel is $\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = (0.22 \pm 0.02)$ mb sr^{-2}. This compares well to the range of values found in previous measurements of this channel of (0.12 $\pm$ 0.01) mb sr^{-2} [4] to (1.21 $\pm$ 0.18) mb sr^{-2} [3]. This order of magnitude variation is due to the range of breakup angles sampled and θ^*/ψ coverage of the various experiments, and makes direct comparisons of cross-sections between different measurements very difficult. A second reason for taking data on a carbon target was therefore to provide a normalisation for the cross-sections obtained from other breakup channels measured in the experiment.

In Figure 2 the reconstructed total energy spectra for the Li_2O(^{24}Mg,^{12}C ^{12}C) channel are shown. In Figure 2(a) the data has been analysed assuming that the breakup occurred following an interaction with an ^{16}O target nucleus. In Figure 2(b) the recoil has been assumed to be ^{7}Li, and in Figure 2(c) a recoiling ^{12}C nucleus has been used (the Li_2O target used had a nominal 10 μg/cm^2 carbon backing). Clear Q_{ggg} peaks can be observed in both Figures 2(a) and 2(c), and both appear at energies in good agreement with the

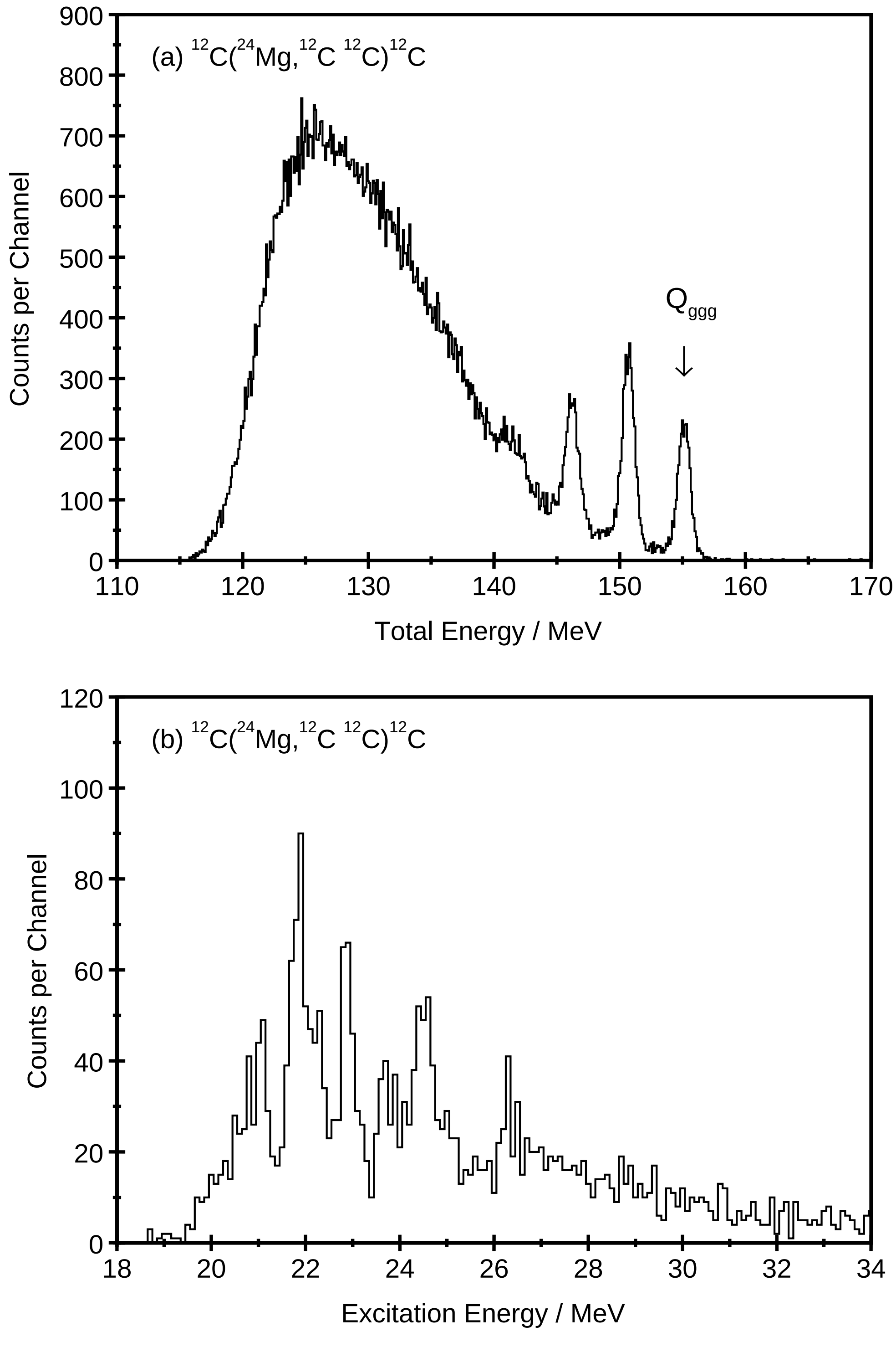

Figure 1: (a) Total energy (including predicted Q_{ggg} peak position) and (b) excitation energy spectra for the ^{12}C(^{24}Mg,^{12}C ^{12}C)^{12}C reaction.

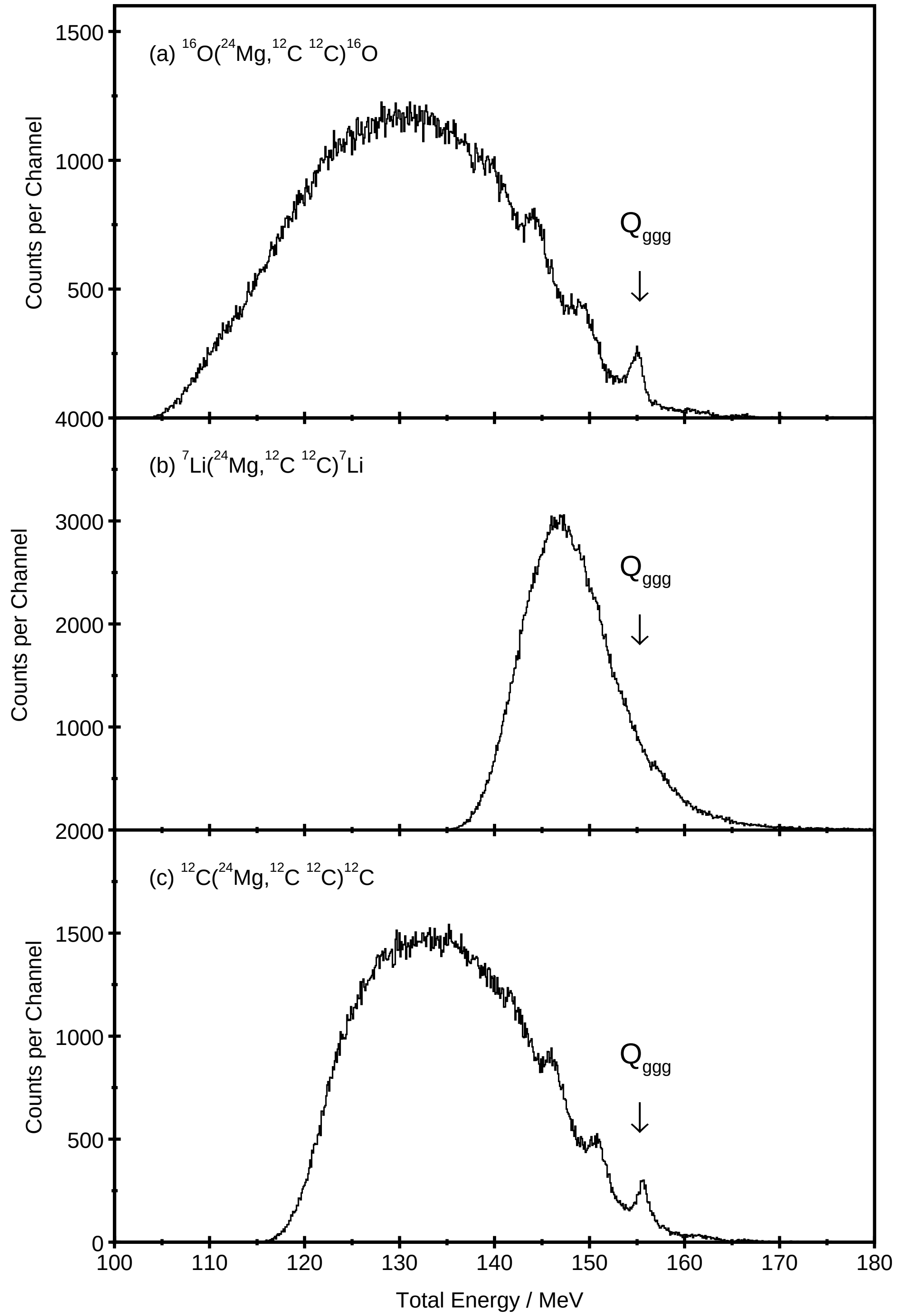

Figure 2: Total energy spectra for the $Li_2O(^{24}Mg,^{12}C\ ^{12}C)$ reaction, assuming a recoil of (a) ^{16}O, (b) ^{7}Li and (c) ^{12}C. The predicted Q_{ggg} peak positions are indicated.

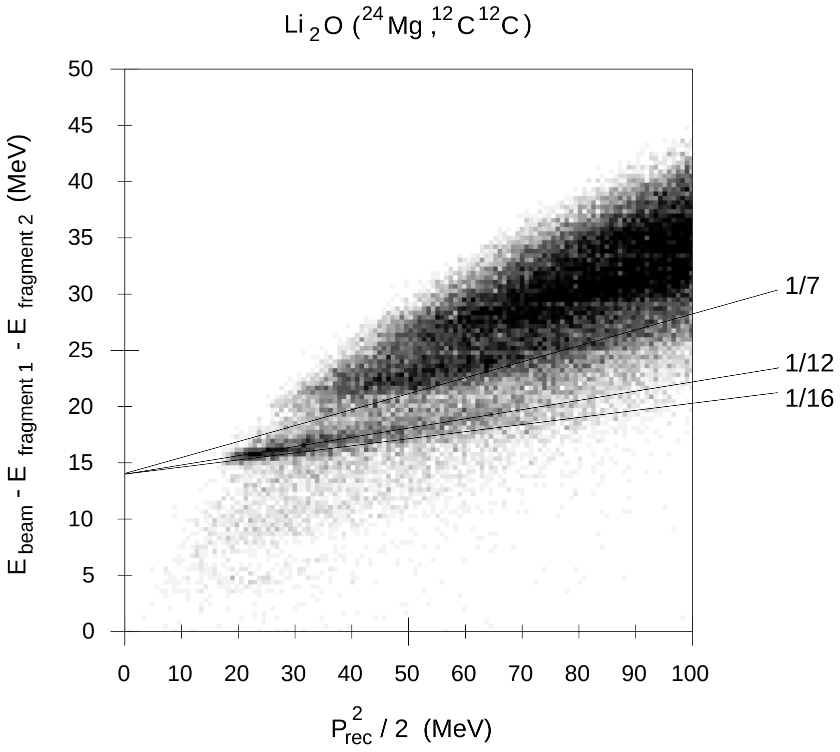

Figure 3: Catania plot for the $Li_2O(^{24}Mg,^{12}C\ ^{12}C)$ reaction. The predicted slopes for ^{7}Li, ^{12}C and ^{16}O recoils are indicated.

predicted Q_{ggg} energies. There is no evidence for a Q_{ggg} peak in Figure 2(b), the data reconstructed assuming a ^{7}Li recoil.

In order to try to distinguish between the two different target possibilities of ^{12}C and ^{16}O a Catania plot has been produced for the data. This is shown in Figure 3. Overlaid upon the data are the predicted slopes for recoils of mass 7, 12 and 16. It can be seen that both the predicted slopes for mass 12 and 16 recoils lie over the broad band of data running from 20 MeV (x axis) and 15 MeV (y axis) to 60 MeV (x axis) and 18 MeV (y axis). Therefore it is not possible to distinguish which of the two possible target/recoil masses is more likely.

By gating on the Q_{ggg} band in the Catania plot shown in Figure 3 an excitation spectrum has been obtained for the ^{12}C + ^{12}C breakup of ^{24}Mg from the Li_2O target, and this is shown in Figure 4. This spectrum appears remarkably similar to that shown in Figure 1(b) for the $^{12}C(^{24}Mg,^{12}C\ ^{12}C)^{12}C$ channel, suggesting that the breakup may be arising from reactions with the carbon backing on the Li_2O target. However, a comparison of the double differential cross-section for the $^{12}C(^{24}Mg,^{12}C\ ^{12}C)^{12}C$ reaction ($\frac{d^2\sigma}{d\Omega_1 d\Omega_2}$ = (0.22 $\pm$ 0.02) mb sr^{-2}) with that obtained from the data shown in Figure 4 suggests otherwise. Assuming all of the data appearing in Figure 4 is due to interactions with carbon target nuclei it is found that the total thickness of carbon in the target would need to be (235 $\pm$ 25) μg/cm^2 in order to produce the statistics seen in the excitation spectrum (Figure 4). The nominal thickness of the carbon backing on the Li_2O target was 10 μg/cm^2, and the remaining $\sim$ 225 μg/cm^2 required seems to be too great an amount to be due to carbon build up on the target during the $\sim$ 39 hours of beam exposure for this target (at an average beam current of only 5 enA). It therefore appears that the additional statistics may be arising from breakup from the oxygen in the target, and it is clear that

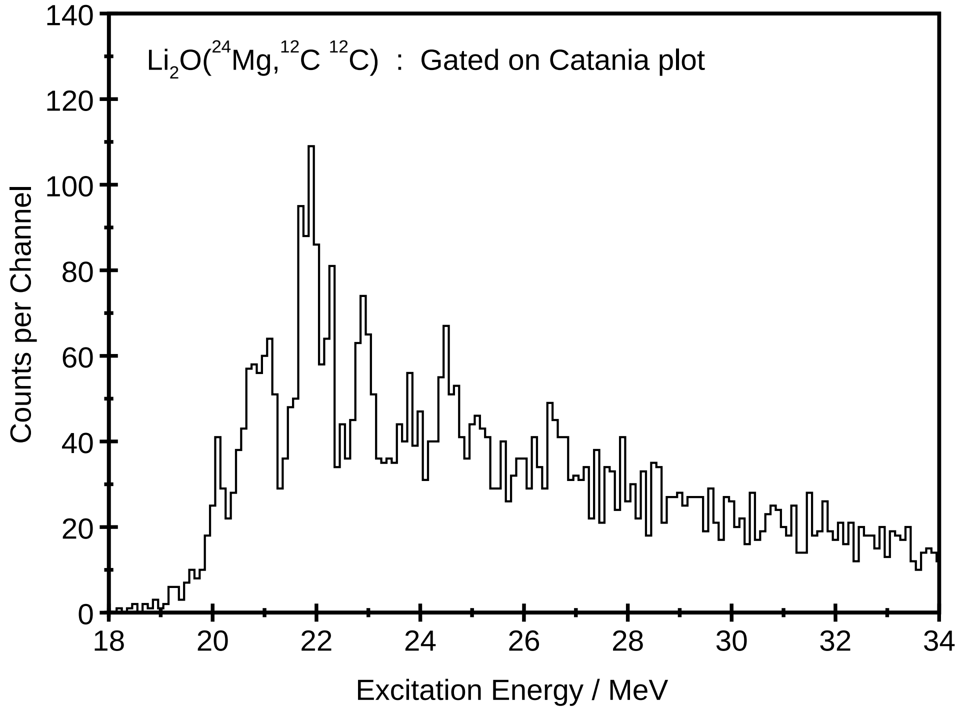

Figure 4: Excitation energy spectrum for the $Li_2O(^{24}Mg,^{12}C\ ^{12}C)$ reaction, gated on the ^{12}C and ^{16}O recoil line in the Catania plot.

this result merits further attention in the analysis. The next stage into the investigation of possible breakup from the ^{16}O target will be to determine the cross-section for the breakup for each data run in turn, in an attempt to observe any change in cross-section value (and therefore carbon build up) with time.

The total energy spectrum for the $^{9}Be(^{24}Mg,^{12}C\ ^{12}C)^{9}Be$ reaction is shown in Figure 5, as is the theoretical Q_{ggg} peak position. There appears to be no evidence for structure in this spectrum. The Catania plot produced for this channel, shown in Figure 6, also lacks structure, indicating that ^{12}C + ^{12}C breakup of ^{24}Mg is not seen from the ^{9}Be target. Interestingly, the absence of any structure in either the total energy spectrum or the Catania plot indicates that carbon build up on the ^{9}Be target was minimal during the experiment, as significant build up would be expected to give rise to Q_{ggg}, Q_{gg} and Q_g peaks as seen in the carbon target data shown in Figure 1(a). This in turn suggests that carbon build up on the Li_2O target may also be minimal, although it is noted that the different physical characteristics of ^{9}Be and Li_2O are likely to effect the rate of carbon build up on these two target materials. If the rate of carbon build up on the Li_2O target was low, however, then the ^{12}C + ^{12}C breakup of ^{24}Mg seen from this target may indeed arise from the oxygen content, as previously mentioned.

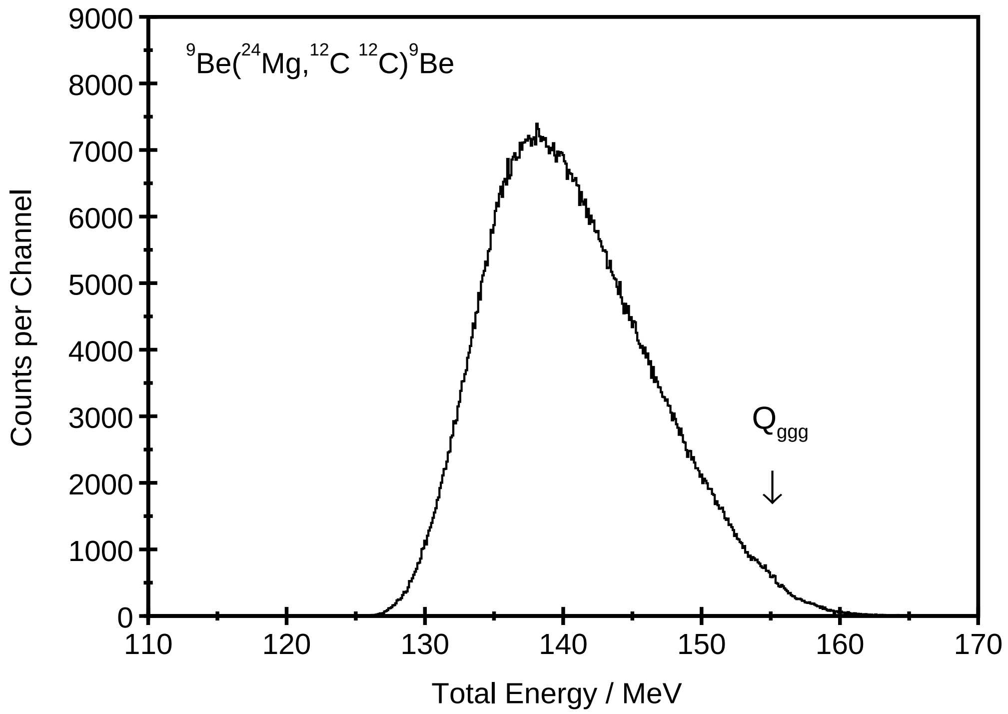

Figure 5: Total energy spectrum for the ^{9}Be(^{24}Mg,^{12}C ^{12}C)^{9}Be reaction. The predicted Q_{ggg} peak position is indicated.

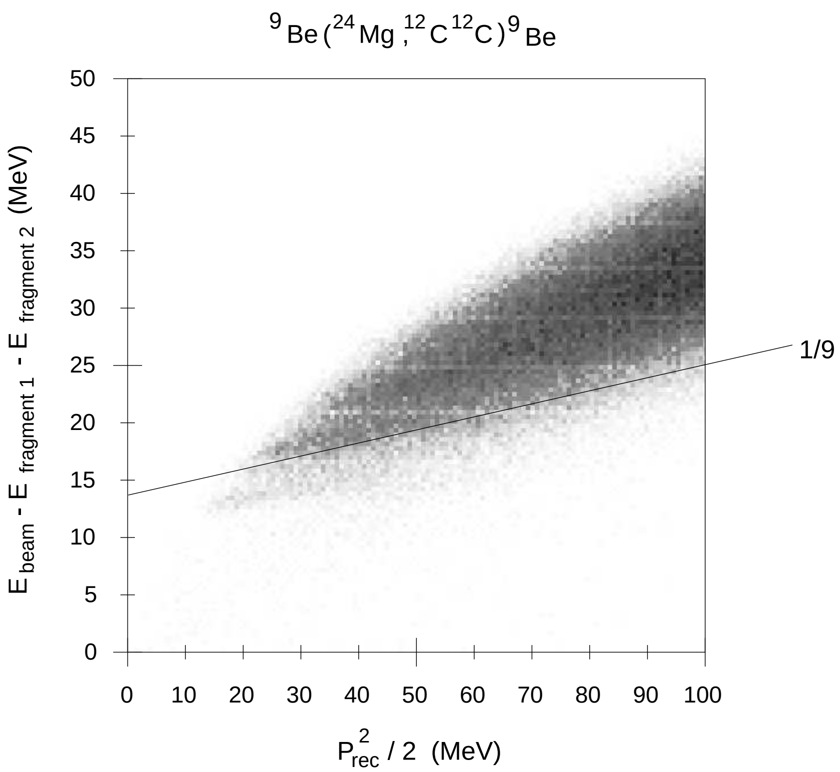

Figure 6: Catania plot for the ^{9}Be(^{24}Mg,^{12}C ^{12}C)^{9}Be reaction. The predicted slope for a ^{9}Be recoil is indicated.

^{12}C target		^{7}Li target		^{9}Be target	
E_x (MeV)	ΔE (keV)	E_x (MeV)	ΔE (keV)	E_x (MeV)	ΔE (keV)
27.98 ± 0.05	840 ± 132	28.12 ± 0.02	516 ± 40	28.12 ± 0.01	512 ± 26
29.81 ± 0.03	814 ± 84	29.78 ± 0.02	1234 ± 72	29.84 ± 0.02	1340 ± 54
33.23 ± 0.03	838 ± 74	33.63 ± 0.04	2366 ± 152	33.54 ± 0.03	1702 ± 98

Table 1: Energies and widths for the states observed in the ^{12}C + ^{16}O breakup of ^{28}Si.

The ^{12}C + ^{16}O Breakup of ^{28}Si

The reconstructed total and excitation energy spectra for the ^{12}C(^{24}Mg,^{12}C ^{16}O)^{8}Be reaction are shown in Figure 7. As for the ^{12}C + ^{12}C breakup data shown in Figure 1, both of the spectra shown in Figure 7 agree well with previous results [3]. This is again seen as an indication that the calibrations and sort codes used are correct. The value of the double differential cross-section obtained for this channel is $\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = (0.61 \pm 0.06)$ mb sr^{-2}.

In Figure 8 the total energy spectra for the ^{12}C + ^{16}O breakup from the Li_2O target are shown. In Figure 8(a) the data have been analysed assuming a ^{12}C recoil, in Figure 8(b) assuming a ^{3}H (triton) recoil and in Figure 8(c) a ^{8}Be recoil. In Figures 8(a) and (c) peaks can be observed at $\sim$ 159 MeV, but in both cases these are approximately 5 MeV higher than the predicted Q_{ggg} peak position. However, in Figure 8(b) the peak seen in the total energy spectrum does appear at the expected energy, suggesting that the breakup is occurring from the ^{7}Li in the target. This is supported by the Catania plot, which is shown in Figure 9. In this spectrum there is no evidence for structure along the lines predicted for mass 8 and 12 recoil nuclei, but there is a band of data ranging from 0 MeV (x axis) and 9 MeV (y axis) to 10 MeV (x axis) and 12 MeV (y axis). This lies along the line predicted for a mass 3 recoil, indicating that the breakup is occurring from the ^{7}Li within the target.

Gating on the data along the predicted 1/3 slope in the Catania plot (Figure 9) allowed the excitation energy spectrum for the ^{7}Li(^{24}Mg,^{12}C ^{16}O)t reaction to be obtained. This is shown in Figure 10. In this spectrum 3 distinct states may be seen, appearing at energies of 28.1 MeV, 29.8 MeV and 33.6 MeV. These energies agree well with those for the states seen in the ^{12}C(^{24}Mg,^{12}C ^{16}O)^{8}Be channel (Figure 7(b)), these being 28.0 MeV, 29.8 MeV and 33.2 MeV. This suggests that the same states are being populated in the reactions off both the ^{12}C and ^{7}Li targets. The measured centroids and widths of the states observed are listed in Table 1. The measured double differential cross-section for the ^{7}Li(^{24}Mg,^{12}C ^{16}O)t reaction is $\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = (0.91 \pm 0.09)$ mb sr^{-2}.

The total energy and excitation energy spectra for the ^{12}C + ^{16}O breakup of ^{28}Si from the ^{9}Be target are shown in Figure 11. Gating on the peak seen in the total energy spectrum just below the predicted Q_{ggg} peak position allowed the excitation energy spectrum seen in Figure 11(b) to be obtained. Additional gating was also applied to the Catania plot produced for this channel. In the excitation energy spectrum several distinct peaks may be observed, and the energies of these states agree well with those observed in both the ^{12}C and ^{7}Li target data sets. The measured energies and widths of the states are given in Table 1. The $\sim$ 2 MeV shift in the position of the experimental Q_{ggg} peak from the predicted energy has yet to be explored in the analysis, but may be due to the use

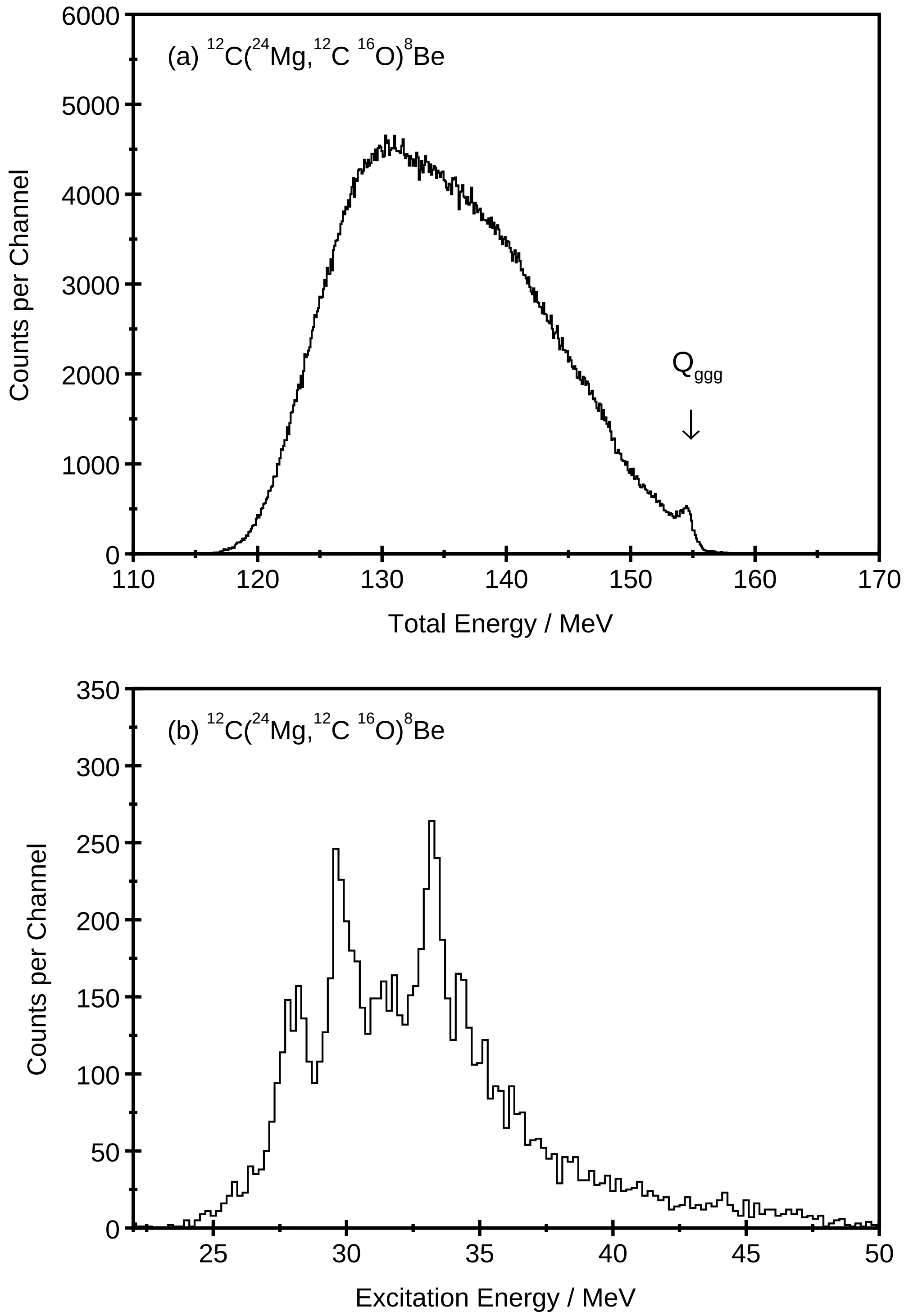

Figure 7: (a) Total energy (including predicted Q_{ggg} peak position) and (b) excitation energy spectra for the ^{12}C(^{24}Mg,^{12}C ^{16}O)^{8}Be reaction.

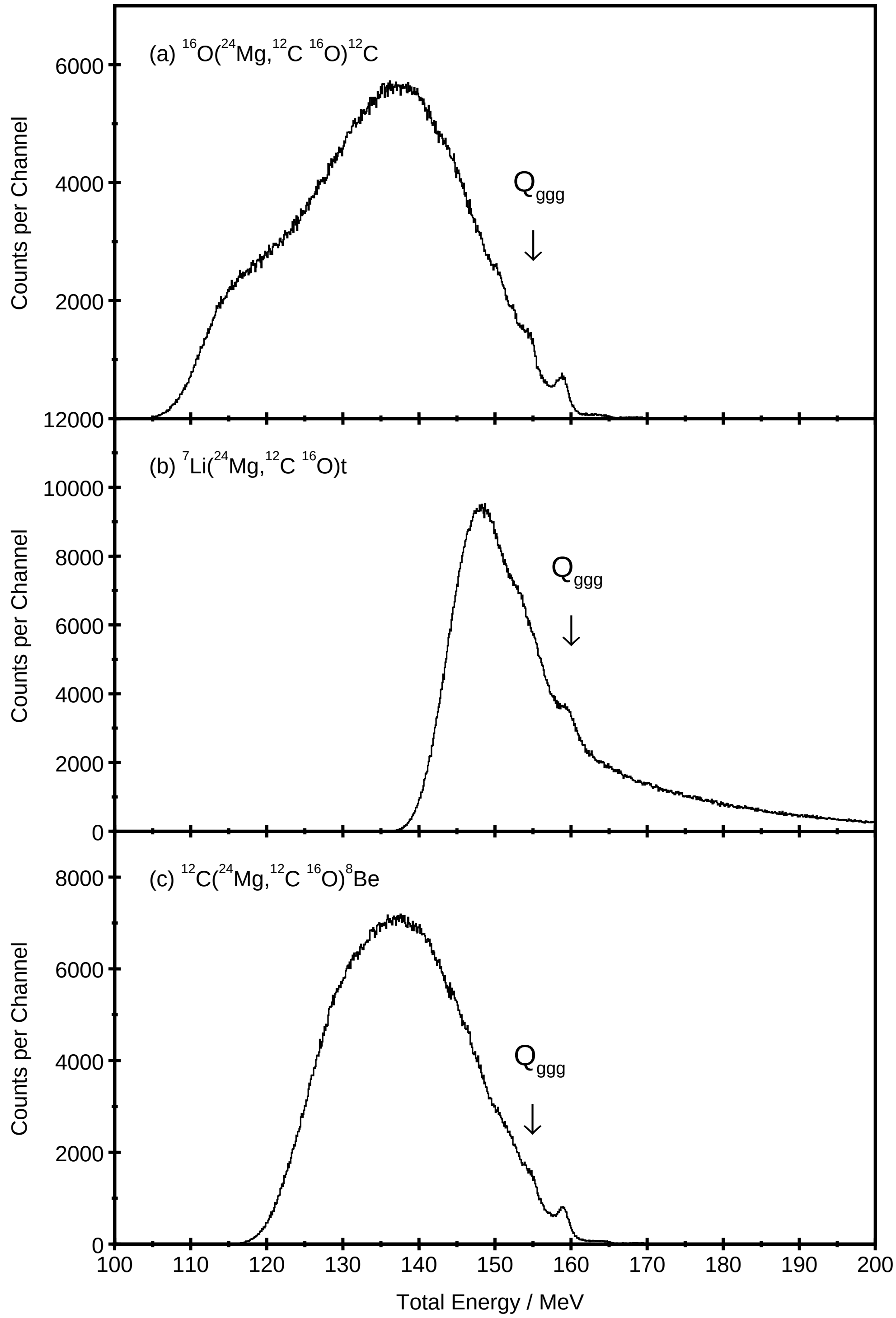

Figure 8: Total energy spectra for the $Li_2O(^{24}Mg,^{12}C\ ^{16}O)$ reaction, assuming a recoil of (a) ^{12}C, (b) ^{3}H (t) and (c) ^{8}Be. The predicted Q_{ggg} peak positions are indicated.

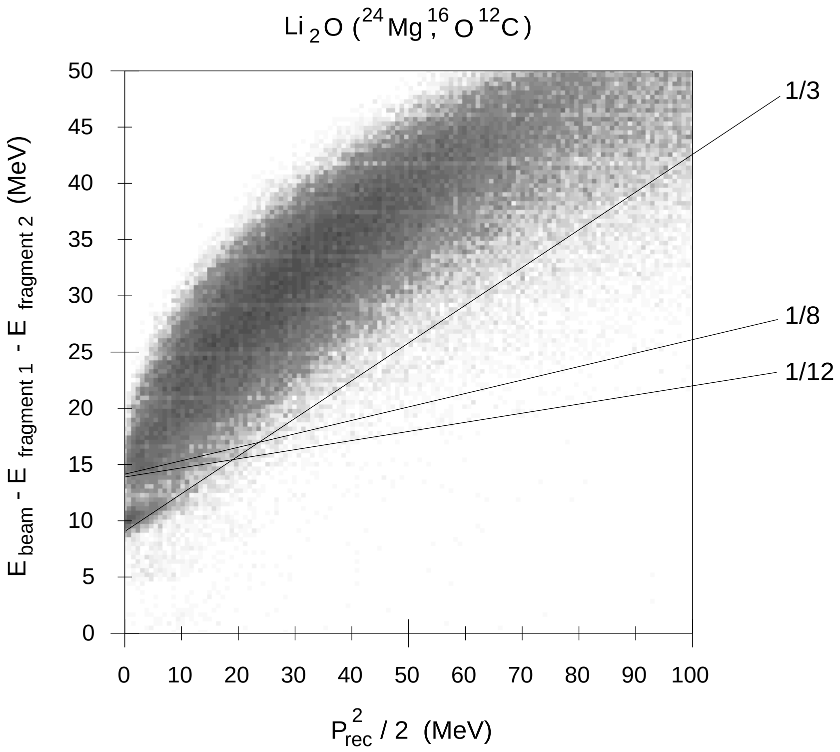

Figure 9: Catania plot for the $Li_2O(^{24}Mg,^{12}C\ ^{16}O)$ reaction. The predicted slopes for ^3H (t), ^8Be and ^{12}C recoils are indicated.

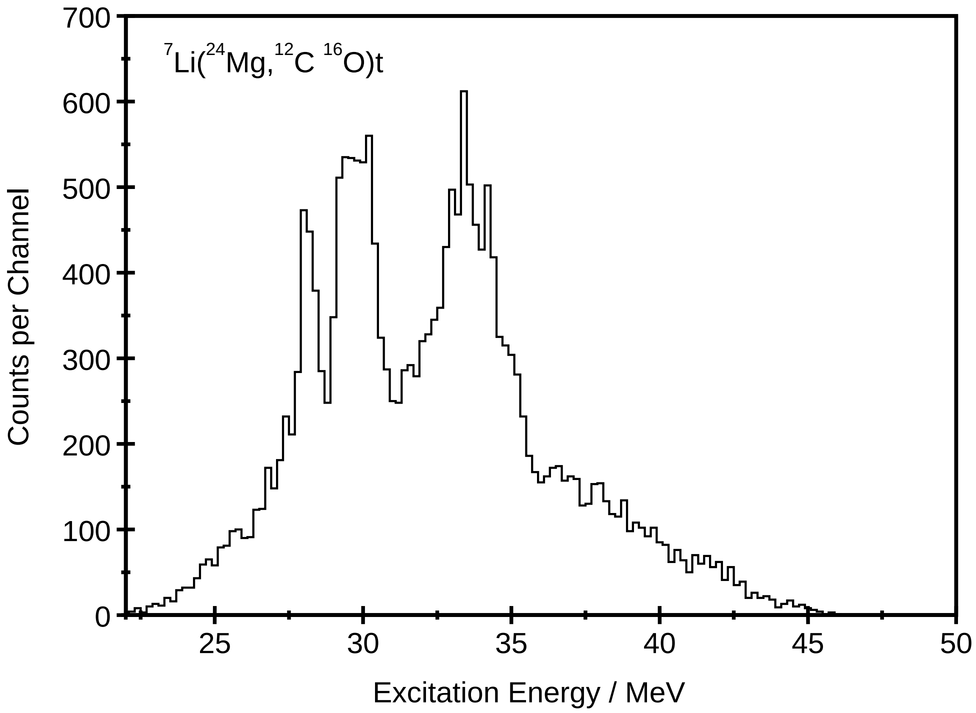

Figure 10: Excitation energy spectrum for the $^7Li(^{24}Mg,^{12}C\ ^{16}O)t$ reaction, gated on the ^7Li recoil line in the Catania plot.

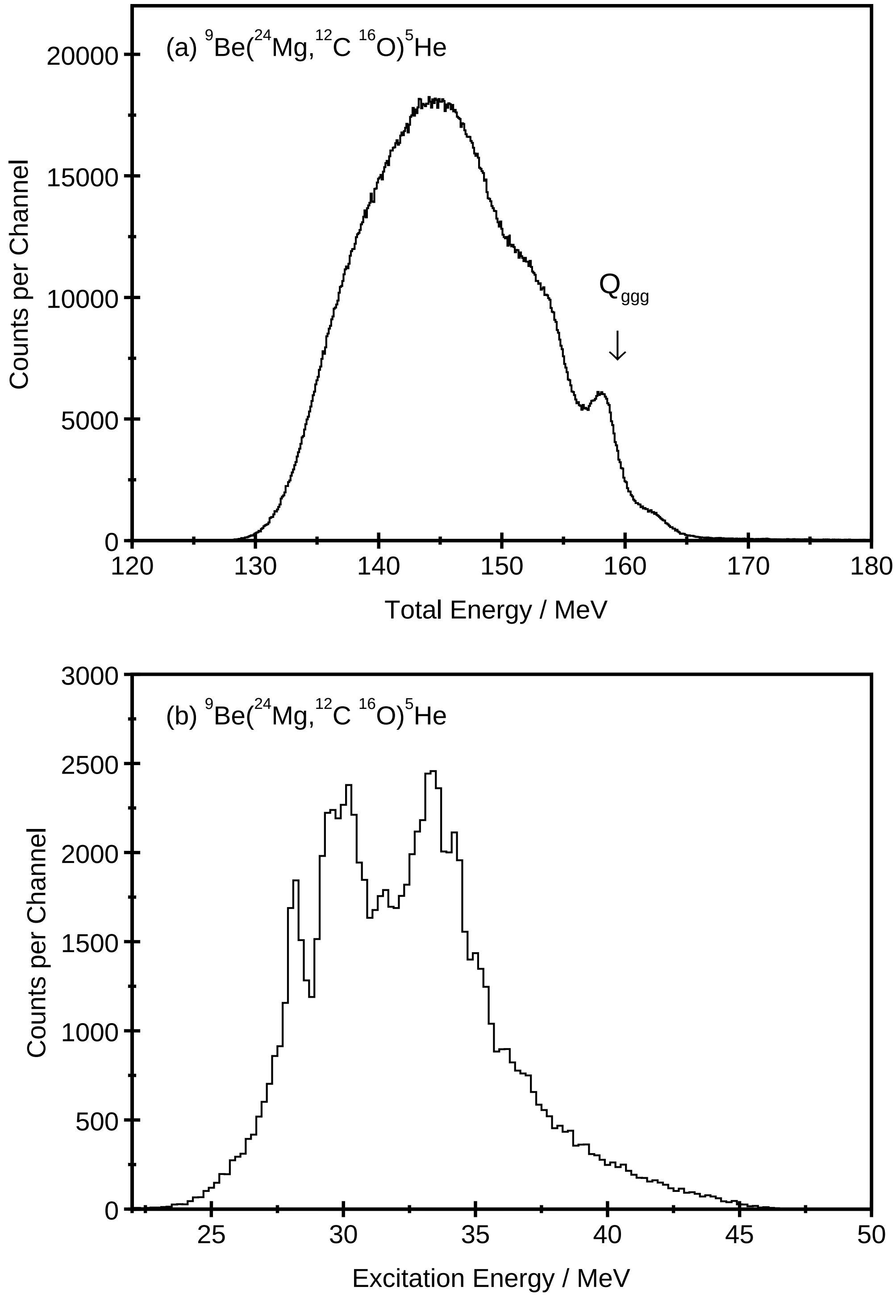

Figure 11: (a) Total energy (including predicted Q_{ggg} peak position) and (b) excitation energy spectra for the ^{9}Be(^{24}Mg,^{12}C ^{16}O)^{5}He reaction.

of an inaccurate target thickness in the reconstruction of the events. It is noted that the ^{9}Be target used in the experiment was split, which caused the central portion of the foil to roll up. It is therefore likely that the beam particles and breakup fragments passed through a significantly greater amount of material than the 350 μg/cm^2 assumed in the analysis. This will be investigated by studying the position of the Q_{ggg} peak as a function of the target thickness used in the event reconstruction. The measured double differential cross-section for the ^{9}Be(^{24}Mg,^{12}C ^{16}O)^{5}He reaction (assuming a target thickness of 350 μg/cm^2) is $\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = (2.40 \pm 0.24)$ mb sr^{-2}.

The excitation energy spectra for the ^{12}C + ^{16}O breakup of ^{28}Si obtained from the ^{9}Be, ^{7}Li and ^{12}C targets are shown for comparison in Figure 12. It can be seen that the positions of the observed peaks are nearly identical for the three different channels shown. Although spin assignments have not been made for the states, the clear resemblance between the spectra indicates that the ^{12}C + ^{16}O breakup of the ^{28}Si nuclei is occurring from the same states in all three reaction channels studied. This suggests that the reaction mechanism populating the resonant ^{28}Si nuclei is alpha transfer. Future work will include analysis of the breakup angular correlations to investigate possible spin information.

The ^{16}O + ^{16}O Breakup of ^{32}S

In Figure 13 the total energy and excitation energy spectra for ^{12}C(^{24}Mg,^{16}O ^{16}O)^{4}He breakup are shown. These spectra agree well with the previous measurement of this channel [3, 5], again indicating that the calibrations used in the analysis are correct. The total energy spectrum for the ^{16}O + ^{16}O breakup of ^{32}S from the ^{9}Be target is shown in Figure 14(a). There is no evidence for a Q_{ggg} peak in either this spectrum or the Catania plot produced from the data. It is seen in Figure 14(a) that the data extend above the beam energy (170 MeV). This is due to the large energy range (up to 200 MeV) of the reconstructed recoil neutrons (the summed energy spectrum of the two ^{16}O fragments has no significant yield above 150 MeV, suggesting that the problem does not lie with the energy calibrations). The reason for the large range of recoil energies has yet to be determined in the analysis.

The data extending above the beam energy in the total energy spectrum has been removed by software gating, in an attempt to observe any evidence for a Q_{ggg} peak that may be hidden in Figure 14(a). The gating was applied by rejecting recoil energies outside the range predicted by a Monte Carlo simulation of the reaction. The resulting total energy spectrum produced following this gating is shown in Figure 14(b). No evidence for a Q_{ggg} peak has emerged following this process, and it is clear that the problem of the large range of recoil energies must be studied in more detail.

Summary

The ^{12}C(^{24}Mg,^{12}C ^{12}C)^{12}C, ^{12}C(^{24}Mg,^{12}C ^{16}O)^{8}Be and ^{12}C(^{24}Mg,^{16}O ^{16}O)^{4}He channels have been analysed, and the results are seen to agree closely with previous measurements. This gives confidence in the calibrations used in the event reconstruction.

There is evidence for ^{12}C + ^{12}C breakup of ^{24}Mg from the ^{16}O content of the Li_2O target used in the experiment. Further detailed analysis is needed to confirm this idea. There is no evidence for ^{12}C + ^{12}C breakup from the ^{9}Be target.

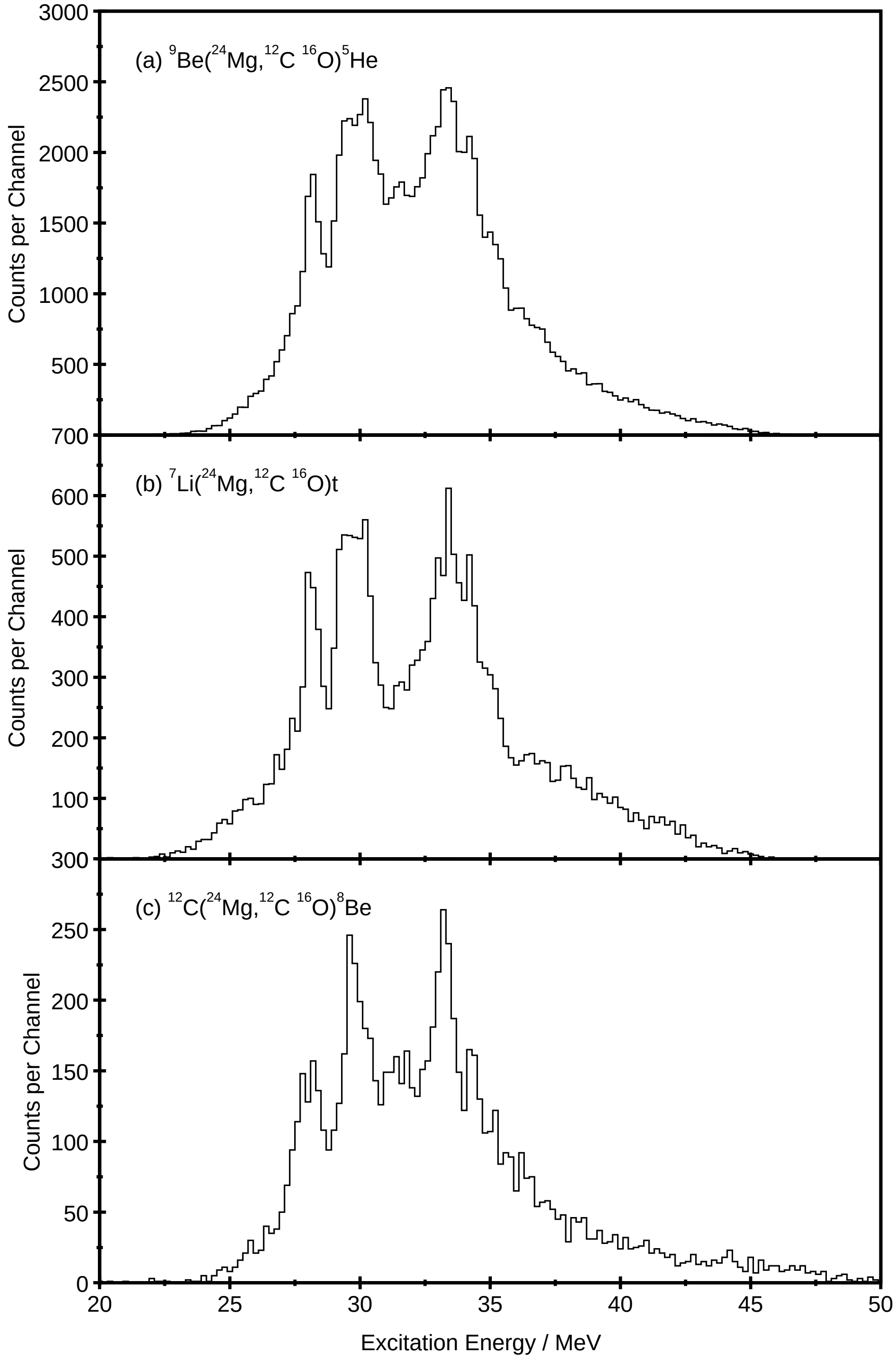

Figure 12: Excitation energy spectra for the $^{12}C + {}^{16}O$ breakup of ^{28}Si, obtained from targets of (a) ^{9}Be, (b) ^{7}Li and (c) ^{12}C.

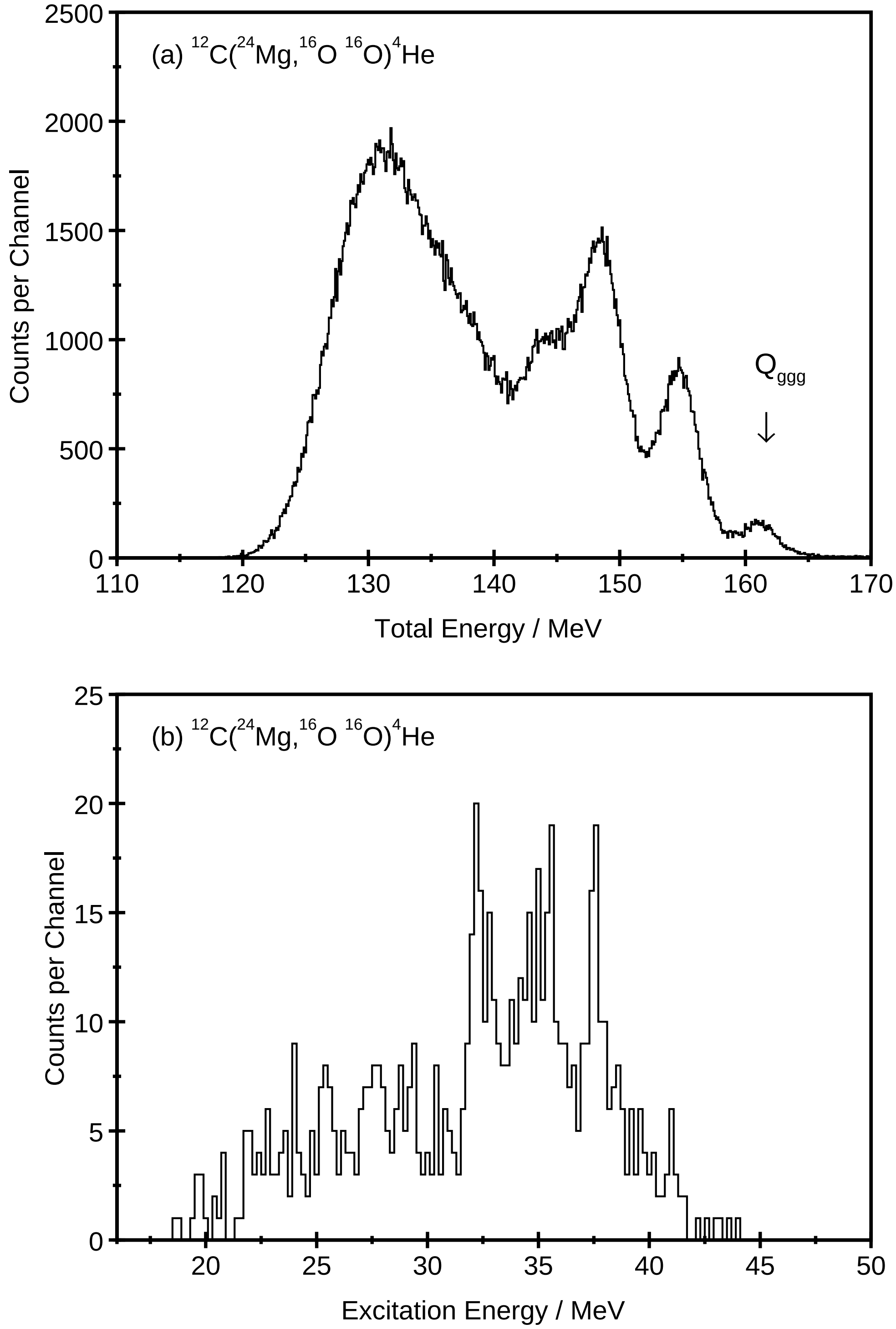

Figure 13: (a) Total energy (including predicted Q_{ggg} peak position) and (b) excitation energy (gated on a Dalitz plot) spectra for the ^{12}C(^{24}Mg,^{16}O ^{16}O)^{4}He reaction.

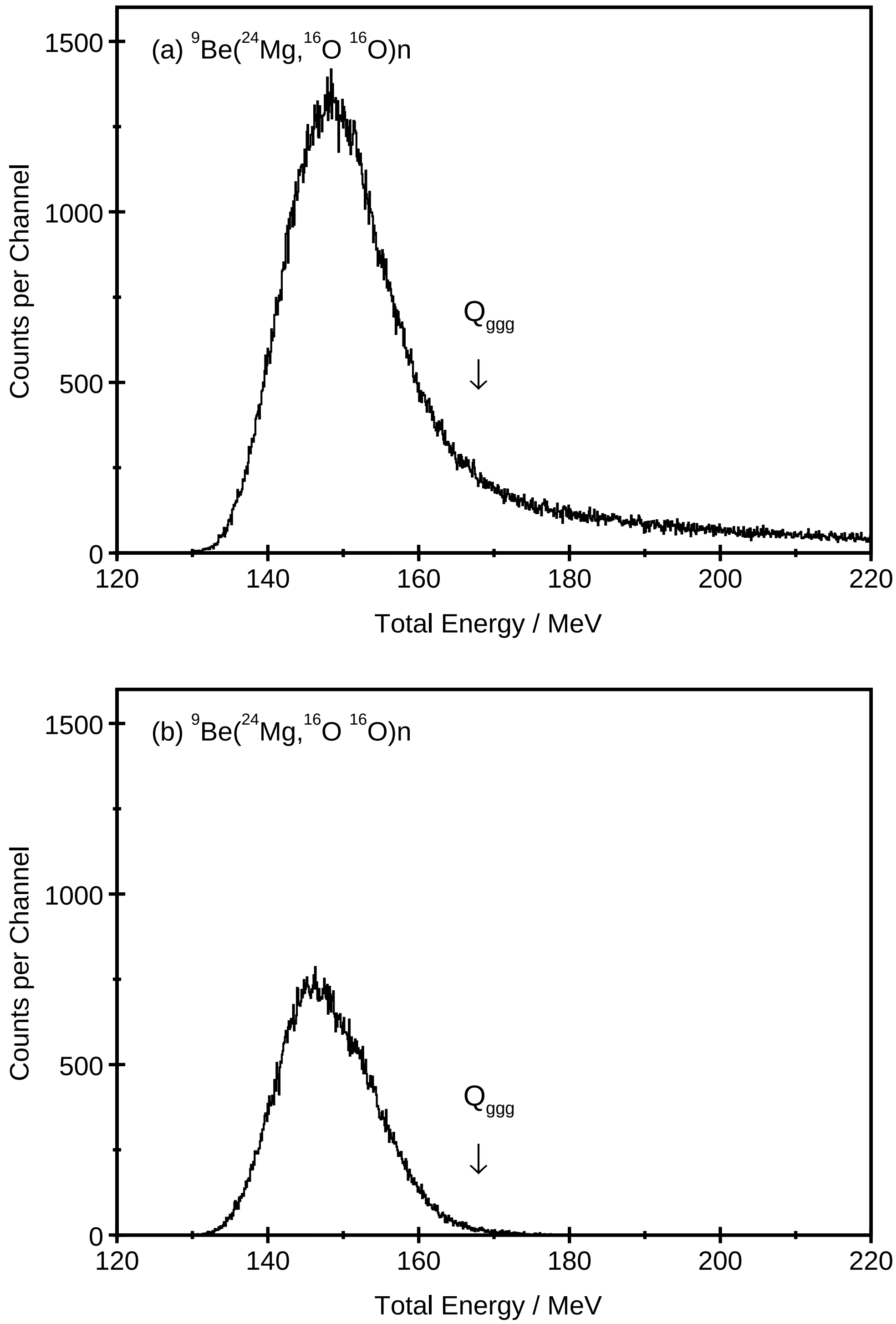

Figure 14: Total energy (including predicted Q_{ggg} peak position) for the $^{9}Be(^{24}Mg,^{16}O\ ^{16}O)n$ reaction. The data shown in (a) includes all reconstructed recoil energies. The data shown in (b) have had gates calculated from a Monte Carlo simulation applied to the recoil energy.

Breakup of ^{28}Si to ^{12}C + ^{16}O has been observed from all three targets used in the experiment, ^{12}C, ^{7}Li and ^{9}Be. The proposed reaction mechanism populating the states seen in the reconstructed ^{28}Si excitation energy spectrum is alpha transfer.

An investigation of the ^{9}Be(^{24}Mg,^{16}O ^{16}O)n reaction has produced no evidence for the breakup of ^{32}S. Further analysis of this channel, as well as the ^{16}O(^{24}Mg,^{16}O ^{16}O)^{8}Be reaction from the Li_2O target data, is planned.

Following the analysis of the ^{12}C + ^{12}C breakup of ^{24}Mg, the ^{12}C + ^{16}O breakup of ^{28}Si and the ^{16}O + ^{16}O breakup of ^{32}S a search will be made for breakup to various other exit channels. As the experimental trigger was set to allow alpha + heavy ion, ^{8}Be + heavy ion and $(3 \times \alpha)$ + heavy ion coincidences to be passed to tape, there are many reactions that may be investigated in the data set. These include ^{16}O + ^{8}Be and ^{20}Ne + α breakup of ^{24}Mg, and ^{20}Ne + ^{8}Be breakup of ^{28}Si (data being taken at arm angles chosen specifically for this channel).

References

[1] Computer code DEDX, (Daresbury Laboratory), unpublished.

[2] N. Curtis, Computer code TARGET, (University of Birmingham), unpublished.

[3] N. Curtis, PhD Thesis, (University of Birmingham, 1995), unpublished.

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[5] N. Curtis, A.St.J. Murphy, N.M. Clarke, M. Freer, B.R. Fulton, S.J. Hall, M.J. Leddy, J.S. Pople, G. Tungate, R.P. Ward, W.N. Catford, G.J. Gyapong, S.M. Singer, S.P.G. Chappell, S.P. Fox, C.D. Jones, D.L. Watson, W.D.M. Rae, P.M. Simmons and P.H. Regan, Phys. Rev. C **53**, 1804 (1996).