Studies of DRAGON energy asymmetry

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Introduction

In an effort to understand the causes of, and possible solutions to, the acceptance problems of DRAGON, a series of studies were conducted. An asymmetry was observed during the $^{12}C(a, g)^{16}O$ experiment in the energy spectra of heavy ion recoils detected at the end of the separator. This asymmetry implied that lower energy recoils were being lost. In this DRAGON experiment, a beam of carbon ions is fired into a gas target, filled with helium. Some ions incident on the helium react, and form oxygen in an excited state. This excited state decays by gamma ray emission. In the center of mass frame, this emission causes the recoil ion, the oxygen, to travel in some direction on the surface of a sphere. In the lab frame, this means that the recoil will be traveling somewhere in the 'recoil cone', with an increased or decreased kinetic energy, and with some momentum in the plane perpendicular to the direction of incident motion.

The asymmetry seen in the $^{12}C(a, g)$ was first examined by running that experiment again on the 2+ resonance. A previous study looking at DRAGON acceptance, the Wobbler study, left a number of questions as to the cause of observed, unexpected asymmetries, and recommended running on the 2+ resonance again to better understand what was going on. The study also discovered that sextupoles 3 and 4 had been running with reversed polarity. Thus it was useful to run again to see the difference in results caused by setting them properly. This experiment was also run with a series of separator 'mistunes' – setting the separator for an energy different than the nominal energy of recoil particles – to look at the difference this made to the asymmetry.

Then a series of tests were run in GEANT to look at this reaction. GEANT simulates the separator optics and reaction cone and can be run to simulate almost any simple tuning change possible in the real separator. For all of these tests GEANT was set to simulate the upper 2+ resonance, corresponding to the 11.52 MeV state of ^{16}O. Tests were done with different energy settings, slit sizes, and beam mistunes to probe the causes of the asymmetry. Also, a totally new standard tune was examined for potential use.

Data Analysis

The ^{12}C(a, g) runs were examined in PAW++. The coincidence and singles spectra were used to look at the asymmetry. Both had very similar shapes, which lends confidence to the singles spectra results. The total counts in both peaks were compared to give a quantitative measure of asymmetry, which is expressed in terms of the percentage ratio of the low energy peak to the high one.

The GEANT runs were examined in PAW++ and the interactive version of GEANT itself. In this case, the simulation outputs two files useful for analysis, an .hbook file and a file called fort.4.

The .hbook file contains a number of histograms and an ntuple. The histograms of use were the recoil energy at the end detector, the reaction z-position, and histograms showing how many recoil particles were stopped in various parts of the separator. The ntuple could be used to show the recoil energies at the moment of reaction, which was useful for comparison to the recoil energies at the end detector.

The fort.4 file contains the stop-coordinates and energies of every recoil that doesn't make it to the end detector. The file uses GEANT 'world' coordinates, which is different from the normal coordinate system used to describe the separator. This file could be read into PAW as a vector, or used in the interactive GEANT with a macro called hits.kumac. This macro reads a specified file as a vector and plots the position of each stopped recoil onto a picture of the separator. The separator can be drawn using the 'plan' macro.

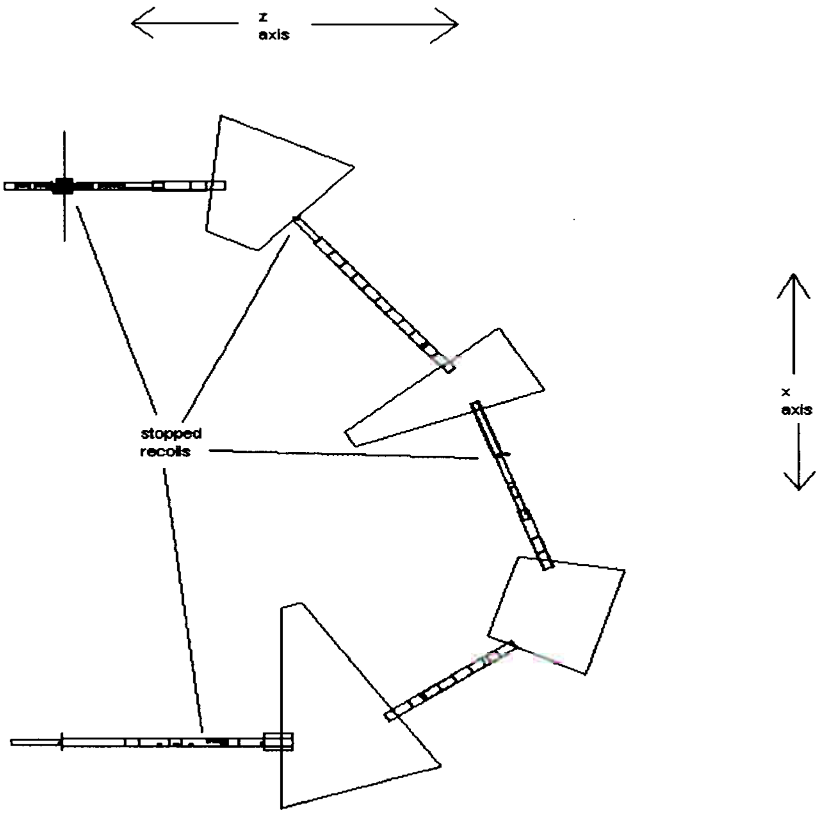


Fig 1. An example of the GEANT drawing done in the interactive version using the 'hits' macro. The drawing is made using 'plan', which draws the separator, and then 'hits' is run, putting black dots wherever a recoil ion has been stopped. GEANT world coordinates are also shown.

To hit the upper 2+ resonance, incoming ^{12}C beam particles must move with 4.34 MeV in the center of mass frame. This resonance has an orbital angular momentum of 2, and in magnetic substate 0. The ground state of oxygen has zero angular momentum, and so the gamma rays emitted by the oxygen recoils must carry away this momentum. This emission is called electric quadrapole emission, and causes gammas to be emitted preferentially in certain directions. The emission pattern of gammas is called a 'butterfly' pattern because of its four distinct lobes. This emission pattern causes the recoils to be deflected with a mean angle of around 14 mrad, with a maximum deflection of 19 mrad. The recoils have a maximum energy spread of around 8 %, with most concentrated in two peaks on opposite sides of the mean, around 4% in energy apart. It is this energy difference that gives the distinct double peak in the DSSSD spectra. Because there is no kinematic reason for one energy peak to be higher than the other, they should be symmetric.

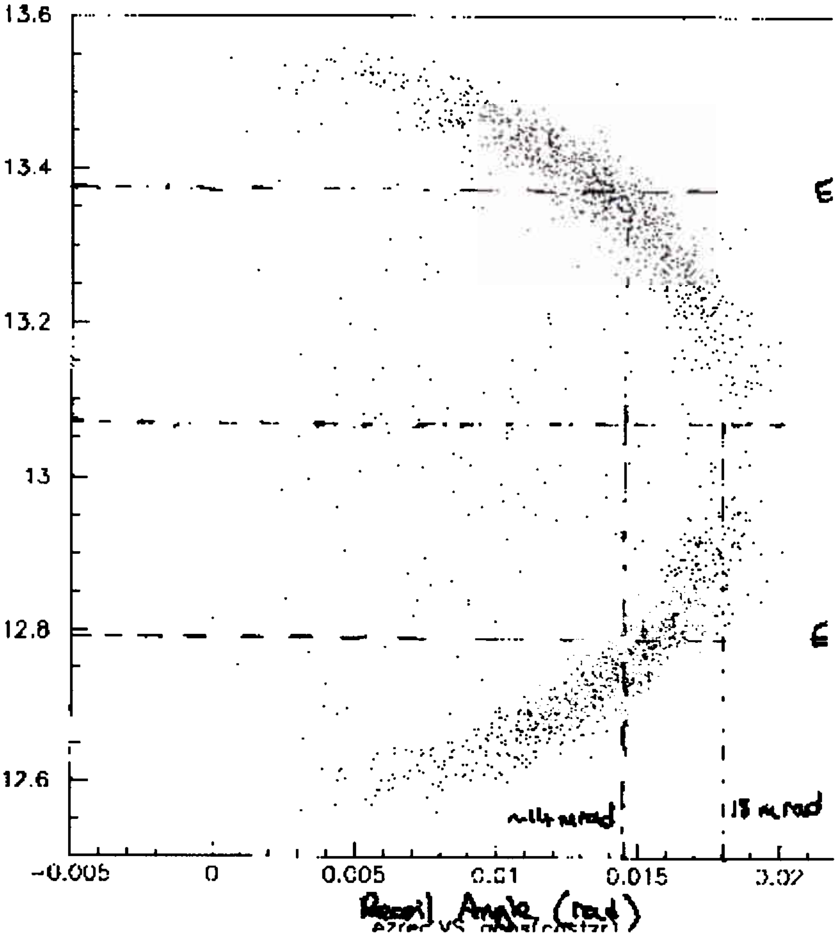


Fig 2. Recoil angle plotted against recoil energy for ^{12}C(a, g)^{16}O on the upper 2+ resonance. The angular distribution about the direction of incoming beam particles should be isotropic, so a uniform cone is made, with a mean angle of around 14 mrad. The two distinct energy peaks can be seen, at around 13.38 MeV and 12.8 MeV for the high and low energy peaks, respectively. The points scattered outside these features are recoils from cascade transitions, which are much less common for this resonance than the ground state transition.

Results

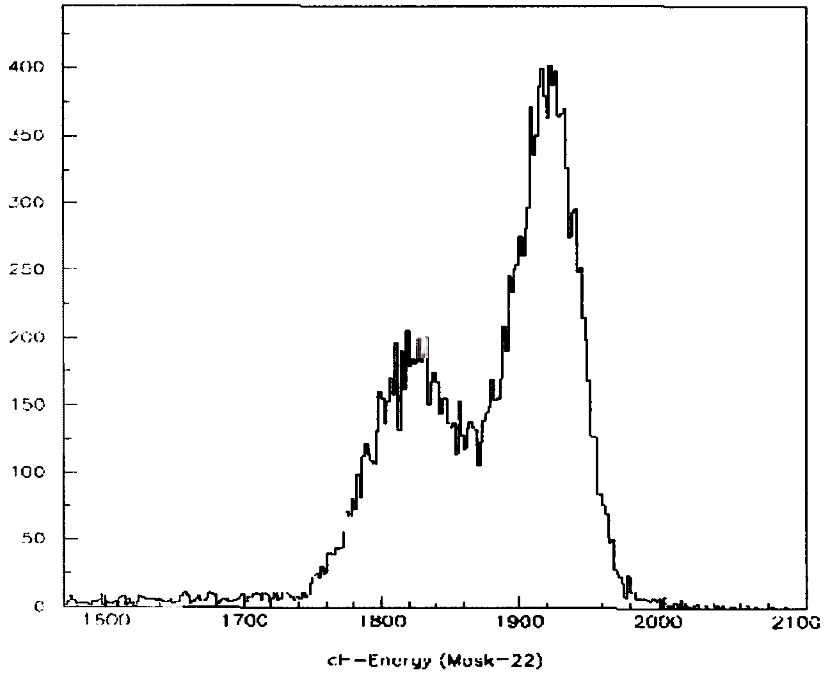


Fig 3. A coincident recoil spectrum of run 8430, a ^{12}C(a, g) run at the 2+ resonance. This was run at the nominal energy, with the sextupoles set incorrectly.

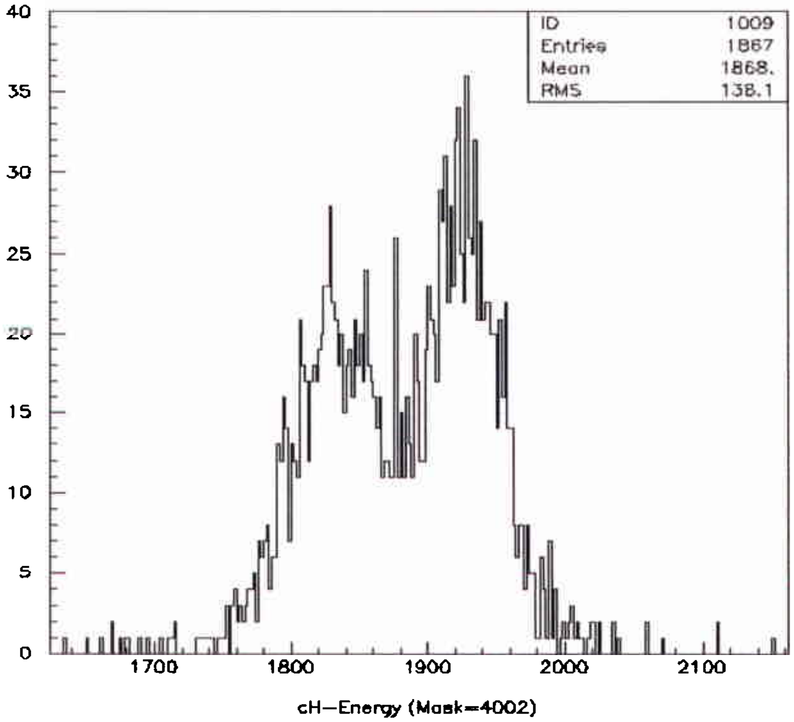


Fig 4. A plot of the coincident recoil energies at the DSSSD, run at nominal energy, with the sextupoles set correctly.

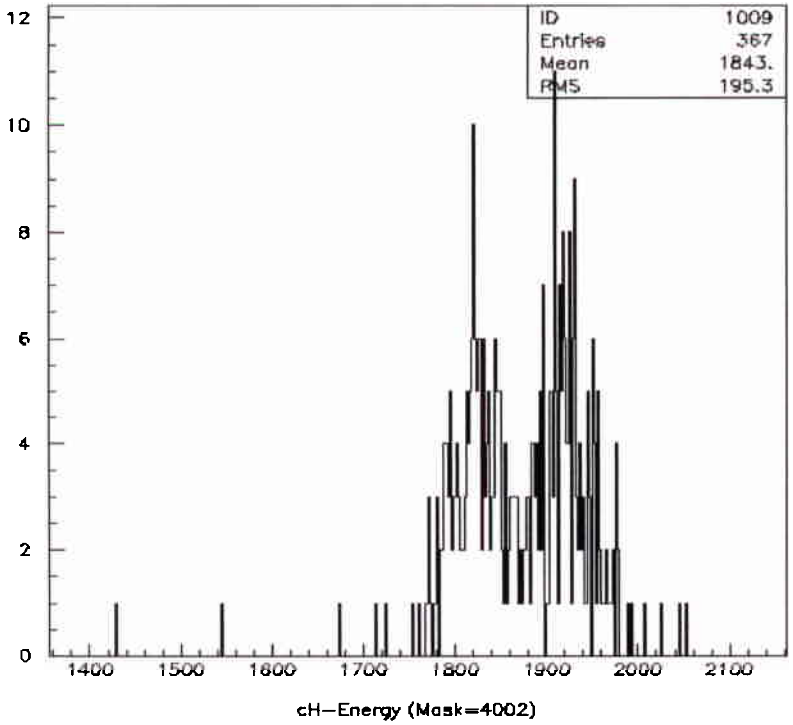


Fig 5. Coincident recoil energy spectrum at the DSSSD, with the energy tuned for -1%, and sextupoles set correctly.

Figure 3 shows an old $^{12}C(a, g)$ run, meaning it was done with sextupoles having the wrong polarity. The low energy peak contains only 50% of the counts contained in the high energy peak. The runs made after the sextupoles were fixed showed much less asymmetry, only around 10%, as shown in Figure 4. It is assumed that the reversal of sextupole polarity is the only major change between those two runs. In Figure 5, a run with a -1% energy mistune, the asymmetry is basically eliminated. Plots of asymmetry against energy mistune were also made.

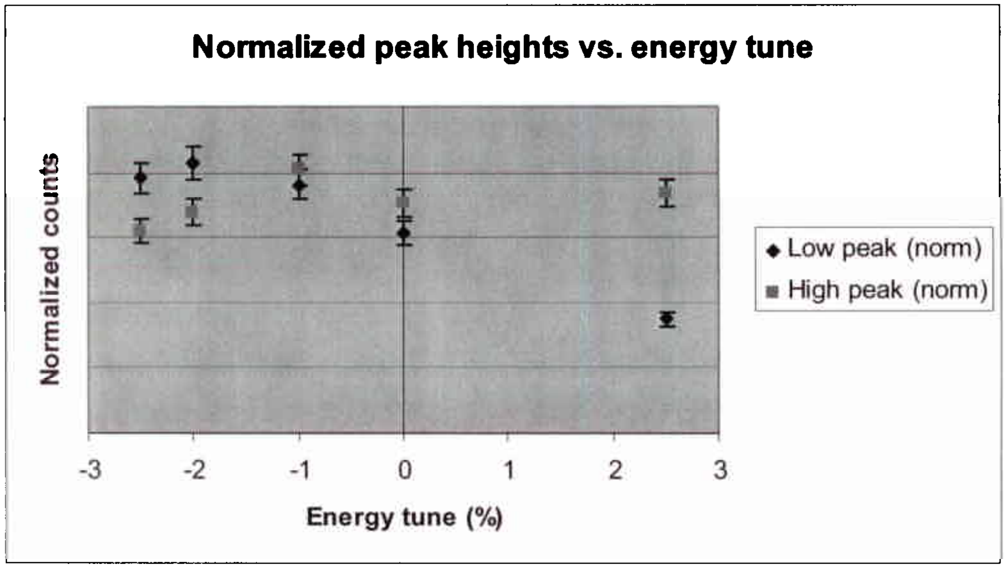


Fig 6. Relative heights of the low and high energy peaks plotted against energy mistune, for the singles spectra.

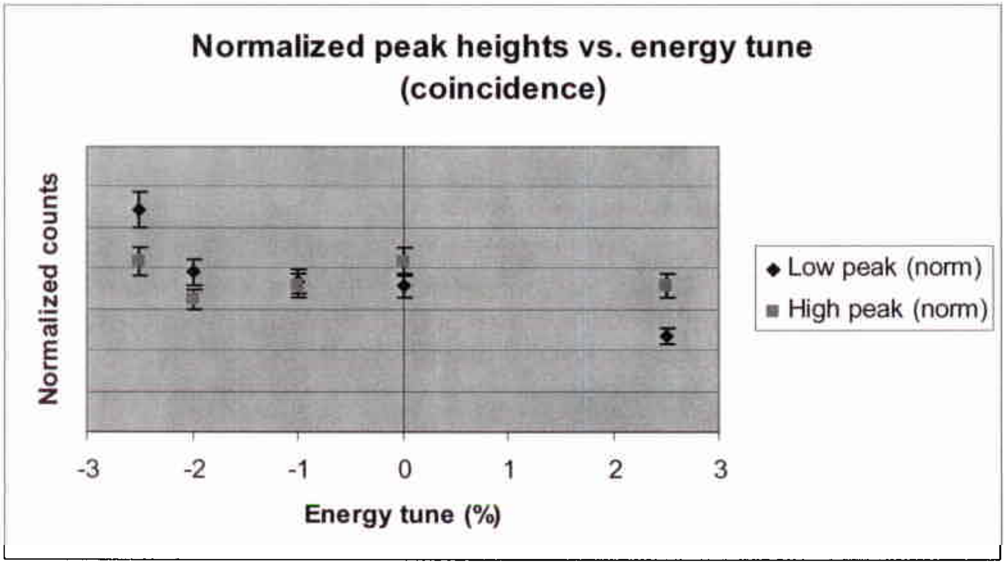


Fig 7. Relative heights of low and high energy peaks plotted against energy mistune, for the coincidence spectra.

Based on these plots, low energy recoils seem to be 'found' when the separator is tuned for them. This is a possible solution to the asymmetry problem, but does not help explain its cause.

While running these tests, a quick study was done to see if recoils were 'falling off' the DSSSD, a question left after the Wobbler study. By moving the final steering magnet, it was observed that no events could be 'found' by moving it either up or down. It was concluded that no events were getting lost there.

The next series of tests were conducted in GEANT. In these plots, the energy spectrum at the DSSSD, in the upper left, is plotted beside the energy of recoils at the time of reaction. Below, the reaction z-position is plotted, showing the broad resonance, and the total number of recoils created. Beside that is a plot of the x-position of stopped recoils, in GEANT world coordinates. A position of zero corresponds to being stopped in the pumping tubes, -75 corresponds to the charge slits, -500 to the mass slits, and -1000 in the final slits and last stages of the separator.

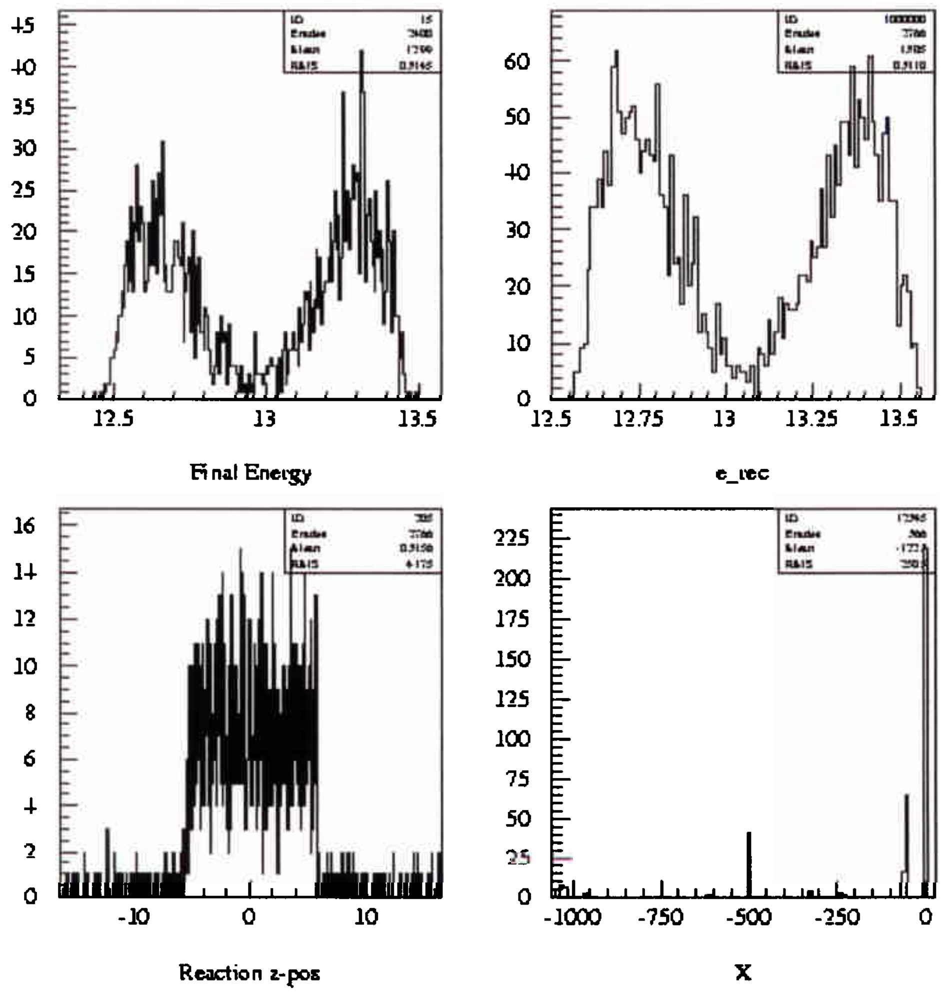


Fig 8. Plots of a simulated run at the nominal energy tune. Asymmetry between the two peaks, observed at the DSSSD, is around 10%, and most losses are in the pumping tubes, with many also lost in the charge and mass slits. No asymmetry is observed in the recoils at the time of reaction, which shows the losses occur in the separator.

After a run at the nominal energy showed the same general spectrum shape as the real separator, a run was done at an energy mistune of +1%. This accentuated the asymmetry and was used to show where exaggerated low energy losses might be occurring.

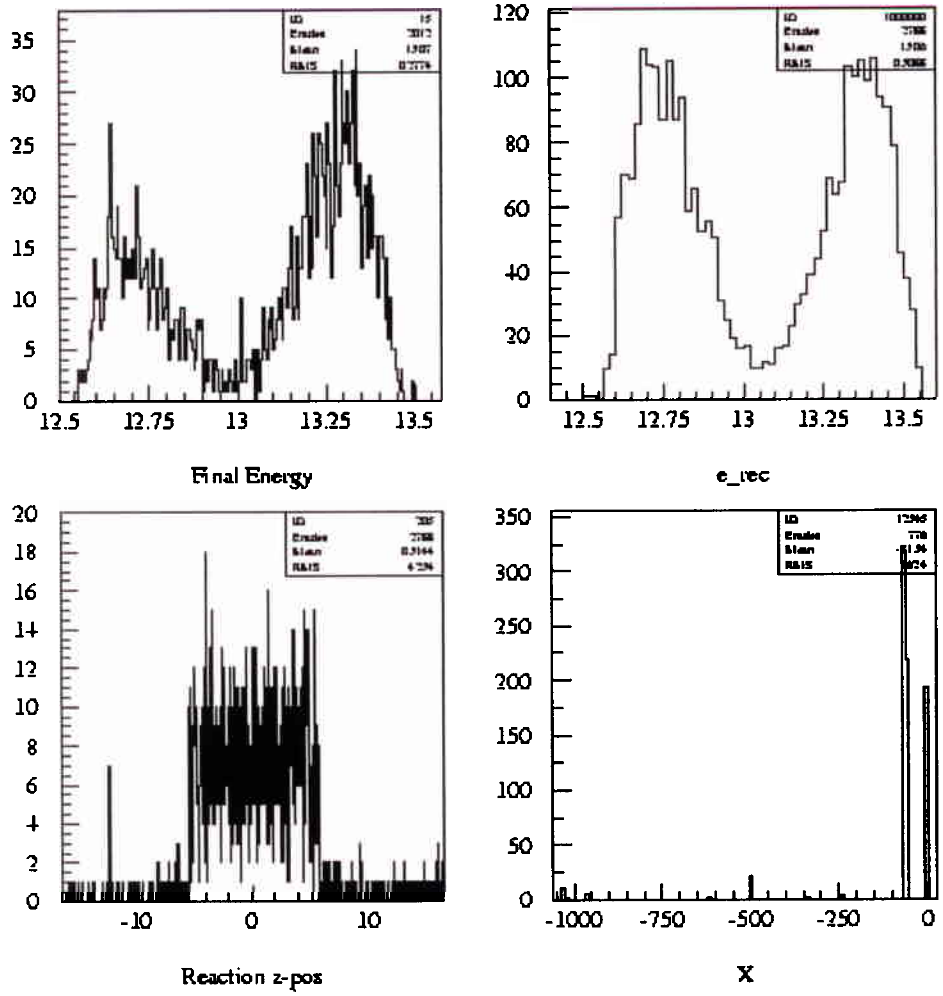


Fig 9. Plots from a simulated run at a +1% energy mistune. The low energy peak is 58% of the high energy peak, with most losses in the charge slits. The same numbers of events were lost in the pumping tubes. Again, the recoils at the time of reaction show no asymmetry.

This run showed that the energy dependant losses did not take place in the pumping tubes, because the same number occurred in both runs, and the asymmetry was considerably worse. The most obvious difference is the number of recoils clipped at the charge slits. Because it seemed to be a possible solution from the actual runs, a simulation was next run at a -.5% energy mistune.

The real separator is tuned by running beam through and tuning for it. This beam is slowed by the gas in the gas target as it moves through. The charge to mass ratio is then used to tune the separator for recoils, so the result is that the separator is tuned for a reaction taking place at the end of the gas target. The simulation tunes the separator for recoils that are formed in the center of the gas target. Because of the difference between these two, running GEANT at -.5% simulates running the real separator at -1%, which was a possible solution discovered by the real runs.

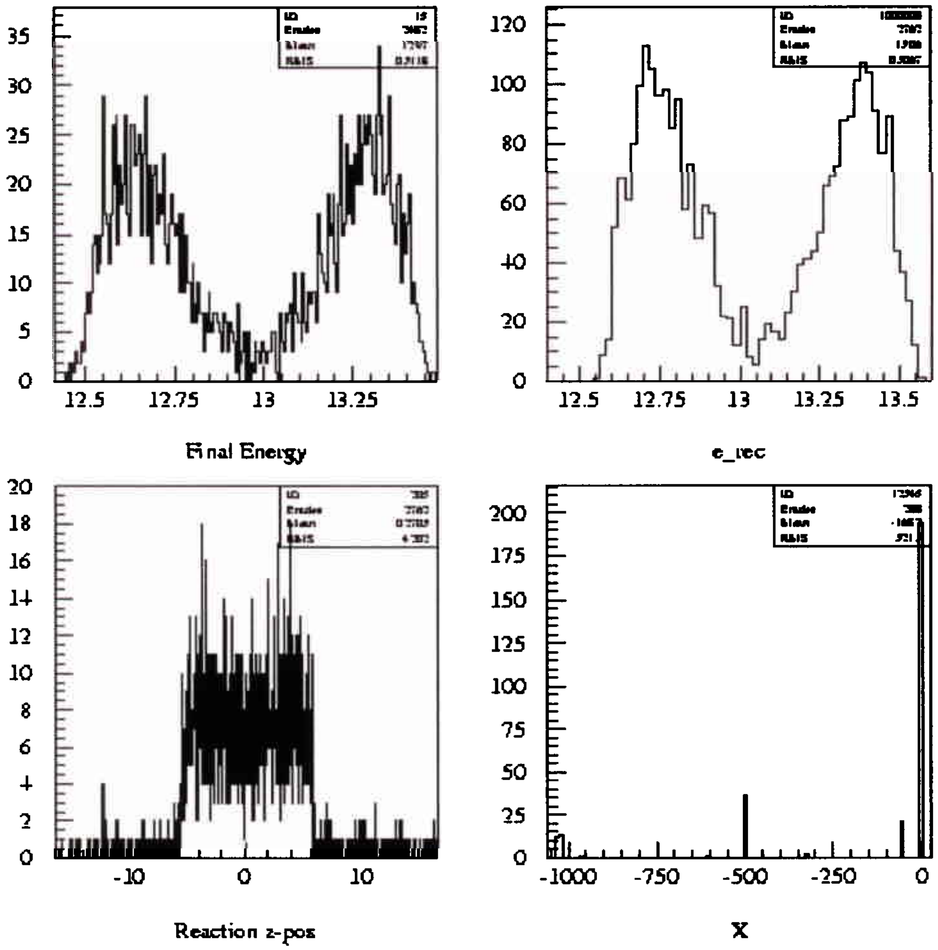
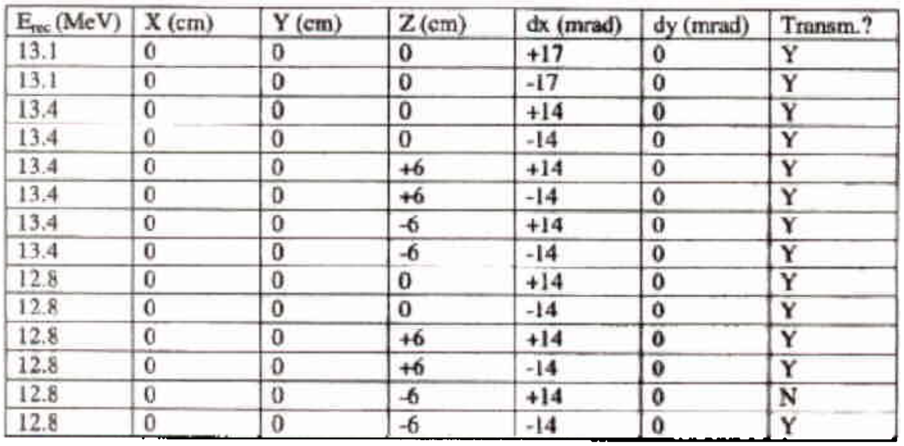


Fig 10. A simulated run at a -.5% energy mistune. The asymmetry is zero, to within statistical errors, and the same rough shape is seen in the spectra at the DSSSD as at the time of reaction. The charge slits have stopped far fewer recoils, so the major obstacle is again the pumping tubes.

The run at -.5% energy mistune showed the same results as the -1% mistune in the real separator; no asymmetry. The run was stable with beam tune, as wobbling the incoming beam to 2 mrad in the positive and negative x direction had no effect on results. As well, the transmission was slightly better in this run than at the nominal energy.

To understand why mistuning the beam helps transmission, the beam interaction in the gas target must be understood. As the beam moves through the gas, it is slowed by interactions that do not result in recoils being created. This same thing happens to recoils as they pass through the gas. The recoils tend to be slowed more easily than the beam particles, and so a recoil traveling through the gas target will end up with less kinetic energy than a beam particle traveling through the gas target, even if they start with the same kinetic energy. This difference in stopping power means that a recoil which is formed in the center of the gas target, even if the gamma emission is identical, will have less energy than a recoil formed at the end of the gas target. This difference is around .5%, and helps explain why running the simulation at -.5% is equivalent to running the real separator at -1%. Also, this means that over the whole gas target, recoils could have a total energy spread of 1% in addition to whatever spread they could have due to gamma emission. Thus, mistuning the separator down is like tuning it for recoils formed at the back (downstream end) of the target. To check this analysis of the situation, GEANT was used in the interactive version to run one particle through at a time, and varying the characteristics of that particle to see which ones are stopped.



E_{rec} (MeV)	X (cm)	Y (cm)	Z (cm)	dx (mrad)	dy (mrad)	Transm.?
13.1	0	0	0	+17	0	Y
13.1	0	0	0	-17	0	Y
13.4	0	0	0	+14	0	Y
13.4	0	0	0	-14	0	Y
13.4	0	0	+6	+14	0	Y
13.4	0	0	+6	-14	0	Y
13.4	0	0	-6	+14	0	Y
13.4	0	0	-6	-14	0	Y
12.8	0	0	0	+14	0	Y
12.8	0	0	0	-14	0	Y
12.8	0	0	+6	+14	0	Y
12.8	0	0	+6	-14	0	Y
12.8	0	0	-6	+14	0	N
12.8	0	0	-6	-14	0	Y

Fig 11. This table shows for which initial conditions particles are transmitted through the charge slits. The only particle not transmitted was a low energy particle, which reacted at the front (upstream side) of the target, and deflected in the positive x-direction.

This also shows another effect of the gas target length. Recoils which are deflected at a certain angle will follow a path through the optical elements to come to a focus at the slits. This focus is smeared out by the length of the gas target because a recoil formed at the front of the gas target will have a longer distance to move away from the magnetic axis, and so will be bent more, and will be focused earlier than a recoil formed further downstream. On a narrow resonance, this effect would not matter because the length of the reacting region is very small. On a broad resonance like the 2+, however, this has an effect.

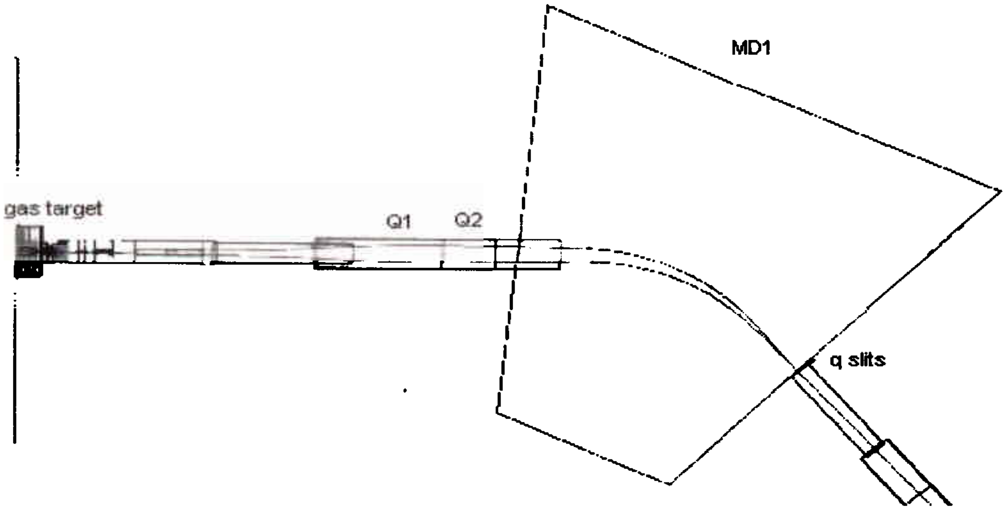


Fig 12. A GEANT drawing of two recoil particles from the chart above. Both reacted at the front of the target, and had low energy, but were deflected in opposite directions. The focus for these particles is slightly in front of the slits, because of the length of the gas target. The positively deflected particle was stopped at the charge slits.

This diagram also seems to imply that simply opening the charge slits could eliminate the problem. A series of runs were made to see what effect opening the slits would have.

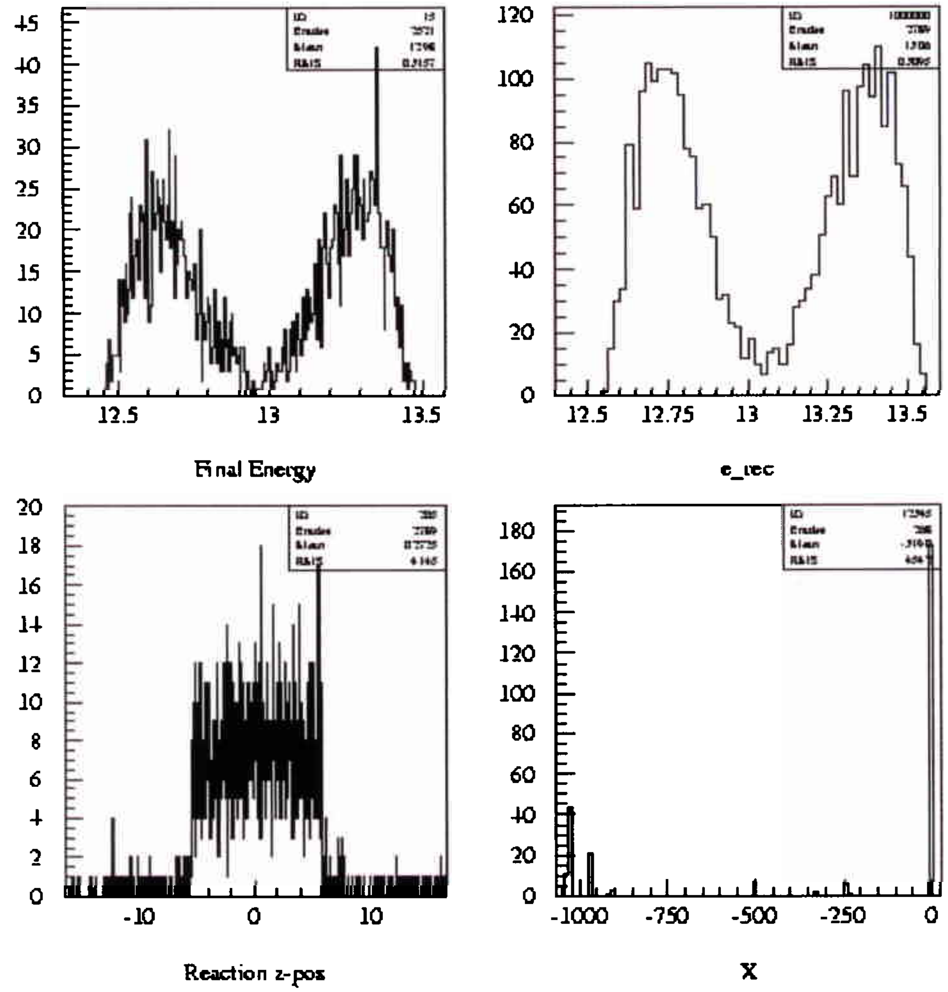


Fig 13. The most successful run with nominal energy and open slits. The slits were 40mm in the x and 45mm in the y at the charge slits, and 40mm in the x and 35mm in the y at the mass slits. The low energy peak is 94% of the high energy peak, with a purely statistical error of 2%.

This is another possible solution to the asymmetry problem. The advantage is that the separator can be tuned normally, and changing slit widths is an easy change, but the asymmetry is not totally gone. Low energy recoils are still lost preferentially in the vacuum tubes and the dipoles, especially ED2. Also, while in a stable beam experiment like ^{12}C(a, g) suppression of leaky beam is not a major issue, with radioactive runs opening the slits too much could cause problems in separating beam particles from recoils. This solution seems to be stable with beam tune; simulating this case with the beam wobbled by 2 mrad in the x direction did not have significant effects at the DSSSD.

The ^{12}C(a, g) experiment has a large recoil cone, but not as large as some experiments that have been proposed. Increasing the angular acceptance of DRAGON is a task that is very similar to investigating the asymmetry. The solution to one is a possible answer to the other. With this in mind, a new tune was devised for all of the quadrapoles. This tune does not have a focus at the charge or mass slits, and so does not bend the recoils as sharply, trying to squeeze it in three parts. This softer bending could allow the beam to avoid possible barriers. This new tune was run in the simulation for the same reaction as previous tests, the upper 2+ resonance.

Q1	0.974
Q2	0.863
Q3	1.273
Q4	1.058
Q5	0.848
Q6	0.902
Q7	0.918
Q8	1.000
Q9	0.905
Q10	0.908

Fig 14. Ratios of new quad settings to quad settings for the standard tune

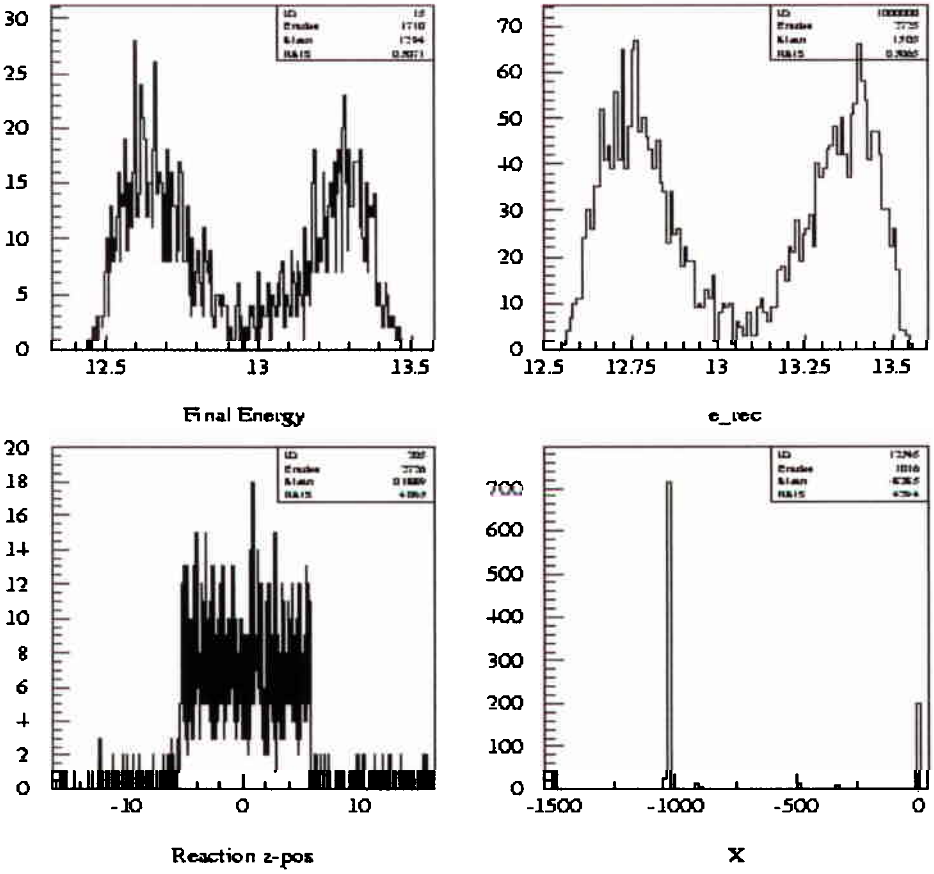


Fig 15. The most successful run with the new quad tune. Slits were opened to 50mm in the x and y at the charge slits, and to 90mm in the x and 50mm in the y at the mass slits. The major contributor to stopped particles is the final vacuum tubes and slits, and the line seen at -1500 in the x plot is particles that have missed the final parts of the separator entirely. Transmission is only 60% at best for this tune.

Recommendations

The energy asymmetry observed in the $^{12}C(a, g)^{16}O$ experiment was significantly improved by fixing the polarities of sextupoles 3 and 4. An asymmetry was still observed, but this was eliminated when the separator was 'mistuned' by -1%. Simulations showed that the major cause of energy asymmetry was clipping at the charge slits due to some 'features' of the gas target. The way the DRAGON separator is tuned causes a further 1% energy spread to recoils, in addition to the energy spread of the recoil cone. This means low energy recoils have an even lower energy than expected. Also, the length of the gas target causes the foci at slits to be spread over that same length, causing certain low energy particles to be clipped.

Two possible solutions have arisen: to run the separator at a -1% mistune always, or to open the charge slits. Both seem fairly stable, but the mistune solution eliminates the asymmetry more thoroughly and doesn't have the problem of possibly hurting suppression. Both are simple, cheap solutions and neither one requires any changes to the existing hardware.

For future experiments, however, the DRAGON acceptance will have to be increased anyways. In order to achieve this, a possible tune was created. The tune only had 60% transmission in the beast case, which makes it not a good candidate for actual use. Other possible tunes are currently being developed in GIOS which may work better. Because a steady 9% of recoils are always stopped at the collimators in this experiment, increasing angular acceptance involves changing the gas target collimators. This means also changing the pumping system.

Many of the tests answered questions left at the end of the Wobbler study. However, none of the tests completed helped to resolve what was causing the angular acceptance problem. Since DRAGON is not getting the angular acceptance it was built for, understanding this problem before undertaking any serious attempt to increase the acceptance further would probably be wise.