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The Electrofission of Magnesium

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Today I would like to give a progress report on some recent work on the electrofission of light elements being carried out by a group at Toronto University. The topic is, I think, an appropriate one for this conference because Professor Goldemberg of São Paulo is one of the group and because it has been found necessary to use both electron linear accelerators and electrostatic accelerators in the work to be reported. As a result of the opening of the Pelletron Laboratory this week, the Physics Institute at São Paulo will become one of the few laboratories in the world with both types of accelerators.

In addition to Professors Goldemberg and Litherland, the people involved in this work are Drs. L. Pai and M. A. Charlesworth and two graduate students, Mr. A. Chung and Mr. W. Diamond.

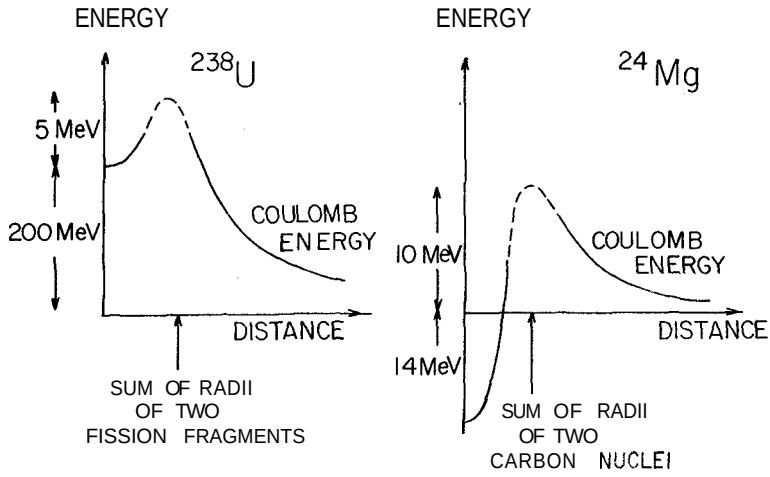


Fig. 1 - Potential energy diagrams to illustrate the differences between the fission of ^{238}U and ^{24}Mg. The region shown wiih dashed lines is not well understood theoretically or experimentally.

The fission of a heavy element such as uranium-238 differs from the fission of a light element such as magnesium-24 in one basic respect. In the first case, the Q-value is ~ 200 MeV positive and in the second case it is ~ 14 MeV negative. This is shown schematically in the potential energy diagrams, Fig. 1. In addition, the uranium nucleus has a barrier against fission of only about 5 MeV but the magnesium-24 nucleus has a barrier considerably higher. Experimentally it seems to be about 24 MeV high. The height of the fission barriers can be calculated with the help of the liquid drop model and the heights of these barriers' are shown in Fig. 2. The barriers for light elements in the region of magnesium-24 are expected to be quite high, in the vicinity of 35 MeV, but shell effects which are not included on the curve shown on the slide, can cause a significant change in the barrier height and consequently on the probability of fission. Also shell effects can favour or inhibit the emission of some species of fission fragments. A study of the fission of light nuclei can therefore yield important information on the effects of the shell structure of the fissioning nucleus and so possibly cast some light on the similar but much more complicated

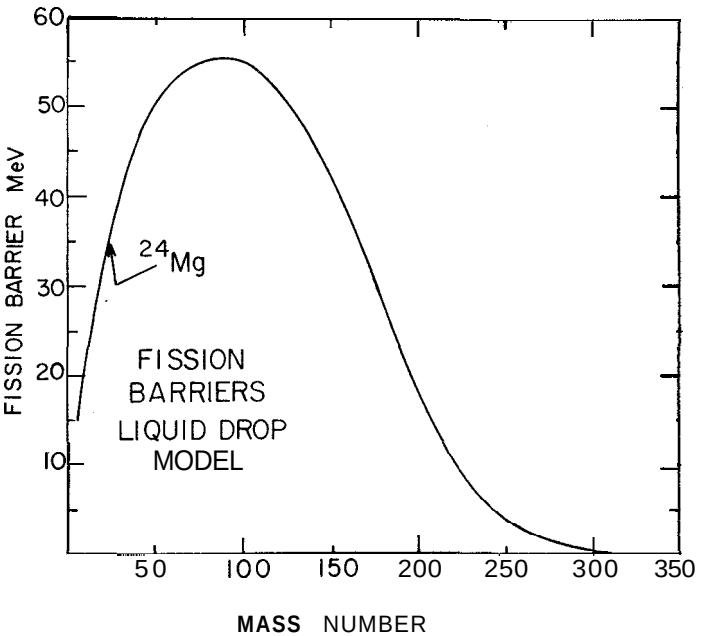


Fig. 2 - The heights of the fission barrier in MeV are shown as a function of mass numbers. The liquid drop model is assumed.

phenomenon in heavier nuclei. Theoretical studies on the fission of light nuclei such as ^{8}Be, ^{16}O and ^{24}Mg are at present being made by Harvey[2] at Chalk River, Canada. Greiner[3] and his colleagues are studying the shell structure of fissioning heavy nuclei.

There is actually very little experimental evidence on the fission of light nuclei and so about one year ago Professor Goldemberg and I decided to try to study the problem with the help of the electron beams from the Toronto Linac.

We chose the electromagnetic interaction because it is simple and well understood and we expected that the fissioning states to resemble closely the ground state of the bombarded nucleus.

In planning the experiment, we were guided initially by fragments of evidence already in the published literature. In 1963, Sherman[4] at Queen's University in Canada published a letter on the "Photofission of Magnesium" by bremsstrahlung with a maximum energy of 70 MeV. He chose magnesium-24 to study because earlier experiments by Bromley, Kuehner and Almqvist[5] at Chalk River had shown some very curious states in ^{24}Mg which were formed by $^{12}C + ^{12}C$ reactions. These states had sur-

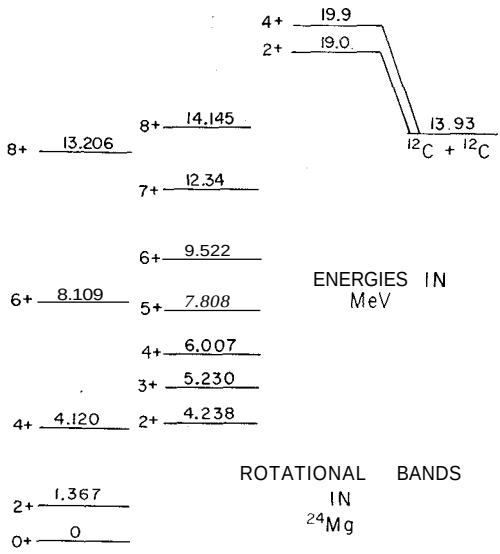


Fig. 3 - Some of the excited states of ^{24}Mg. The two well known rotational bands are shown together with two of the quasimolecular states.

prisingly large reduced widths for the emission of Carbon ions and these states are often called the quasi-molecular states in ^{24}Mg. They are shown in Fig. 3 together with the well known rotational bands[6] in ^{24}Mg. Sherman argued that quasi-molecular states, such as the one shown in the slide with spin two and even parity, might be excited by photon absorption. He therefore looked for the emission of ^{12}C ions following the absorption of photons by ^{24}Mg.

Fig. 4 shows one of the events observed by Sherman[4]. He used photographic emulsions containing MgO and saw a total of six tracks like the one shown in the slide. Each of the carbon-12 tracks is about 4μ long. He interpreted the events as the absorption of photons by a state in ^{24}Mg

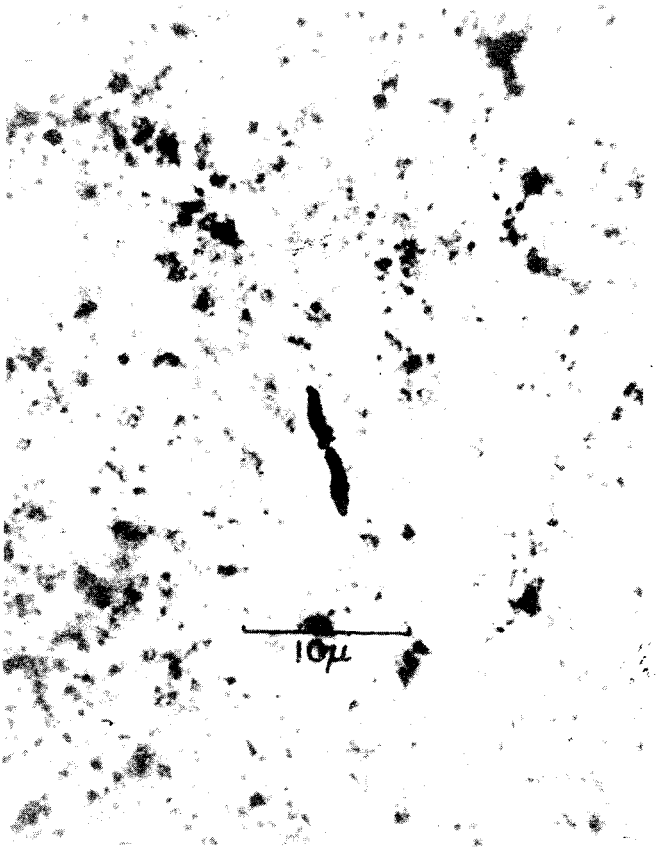


Fig. 4 - A photofission event observed in a photographic plate loaded with MgO.

at about 23 MeV followed by breakup into two carbon nuclei. Sherman also used photographic plates containing Al_2O_3 and saw no tracks of this form.

As a result of the measurements of Sherman[4] and the evidence[5] of quasi-molecular states in magnesium we decided first of all to look for the fission of magnesium-24 generated by a beam of electrons.

Electrons rather than photons were used to bombard the thin self-supporting targets because it is possible, at least in theory, to control the beam well enough so that the majority of the background comes from the target itself. Also, it is worth remembering that a beam of electrons is in some respects like a beam of photons, and the spectrum of these virtual photons is similar in shape to a thin target bremsstrahling spectrum[7]. In addition *EO* excitations of nuclei are possible with electrons. Thin self-supporting targets were chosen because of the large value of dE/dx for heavy ions and because there is sufficient uranium and thorium in most backing materials to cause background problems from the heavy fission fragments from electrofission.

The detectors we chose are of the plastic foil type[8,9]. These detectors have the very useful property of being sensitive only to heavy ions and, in the case of the Makrofol type of plastic film which we use, they are sensitive only to ions heavier than boron. They are also almost completely insensitive to gamma rays and neutrons which are, unfortunately, very plentiful near an electron beam.

The detectors of the electron induced fission of magnesium also have to discriminate against the photons, neutrons and alpha particles from the electro-disintegration of magnesium because the cross section is larger for such reactions. The insensitivity of the plastic detectors to protons, neutrons and alpha particles is therefore a great advantage.

The various channels of breakup of ^{24}Mg are shown in Fig. 5. The breakup of ^{24}Mg into two ^{12}C nuclei has a Q-value of – 13.9 MeV but the emission of alpha particles, neutrons and photons also have similar Q-values. The only heavy ion breakup which could compete significantly with the breakup into two ^{12}C nuclei below 30 MeV excitation energy is the breakup of ^{24}Mg into ^{16}O and ^{8}Be.

The plastic foil detectors record the heavy ions because of the radiation damage along the track of the ion through the plastic. The amount of radiation damage depends, of course, on the rate of energy loss in the

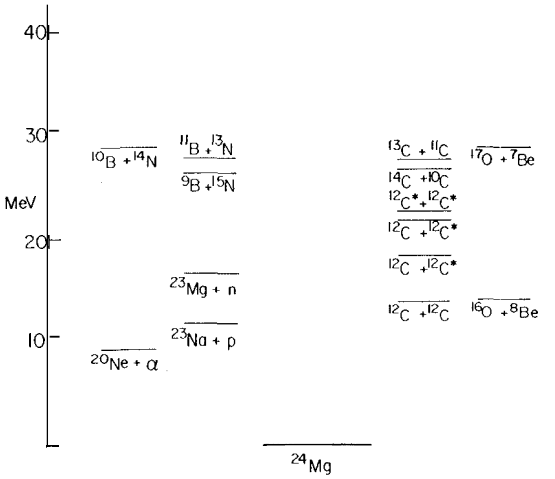


Fig. 5 - Thepossible breakup modes of ^{24}Mg are shown up to an excitation energy of 30 MeV.

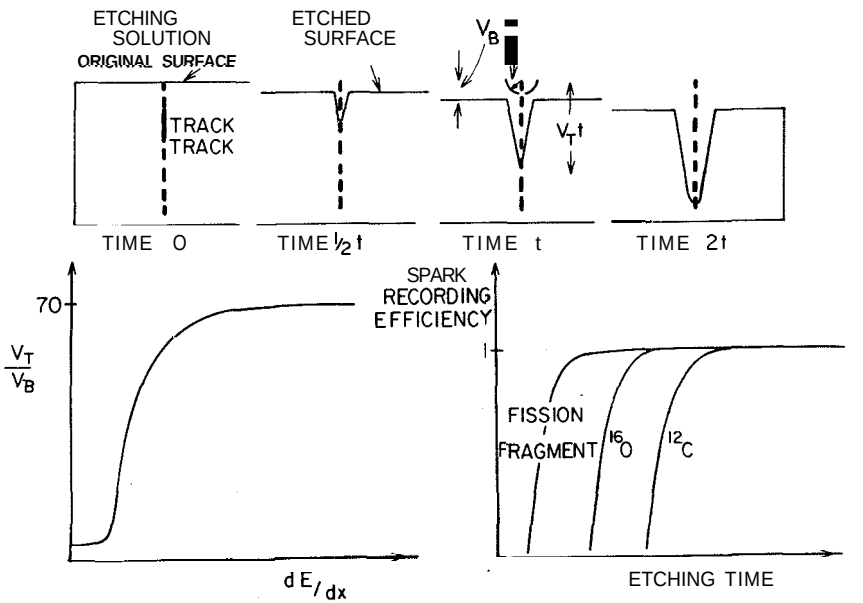


Fig. 6 - The time evolution of the tracks in a plastic film is shown at the top. The ratio of the track etching speed V to the bulk material etching speed V_B is also shown as a function of the dE/dx of the heavy ion for cellulose nitrate. A schematic drawing of the spark recording efficiency as a function of etching time for various ions is also shown.

plastic film[10]. Fig. 6 shows how the region of radiation damage can be observed.

The original track of damaged plastic is possibly only a few tens of angstroms in diameter but the region of radiation damage has the property that it etches much more rapidly in concentrated caustic soda solution than the undamaged bulk material. The etching speed of the damaged plastic in the track V_T divideú by the etching speed of the undamaged plastic[9] V_B is shown on the slide as a function of dE/dx. This case is for cellulose nitrate etched at 60^0C in a $10N$, $NaOH$ etching solution. The ratio V_T/V_B is a high as 70 if the dE/dx is high enough, and the time evolution of the track is shown in the upper part of the slide. It is easy to see that the angle of the cone etched into the plastic is approximately V_B/V_T radians.

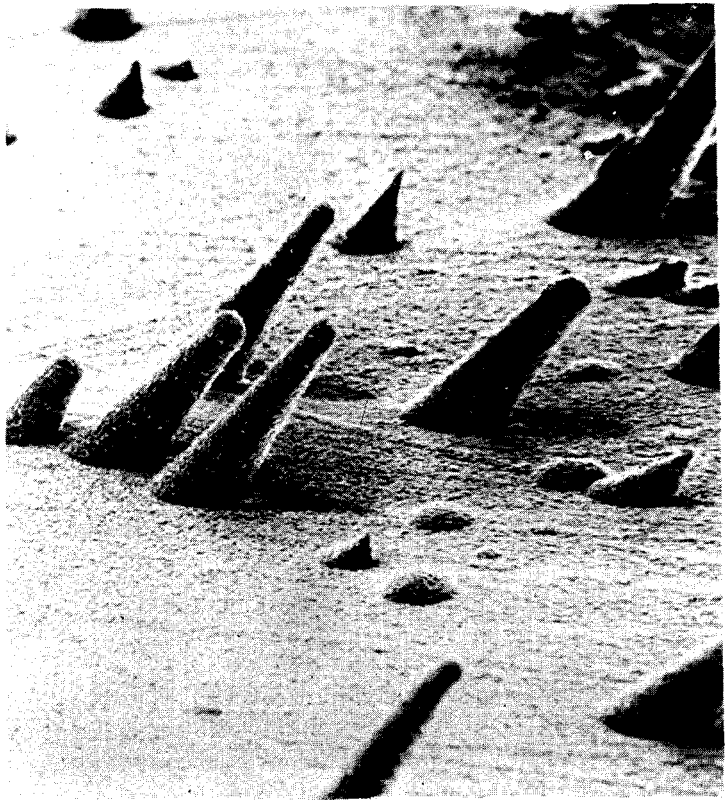


Fig. 7 - A microscopic view of a silicone replica of sulphur ion tracks in a plastic sheet.

Under certain conditions, it is possible to observe the tracks with a microscope and a silicone replica technique[11]. A striking example of the application of this technique is shown in Fig. 7. These tracks are of sulphur ions, from an accelerator, incident upon the plastic of an Apollo helmet[11]. The tracks shown on the slide are, however, over ten times longer and much wider than those we are studying in the electrofission experiment and so we employed a different technique for their observation.

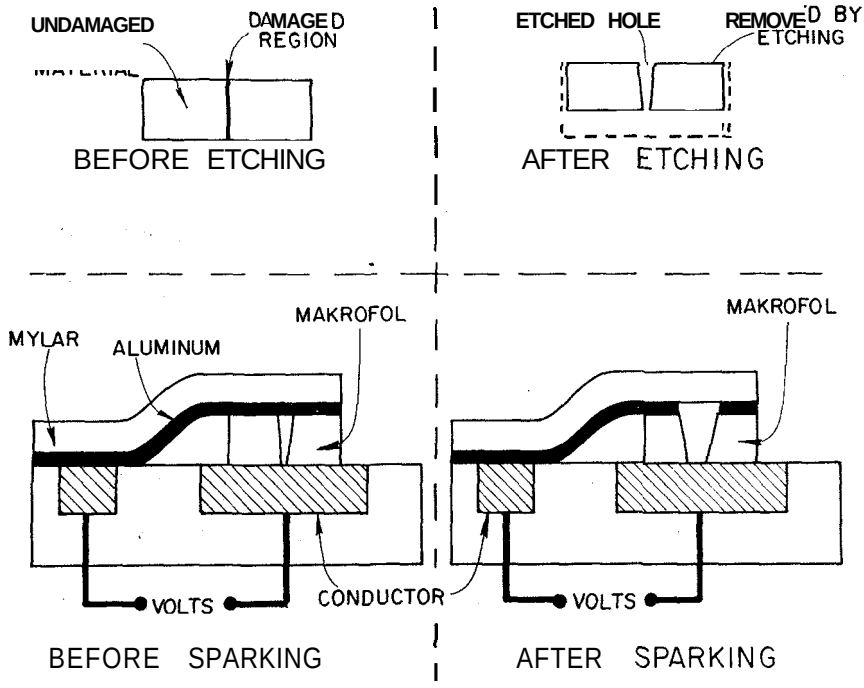


Fig. 8 - Some details of the sparking technique are illustrated.

The technique we are using was developed by others[12] and is illustrated in Fig. 8. After etching the plastic film, a track which originally penetrated the film becomes a small hole in the film. This hole can readily be observed by the sparking technique. In this technique a sheet of aluminized mylar is placed over the hole in the manner shown and a voltage of up to 600 volts is put across the plastic sheet by the arrangement of electrodes also shown in the slide. Normally the plastic sheet would not break down

under these conditions but a discharge can actually pass through the hole enlarging it and evaporating aluminum from the mylar sheet. The result is an easily visible hole in the aluminized mylar. The number of holes can either be counted by eye or by an electronic scaler which counts the pulses from the discharges through the plastic film.

An important feature of the plastic track detectors which we have exploited in our work was shown in Fig. 6. We have found that the sparking method can be used to distinguish between certain types of heavy ions that penetrate the detectors provided the number of counts is recorded as a function of etching time[13]. This is a very simple idea and is based on the very non linear variation of the etching speed V_T for ions of different dE/dx. The spark recording efficiency of heavy element fission tracks and oxygen and carbon tracks as a function of etching time is shown schematically in Fig. 6. The differences are due to the very different V_T for the three types of ions. This feature of the detectors has proved to be very useful because there is always a variable background of heavy element fission fragment tracks in the experiments on the electrofission of light elements.

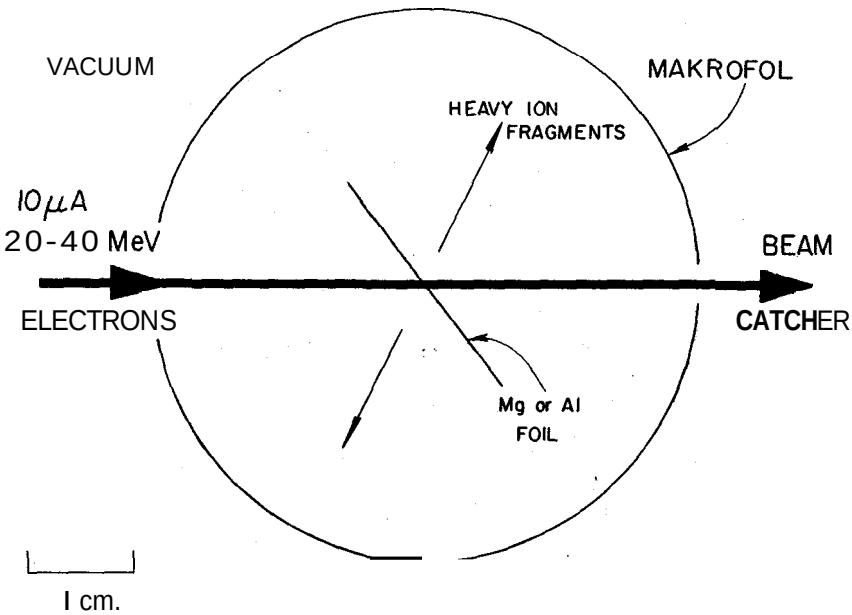


Fig. 9 - The arrangement of electron, target and Makrofol detectors is shown.

It is not possible to deduce the curves of spark recording efficiency as a function of etching time and the ion species from any available data Consequently, we have found it necessary to determine such efficiencies by using ion beams of known energy and species. These ion beams we have obtained from the electrostatic accelerators at Chalk River, McMaster University and Toronto and almost as much time has been expended on calibrating plastic films with known beams as has been spent on the actual electrofission experiments with the linac.

A typical experimental arrangement used for measuring the angular distribution of the fission fragments from the electrofission of light elements is shown in Fig. 9. Currents of about 10 μA of 20 – 40 MeV electrons were obtained from the Toronto Linac and passed through Mg or *Al* foils about 0.7 mgm/cm^2 thick. The electron beam then travelled another 2 meters to a beam catcher.

Although cylindrical foils were found to be necessary for angular distributions we discovered that planar foils give some very valuable information.

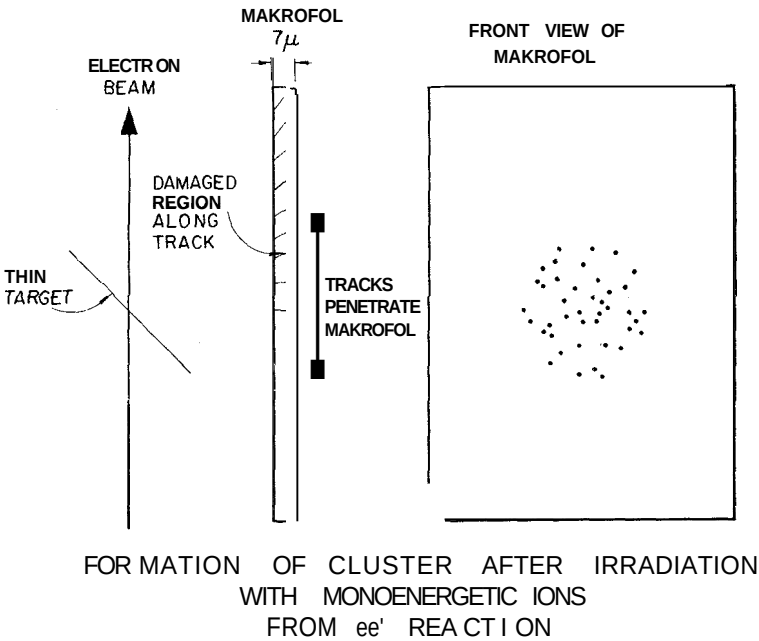


Fig. 2 - The formation of a cluster of holes from monoenergetic heavy ions in a sheet of Makrofol is illustrated.

This feature is illustrated in Fig. 10. We discovered that the tracks which did not penetrate the plastic Makrofol detectors were not registered by the sparking technique. Consequently, if monoenergetic heavy ions were emitted by the target a cluster of holes was observed after sparking had been carried out. Obviously, the observed radius of the cluster, the distance of the foil from the target and the thickness of the Makrofol, can be used to deduce the range of the ions in the Makrofol film.

This is what we observed when the magnesium targets were used and the most clear evidence we have for the electrofission of magnesium is shown in Fig. 11. This data was taken at an electron energy of 36 MeV and the Makrofol thickness was 7μ.

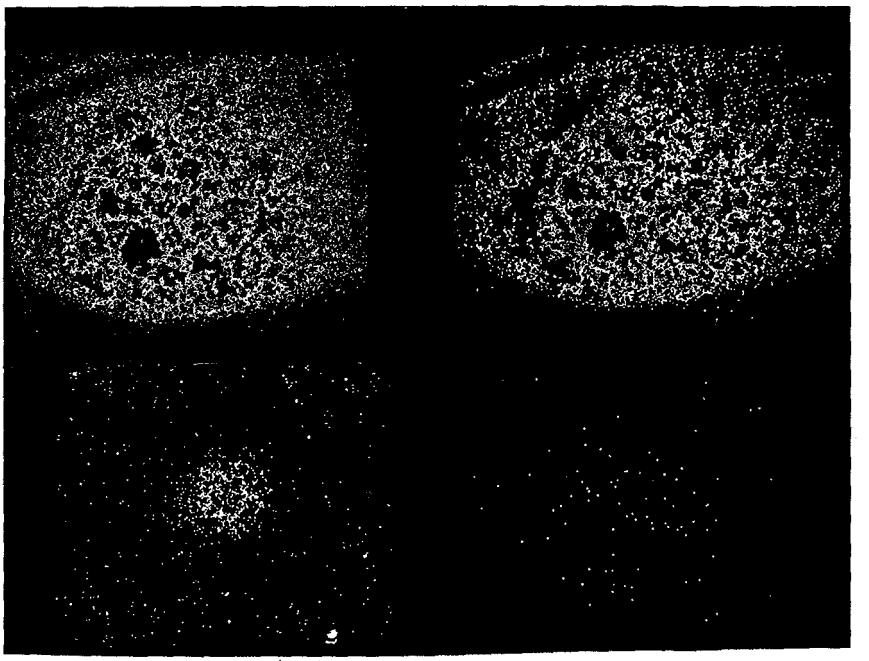


Fig. 11 - The results obtained for thorium are shown in the top part of the figure and the results for magnesium are shown in the bottom part of the figure. The effect of increasing etching time in the case of the magnesium is clearly shown.

On the top half of the slide the data from the electrofission of thorium is shown. The top left hand case was etched for 20 minutes and the top right hand case for an etching time of 50 minutes. There is very little difference between the two cases which is expected for the heavy fission fragment tracks. The bottom part of the slide is quite different. The 20 minute etching time shows only a few scattered fission fragment tracks from the electrofission of heavy element contaminants in ihe magnesium target. After etching for 50 minutes, there appears a circular cluster of holes in the aluminized mylar after sparking and these are most probably due to carbon ions. The size of the cluster tells us that the main group of carbon ions has a maximum energy of about 6.1 MeV. This conclusion was confirmed by using 8μ Makrofol instead of 7μ Makrofol. No circular cluster was observed in the 8μ Makrofol. Also no circular clusters have been observed when an aluminum foil is substituted for a magnesium foil so the circular cluster is a particular feature of magnesium.

Further measurements at other energies showed a rather peculiar result. The size of the cluster was observed to change very little with electron bombarding energy. This is shown in Fig. 12. The top circular cluster

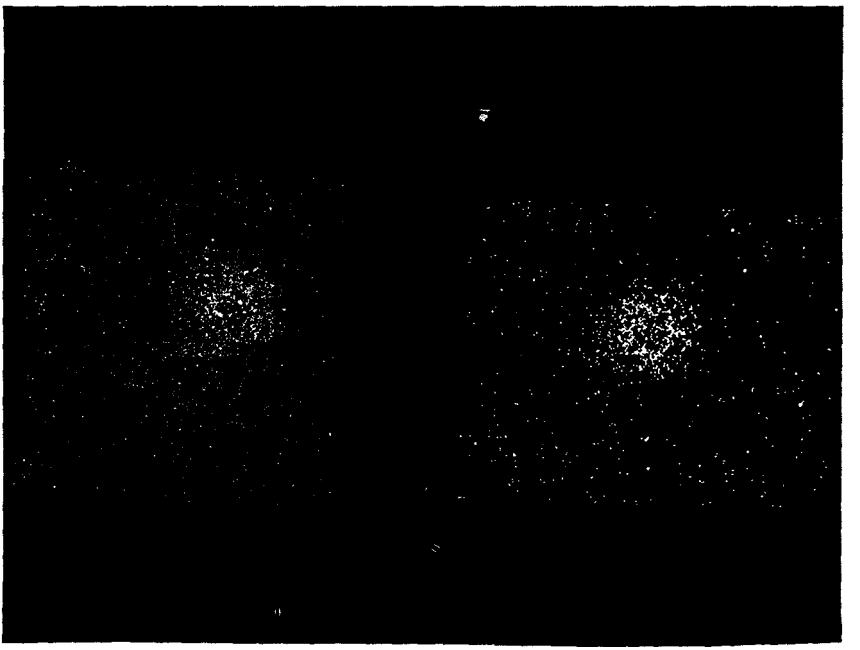


Fig. 12 - The size of the cluster is shown as a function of electron bombarding energy.

shown on the slide was observed at 36 MeV and the bottom cluster was observed at 41 MeV. In addition, a rather rapid rise in the number of holes in the cluster attributable to carbon ions was observed at 30.5 MeV electron energy. In Fig. 13, there is a summary of the yield curve data we have at present in the vicinity of 30.5 MeV electron bombarding energy. The main feature is the rapid rise at 30.5 MeV which is attributable to the appearance of the 6.1 MeV group of carbon ions. The total cross section at 36 MeV is estimated to be 15 nbams. At present we estimate the total cross section of ^{27}Al to be less than 5 nbarns.

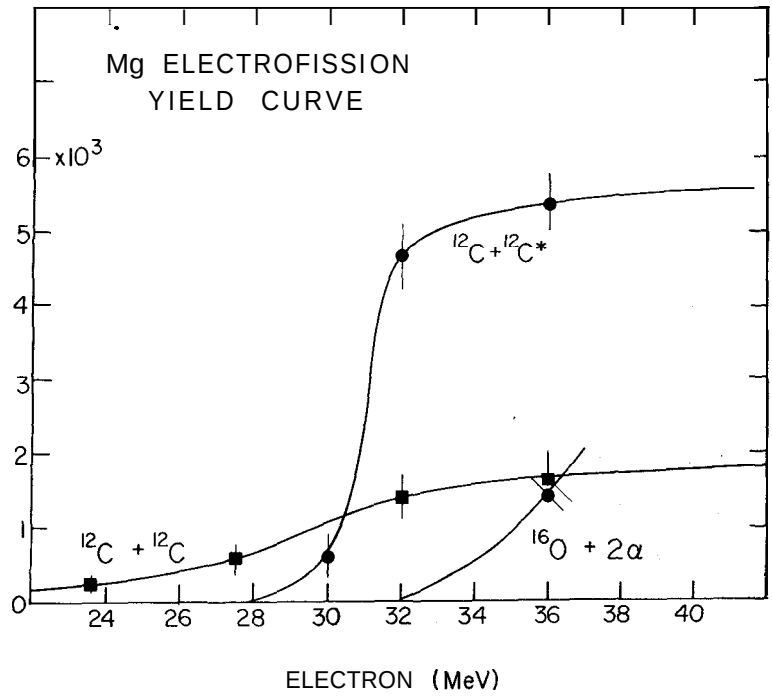


Fig. 13 - Yield curves for the electrofission of magnesium.

We interpret the 6.1 MeV group of carbon ions generated above 30.5 MeV electron energy to be due to a resonance, or cluster of resonances, near 30.5 MeV in ^{24}Mg which emits one carbon-12 nucleus in its ground state and one carbon-12 nucleus in its first excited state. If both carbon-12 nuclei were in the ground state their maximum energy would be 8.3 MeV.

There also appears to be some yield with both carbon-12 nuclei in their ground states and also possibly some indication of the appearance of oxygen ions possibly from the $^{8}O + {}^{8}Be$ channel.

Assuming that the yield curve implies a resonance at about 30.5 MeV, the preliminary values obtained for the total cross sections and angular distributions can be interpreted in terms of the partial width for emission of the carbon ions $\Gamma_{cc'}$, the partial width for E2 gamma ray absorption Γ_{γ} and the total width Γ. The result we obtain is

$$\frac{\Gamma_{cc'}}{\Gamma} \times \Gamma_{\gamma} \simeq 3 \text{ eV}.$$

At the moment we do not have enough information to interpret this result but if $\Gamma_{cc'}/\Gamma$ were equal to 1/20, the gamma ray width would be about one Weisskopf single-particle Unit.

At this point, I should emphasize that this result, which seems quite remarkable, is a preliminary one. The experiments are only just beginning and there are many experimental problems still to be solved. For example, we still are not sure whether it is the ^{24}Mg or ^{25}Mg isotope of magnesium which is responsible for the observed carbon ions. The reason for this is that we were forced to use natural magnesium when we discovered that our separated isotope targets contained too much heavy element contamination. It is clearly of great importante to solve this problem. Also, at present, our targets are thick enough to make the corrections due to target thickness appreciable. We are, of course, planning to use thinner targets as soon as possible.

Discussion

The preliminary results which we have obtained on the cross section of Mg divided by the cross section for Al of > 5 is consistent with the result of Sherman. He observed 6 fission events from natural magnesium and none from aluminium. However, he interpreted the 6 events from magnesium as being associated with the breakup of a 23 MeV excited state in ^{24}Mg into 2 carbon nuclei in their ground states. Subsequent work at the California Institute of Technology[14] on the radiative capture of ^{12}C ions by ^{12}C nuclei showed that the 23 MeV state decays mainly to the first and higher excited states of ^{24}Mg. No ground state transition was observed. It is tempting to suggest that events Sherman observed are the same as the ones we observe. This, however, requires that he underestimated the energy of the carbon ions by about 1.5 MeV.

There is some additional evidence for the existence of a state in ^{24}Mg at 30.5 MeV but it is fragmentary and it may be contradictory. Unpublished work by Kuehner and Almqvist in 1962 on the $^{12}C(^{12}C, ^{12}C)^{12}C^*$ reaction shows a peak in the cross section corresponding to an excitation energy of 30.5 MeV. This is shown in Fig. 14. This seems to be a remarkable coincidence but, unfortunately, the peak cannot be attributable to a resonance until other angles have been studied.

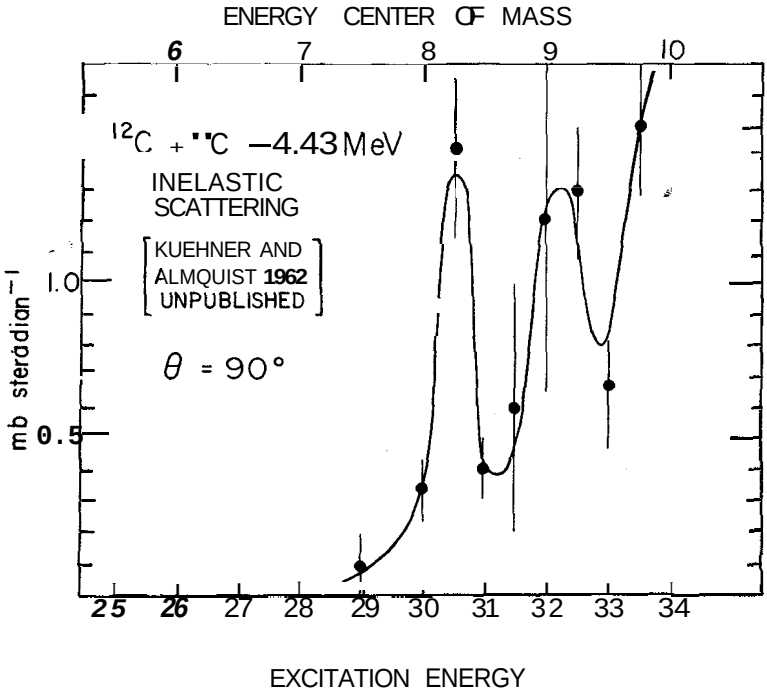


Fig. 14 - The 90° (center of mass) yield of the inelastic scattering of ^{12}C by ^{12}C.

Recent work by Bromley et *al.*[15] has shown that there is a prominent state in ^{24}Mg at 30.7 MeV. Unfortunately, the state shows only the emission of ^{12}C nuclei in their ground states. No evidence has been obtained for the emission of one ^{12}C in its ground state and one in its first excited state and the 30.7 MeV state is also suspected to be of high spin.

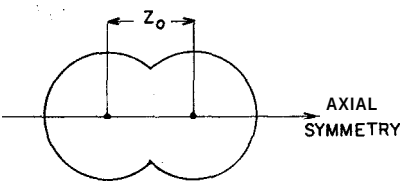
Clearly more experimental evidence of this type is badly needed.

Conclusions

The interpretation of the data we have obtained so far presents many problems but, in wnclusion, I would like to try to give an explanation why ^{24}Mg might be expected to show a larger cross section for electrofission than ^{27}Al.

You will remember that this conclusion is supported by the work of Sherman as well as the work I am reporting today.

Greiner et *al.*[3] have recently reported the results of a calculation on what might be called the two-centre Shell Model. It is basically two spherical Nilsson potentials with the distance between their centres variable. At small separations, the energy level diagram is strongly reminiscent of the Nilsson diagram. This is shown in Fig. 15. At larger distances, however, the potential becomes two separate Nilsson potentials.



TWO CENTERED NILSSON MODEL

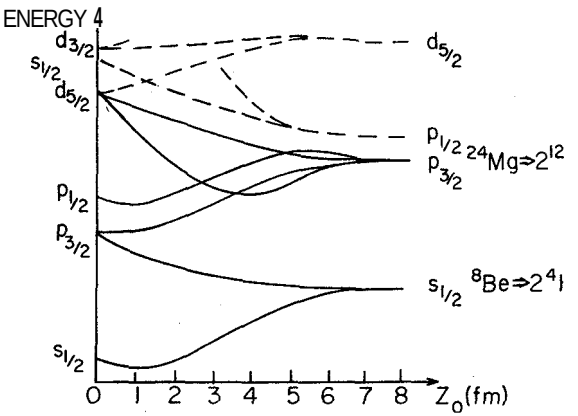


Fig. 15 - The energy levels of the two centered shell model.

During the separation of the two potentials, the K-quantum number remains a good quantum number because the fissioning potential remains axially symmetrical. This brings out a basic difference between ^{24}Mg and ^{27}Al. The symmetrical fission of the ground state of ^{24}Mg proceeds smoothly to two carbon-12 nuclei with possibly quite low excitation energy whereas the fission of the ground state of ^{27}Al produces two fragments, possibly ^{15}N and ^{12}C, but with three nucleons in the K = 5/2 Nilsson orbit. This implies that at least one of the fragments must be in a highly excited state and the reaction must consequently have a very negative Q-value.

Of course, the electrofission of ^{24}Mg and ^{27}Al does not take place from the ground state but they might be expected to fission from states strongly resembling the ground states because of the simplicity of the electro-magnetic excitation. For example, the vibrational motion of the pair of carbon nuclei could be excited in the case of ^{24}Mg. Consequently, it seems likely that the shell structure of the fissioning ^{24}Mg and ^{27}Al may be playing a role in determining the electrofission cross sections. This is, of course, what we hoped to find and so maybe we will now be able to leam something about heavy element fission by the study of light element fission.

We would like to acknowledge the invaluable assistance in this work of Mr. J. Gallant of the Atomic Energy of Canada Ltd. who made many of the targets we used.
Mr. K. Ishii of Bayer Dyestuffs and Chemicals, Canada, provided us with samples of the Makrofol and Mr. I. Wilson of Canada Foils Ltd., Alcan, provided us with the aluminized mylar. The work was supported in part by the National Research Council of Canada.

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