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# RESEARCH WITH AVF CYCLOTRONS IN THE USA*

Invited Paper

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In the past several years many interesting experiments have been performed with AVF cyclotrons. In the brief period of time allotted to me it is only possible to discuss a small fraction of them.

Of the broad range of experiments performed I thought it might be of interest to review some of the applications to nuclear reaction mechanisms and nuclear spectroscopy.

An important class of experiments are the scattering of various projectiles from nuclei. These experiments are interesting for a variety of reasons: 1) The elastic scattering, especially of nucleons, gives some measure of the gross properties of the nucleus, for example its size and its shape; 2) Another aspect of the elastic scattering is that it gives information about the average interaction of the projectile with the nucleus; and 3) Modern reaction theories, in one sense or another, require knowledge of the elastic scattering.

The problem is exceedingly complicated - the nucleus is made up of a collection of protons and neutrons and, in principle, one should consider the interaction of the projectile with each of these target nucleons.

Fortunately, to a good approximation, it is possible to reduce this many body problem to a two body problem in which the complicated sum of interactions is replaced by an effective two-body potential between target and projectile. Since the nucleus, and sometimes the projectile, is not an inert object this potential has an imaginary part to account for the various excitations and reactions which the system can undergo. Thus particles are removed from the incident beam and this has a profound effect on the elastic scattering.

The model to which I am referring is, of course, the optical model. It has proven to be quite a good approximation for the elastic scattering of almost every projectile used in nuclear physics, and in a different but related form it has been applied to the projectiles of high energy physics, the pions and kaons, and at the other end of the energy scale, to the scattering of slow electrons from neutral atoms.

The model is difficult to justify, from first principles, except for the scattering of fairly high energy nucleons. For the same reasons the form of the optical potential is not well defined. Fundamental theory gives, at best, only a hint. One can turn the problem around and study the scattering in terms of a phenomenological potential with parameters dictated by fitting to experiment. Careful perusal of these parameters then give some idea of the physical processes.

It is useful to extend these studies to the particles and energies spanned by the AVF cyclotrons for many reasons. Several of these are: 1) The optical potential is energy dependent, in part because of the energy dependence of the non-elastic processes; 2) The scattering at low energies is insensitive to details of the potential. This is easily understood if one realizes that the wave length of, say, a 10-MeV proton is larger than most nuclei bombarded; and, 3) In connection with various reaction studies carried out at the same energy.

In this vein a group at Oak Ridge consisting of L. N. Blumberg, E. E. Gross, A. Van der Woude, and A. Zucker have measured polarizations and differential cross sections of elastically scattered protons at a bombarding energy at 40 MeV. The targets considered ranged from $^{12}C$ to $^{208}Pb$ so that the mass dependence of the optical potential could be studied.

The first slide shows the differential cross section data and the optical model attempt to describe it. The fits shown in this slide are the results of forcing the model parameters to vary smoothly with target mass. In general, the agreement is good though not perfect. On the next slide are shown the measured polarizations and the optical model fits to the data. A striking feature of the measurements is the fact that back angle polarizations are predominantly positive for the light nuclei. As you go to heavier targets this feature gradually goes away until at Pb the polarization pattern oscillates about a zero mean.

These features place severe and rather interesting restrictions on the optical model parameters which fit the data.

The shape of the real potential follows, in some sense, the density distribution of the nucleus. That is, at small distances, there is a great deal of nuclear matter while at large distances the potential falls smoothly to zero - reflecting the fact that there is some probability for nucleons to exist far from the center of the nucleus.

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The shape of the imaginary potential is not as simply described. It is proportional to the nuclear density distribution but also depends on the probability that a reaction can take place. Deep within nuclear matter nucleons are tightly bound and it takes a great deal of energy to initiate a reaction. For low proton (10-17 MeV) energies, this is improbable and the imaginary potential is peaked at the nuclear surface. At the energy of the Oak Ridge experiments this situation has changed and it is necessary that there be some absorption in the body of the nucleus as well as in the nuclear surface.

Another feature of the potential is that the spin-dependent interaction is centered somewhat within the body of the nucleus. Its precise position and shape, however, are not known. The reasons for this are not clearly understood although more fundamental considerations at high energy indicate that it is plausible.

There are other, esoteric, features of this potential which distinguish it from the potentials found for protons at lower energies. Among these are the fact that the central real well radius parameter is smaller while the fall off distance is larger.

Clearly, there is need for more measurements both at different energies and on more targets. It goes without saying that polarization measurements are a useful, indeed necessary, adjunt to differential cross section experiments. Measurements of the total reaction cross section would also aid in pinpointing the parameters of the potential.

Let me turn now to the elastic scattering of more complex projectiles. The fundamental theory for the scattering of projectiles with internal structure is in very poor shape. In fact, it hardly exists at all. One depends almost entirely on a phenomenological theory whose justification rests mainly on its success and the smoothness of its parameters with energy and target mass.

For a particular example, let me choose the $^3$He ion. This projectile is of great importance in nuclear physics since its use allows the study of proton single particle and hole states in the same way that the deuteron stripping and pickup reactions give information about single neutron states.

The $^3$He ion is doubly charged and relatively easy to break up, since it takes only 5.49 MeV to remove a proton. This latter fact suggests that the $^3$He ion should be strongly absorbed at the nuclear surface and indeed the optical model reflects this in its parameters. The characteristic potential has an absorptive well which is much weaker than, and extends much further than the real well. The success of the optical potential for $^3$He ions is illustrated on the next slide which shows the data and optical model fit for 43.7-MeV $^3$He ions scattered from $^{89}$Y and $^{90}$Zr. The data is from the University of Colorado and was taken by Gibson, Kraushaar, Rickey, and Ridley. The smooth fall off of the differential cross section with angle is a characteristic of strongly absorbed projectiles even though the energy is well above the classical Coulomb barrier.

That the model works well over a range of energy is illustrated on the next slide which shows data and fits to the scattering of $^3$He ions from $^{58}$Ni at energies from 22 → 44 MeV. These fits were achieved by allowing only the depths of the real and imaginary wells to vary with energy as shown on the next slide.

The potentials found thus far have not included a spin-dependent interaction although the $^3$He ion has an intrinsic spin. The spin-dependence must await detailed measurements of polarization and consistent analyses in connection with the differential cross section. Such measurements are planned at a number of laboratories, Oak Ridge and Colorado, and some experiments have already been carried out at Birmingham.

Again, data is needed over a wide range of energy and target nuclei.

Another, related, topic is inelastic scattering. The goals of these experiments and theories are very ambitious. In principle, it should be possible to learn a great deal about nuclear structure - the detailed composition of nuclear states - and the effective interaction between the projectile and a target nucleon. The theory for such a microscopic approach is only now being developed, and is, in any case, beyond the scope of this review. Again, we are fortunate in that an alternative macroscopic theory has been developed for a certain class of excited states - the collective states. This theory is closely related to the optical model theory for elastic scattering. Briefly, the collective model of nuclear structure assumes that either a nucleus is permanently deformed, or easily deformable. It is then reasonable to assume that the interaction between such a nucleus and a projectile is related to the density distribution of the nucleus, i.e., the optical model potential is deformed. If the reaction happens fast enough so that the excited nucleus is not de-excited by the projectile, it is easily demonstrated that only the spherical part of the potential contributes to elastic scattering, since there is no angular momentum change, while the nuclear excitation arises from the aspherical part. The measured inelastic scattering then gives some idea of how deformed the permanently deformed nucleus is, or, for the vibrating nucleus, how easy it is to set into oscillation.

This model has been used, with outstanding success, to describe the inelastic scattering of protons, neutrons, deuterons, $^3$He ions, alpha

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particles, and even heavy ions. A remarkable feature is that all of these projectiles give essentially the same number which characterizes the excited nuclear state.

An example of the success of the theory is illustrated on the next slide, which compares the collective model theory with the data for the excitation of states in $^{90}$Zr by 44-MeV $^3$He ions. The data again is from Colorado. Similar studies have been and are being conducted at ORNL and at Los Alamos.

The theory seems to give an adequate representation of the differential cross sections. In order to test it further and to gain more insight into the nuclear structure and reaction mechanism, it is necessary to devise other measures of the amplitudes. One such, which is a sensitive test of the theory, is the measurement of the angular correlation of $\gamma$-rays following the excitation. Another is to measure the asymmetry of inelastically scattered polarized protons.

The latter process has been measured by a group at Oak Ridge, M. P. Fricke, E. E. Gross, B. J. Morton, and A. Zucker and analyzed by Fricke and R. M. Drisko. The next slide shows the measurements for excitation of 2+ states in $^{28}$Si and $^{58}$Ni, and the preliminary analysis of this data.

Intuitively, it might be thought that only the real part of the potential would be deformed. As can be seen from this slide, this form of the theory gives a rather smooth asymmetry pattern while the data has much more structure. What is necessary to give reasonable agreement with the data is to also allow the imaginary and spin-dependent parts of the interaction to follow the motion of the vibrating nucleus. Even then, for angles less than 40$^\circ$, the theory misrepresents nature. I should emphasize that the theoretical predictions are very sensitive to the parameters and that the best parameters haven't yet been found. However, the failures at forward angles suggest a more fundamental gap in the theory, and this is being studied.

Let me turn to another topic where I think AVF cyclotrons will dominate the field for several years to come. This is the study of proton hole and particle states using the (d,$^3$He) and ($^3$He,d) reactions, and neutron states in heavy nuclei with (d,p), (d,t) and (p,d) reactions. Because of the Coulomb barrier, these reactions are difficult or impossible to study with low energy machines. As you know, the shape of the angular distribution of the outgoing particle is a measure of the angular momentum transferred to the nucleus, while the magnitude of the cross section is a measure of the single particle or hole character of the nuclear state.

An example of this, unfortunately not the best one, is the study of states in $^{50}$Ti reached by the $^{51}$V(d,$^3$He)$^{50}$Ti reaction. The states that we shall consider are 0+, 2+, 4+, and 6+ states which are assumed to be made up of two protons in $f_{7/2}$ orbits outside a nuclear core with zero angular momentum. That is, each of these protons has orbital angular momentum of 3 and a total angular momentum of 7/2 in units of Planck's constant divided by $2\pi$. Since $^{51}$V has 3 protons in $f_{7/2}$ orbits, these states are reached by picking up one of them. The shell model, which is believed to be applicable here, predicts after dynamical factors are removed, that the states (0,2,4,6) should be excited in the ratio 9:5:9:13.

This experiment has been done at Argonne with 21-MeV deuterons, by T. H. Braid and B. Zeidman, and repeated at Oak Ridge by J. C. Hiebert and E. Newman using 34-MeV deuterons from ORIC.

With 21-MeV deuterons one finds the raw spectrum shown on the next slide. The most probable transition, to the 6+ state, is weaker than the transition to the ground state (0+). The transition to the 4+ state, which would be comparable to the cross section for the 0+ state, if dynamical effects were unimportant, is also weak.

With 34-MeV deuterons the raw data for these transitions is closer to the ratio predicted by the shell model as shown on the next slide.

The energy difference is reflected in the angular distributions as well. The next slide shows the differential cross section for the reactions initiated by 21-MeV deuterons. If the simple shell model were perfect only $\ell$ = 3 transitions would be allowed to all these states. This slide illustrates a minor breakdown in that there is an $\ell$ = 1 transition to the 2+ state. In any case, the transitions to the 0+ and 6+ states must be pure $\ell$ = 3 and this slide shows that these two angular distributions are quite different. However, at 34 MeV, the shapes are very similar as can be seen in the next slide, and orbital angular momentum transfers could be assigned by inspection, although extraction of magnitudes is still theory dependent.

This effect will be much more important for higher Z targets.

Finally, I shall report on some (d,p) and (d,t) experiments done at the University of Michigan by two graduate students, A. Poltorak and G. Muelhlehner, under the direction of Professor W. C. Parkinson. Professor Parkinson and his group intend to investigate nuclei in the deformed region where the spectra are complicated. As a preliminary to this work these people thought it advisable to study a heavy nucleus where the structure is well known. In this way the theory could be tested for reliability and the sensitivity to deuteron energy studied. The logical target is $^{208}$Pb since particle states in $^{209}$Pb and hole states in $^{207}$Pb are assumed to be pure.

 

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The next slide shows angular distributions of tritons for three incident deuteron energies. At the lowest energy Coulomb effects are important for the angular distributions, although there are nuclear effects present which show up at forward angles. The angular distributions at back angles differ subtly in slope for the various ℓ-transfer values. At the median energy, 20.3 MeV, nuclear distortions are more important and angular distributions are shifted forward. At 25 MeV, twice the energy of the Coulomb barrier, the angular distributions are shifted forward even more. At the latter two energies, angular distributions are sufficiently different so that perhaps, with experience, ℓ- values could be assigned.

The theoretical predictions, solid lines, are in reasonable agreement with the data both in the predicted shape and in the absolute magnitude.

Much the same remarks can be made about the stripping reactions shown on the next slide. Here, since Q values are positive, nuclear effects set in at quite low energy. The difference between angular distributions for different ℓ-transfers are not large. Compare, for example, the d-transitions with the g-transitions. This points out the care necessary in analyzing the data.

These results are encouraging and indicate that meaningful spectroscopy can be done for heavy nuclei.

Of course, I have only touched on the experiments performed. I hope, however, that this sampling has shown some of the progress made and indicates areas of future experiments.

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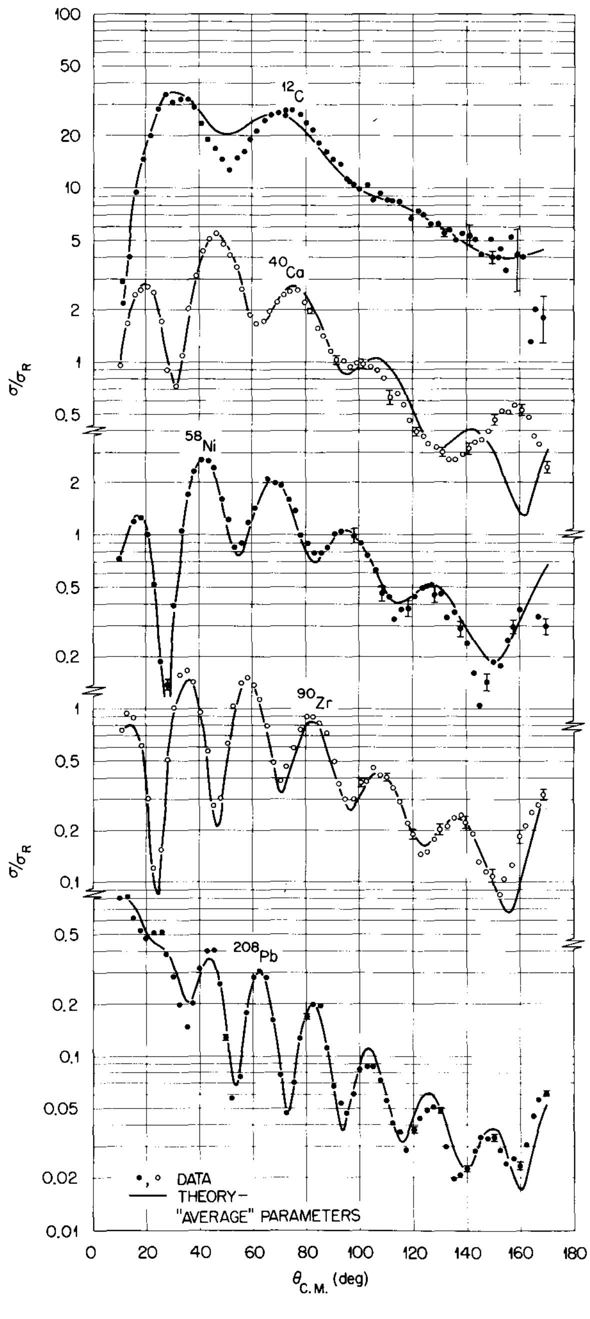


**Fig. 1. "Average" parameter fits to 40-MeV elastic proton scattering data.**

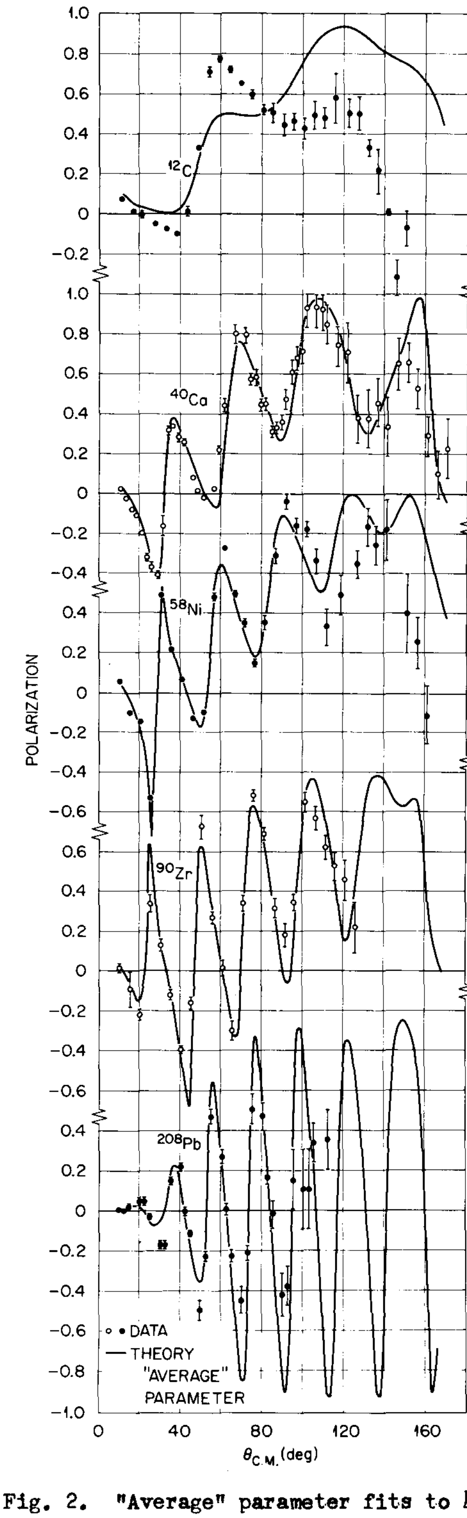


**Fig. 2. "Average" parameter fits to 40-MeV elastic polarization data.**

 

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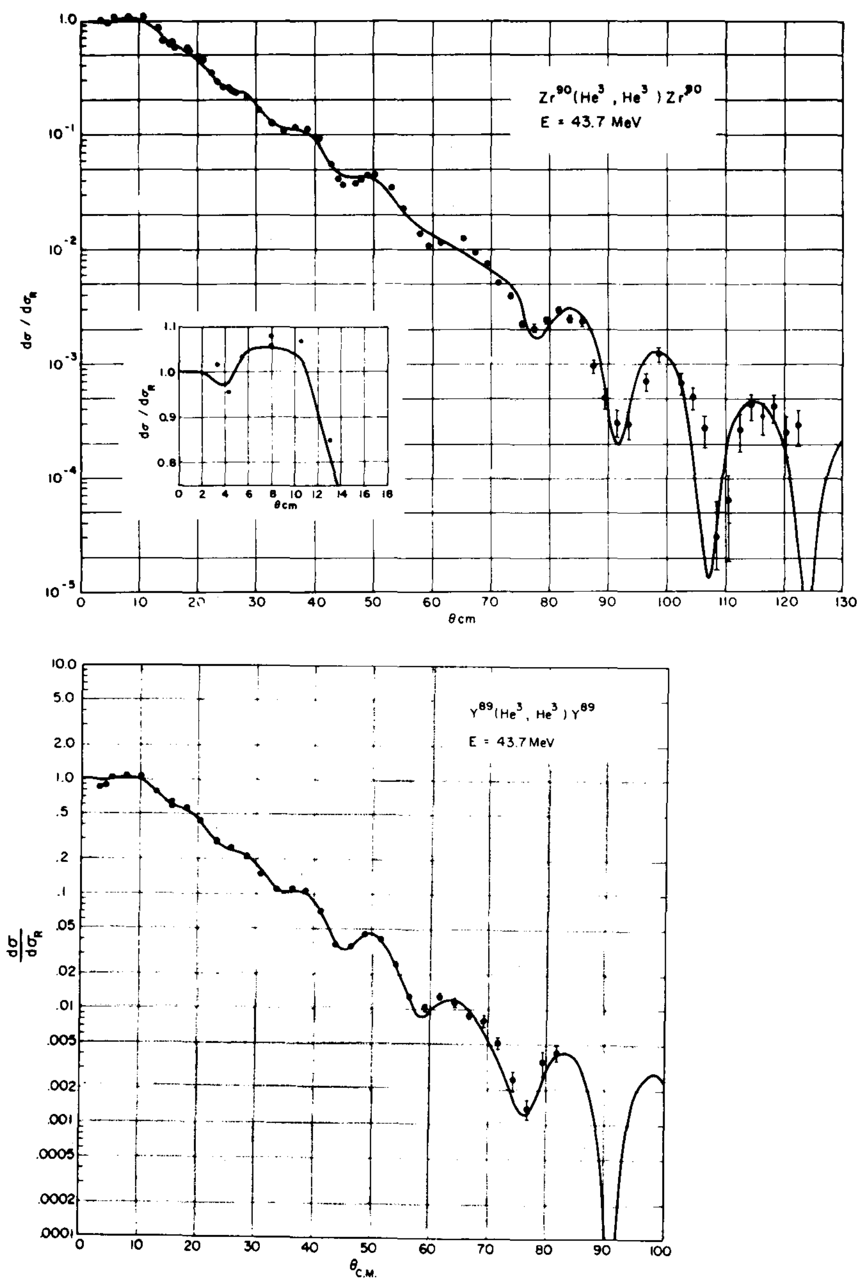


Fig. 3. Optical model fits to the scattering of 43.7-MeV $^3$He ions from $^{89}$Y and $^{90}$Zr.

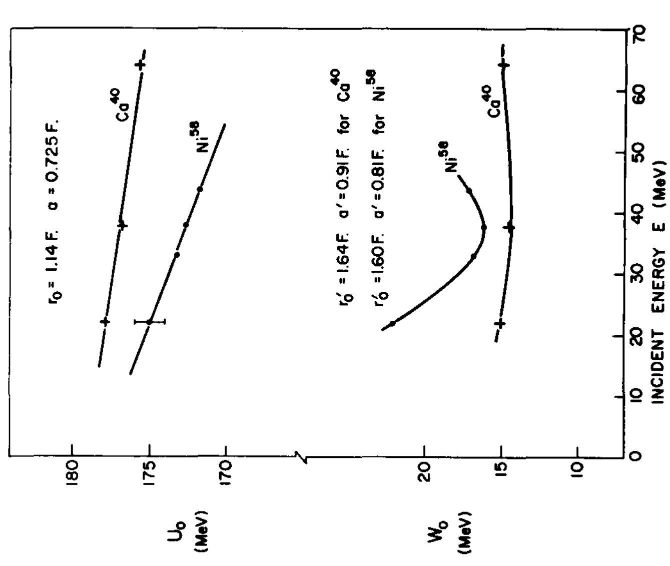


Fig. 5. Variation of real and imaginary well depths with energy for the scattering of $^3He$ from $^{58}Ni$.

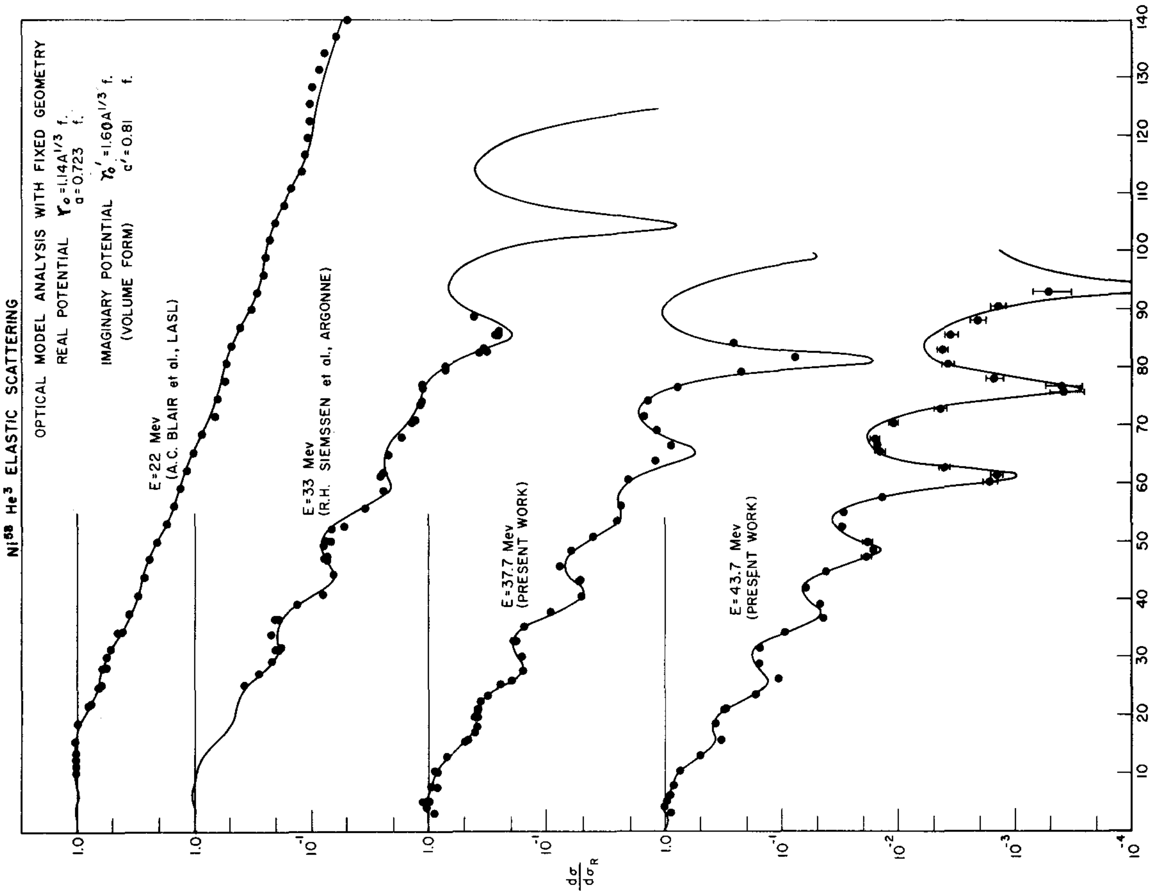


Fig. 4. Optical model fits to the elastic scattering of $^3He$ ions from $^{58}Ni$ as a function of bombarding energy.

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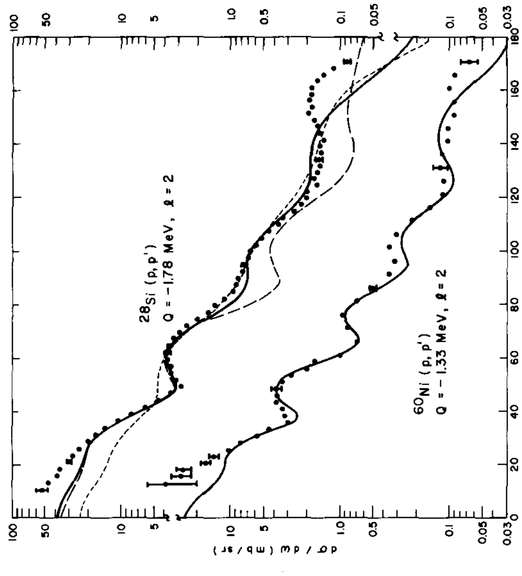


Fig. 7. Comparison of distorted wave predictions for inelastic scattering and asymmetry of 40-MeV protons with the data for $^{28}$Si and $^{60}$Ni.

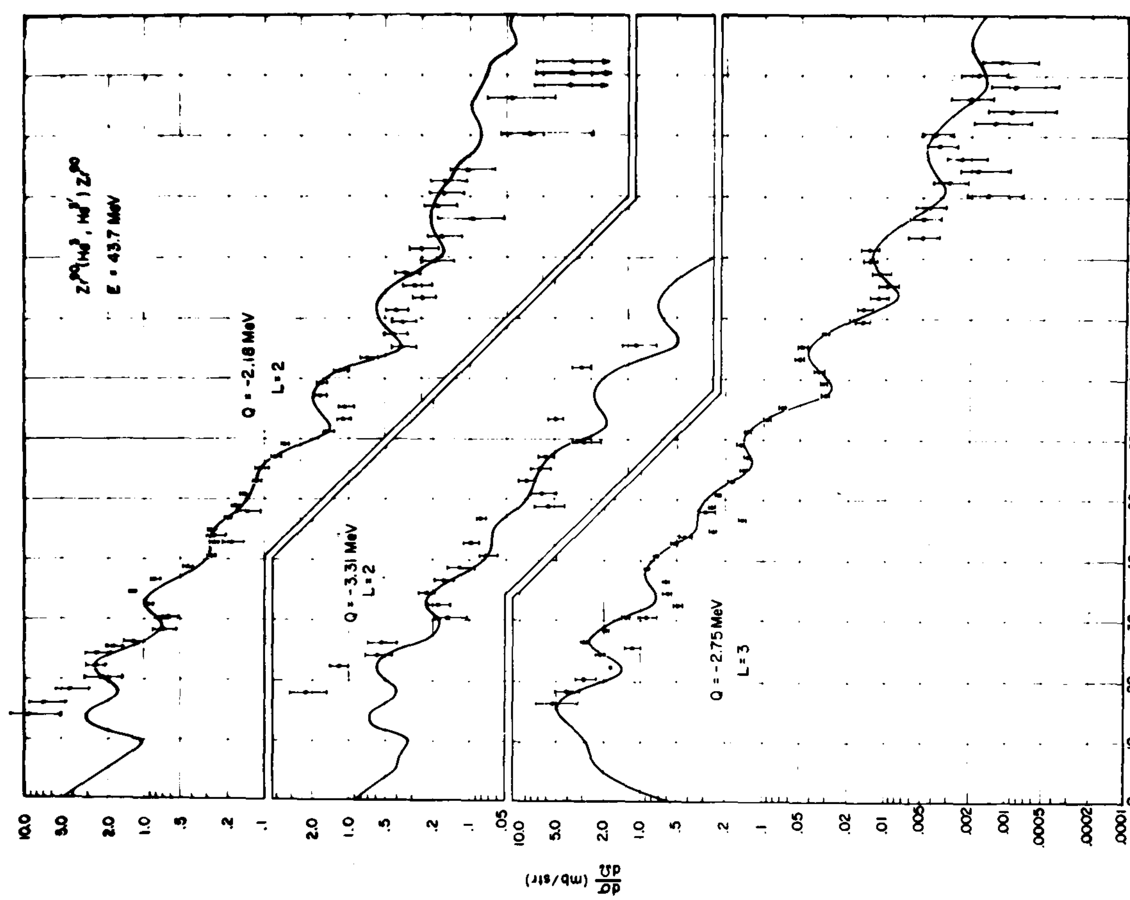


Fig. 6. Distorted-Wave predictions for the excitation of states in $^{90}$Zr by 43.7-MeV $^{3}$He ions.

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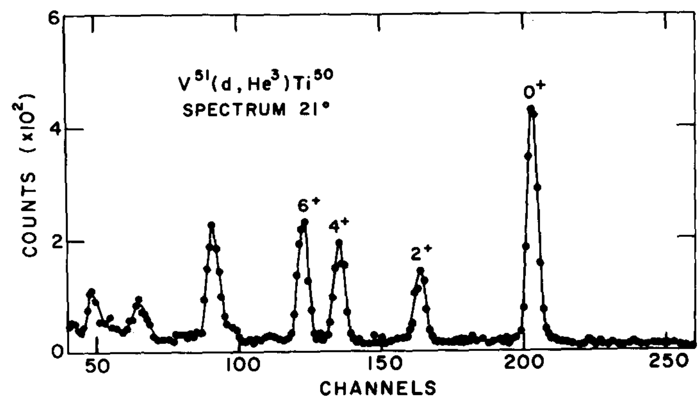


Fig. 8. Spectrum of $^{3}$He ions from the $^{51}$V(d,$^{3}$He)$^{50}$Ti reactions at a deuteron energy of 21.4 MeV.

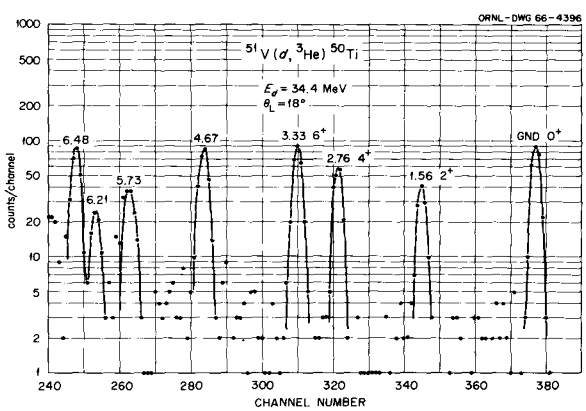


Fig. 9. Spectrum of $^{3}$He ions from the $^{51}$V(d,$^{3}$He)$^{50}$Ti reactions at a deuteron energy of 34 MeV.

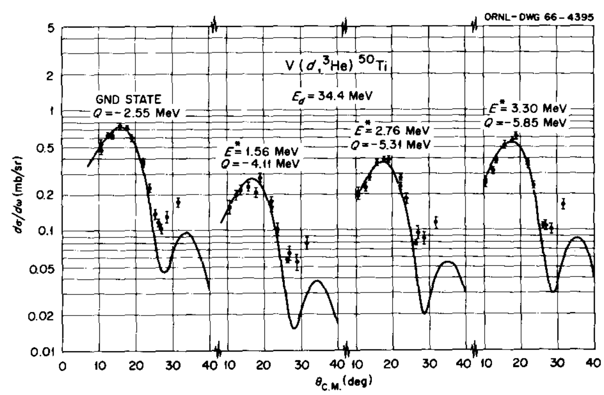


Fig. 11. Angular distributions of $^{3}$He ions from the $^{51}$V(d,$^{3}$He)$^{50}$Ti reactions at a deuteron energy of 34 MeV.

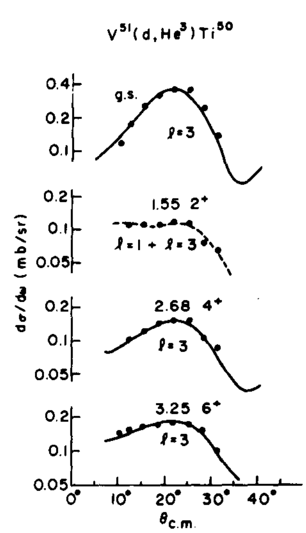


Fig. 10. Angular distributions of $^{3}$He ions from the $^{51}$V(d,$^{3}$He)$^{50}$Ti reactions at a deuteron energy of 21.4 MeV.

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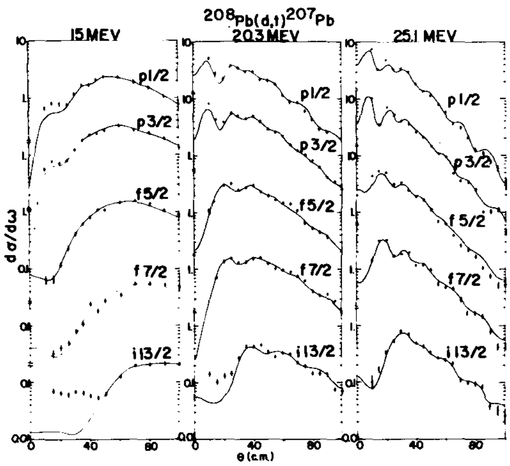


Fig. 12. Angular distributions of tritons from the $^{208}$Pb(d,t)$^{207}$Pb reactions as a function of energy.

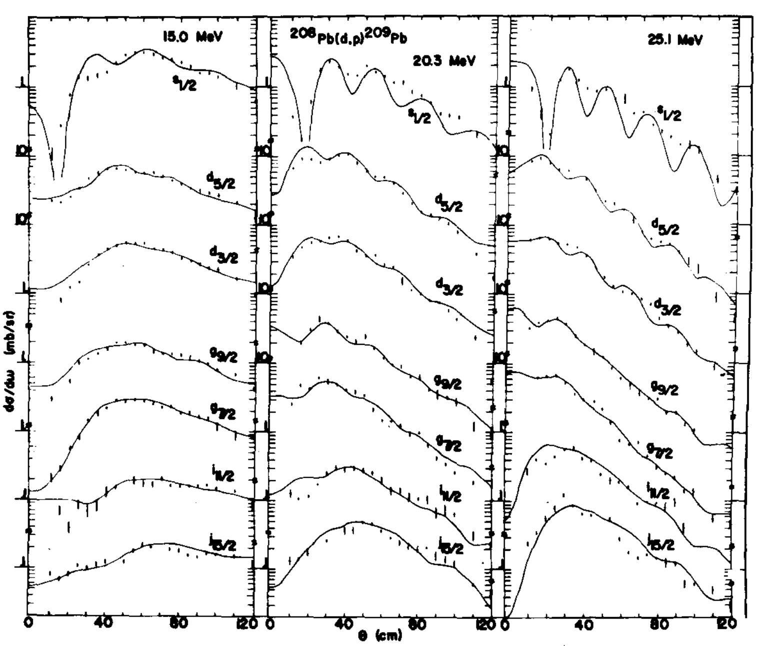


Fig. 13. Angular distributions of protons from the $^{208}$Pb(d,p)$^{208}$Pb reactions as a function of energy.

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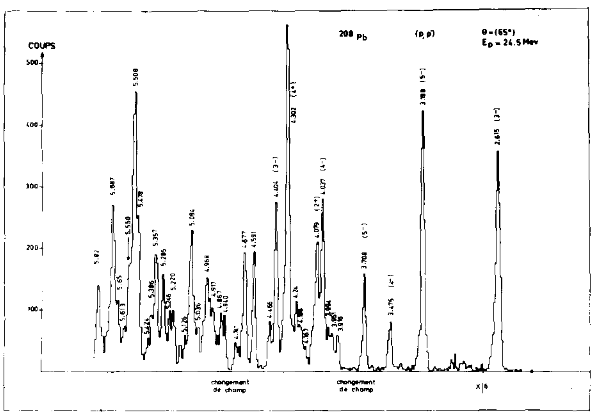
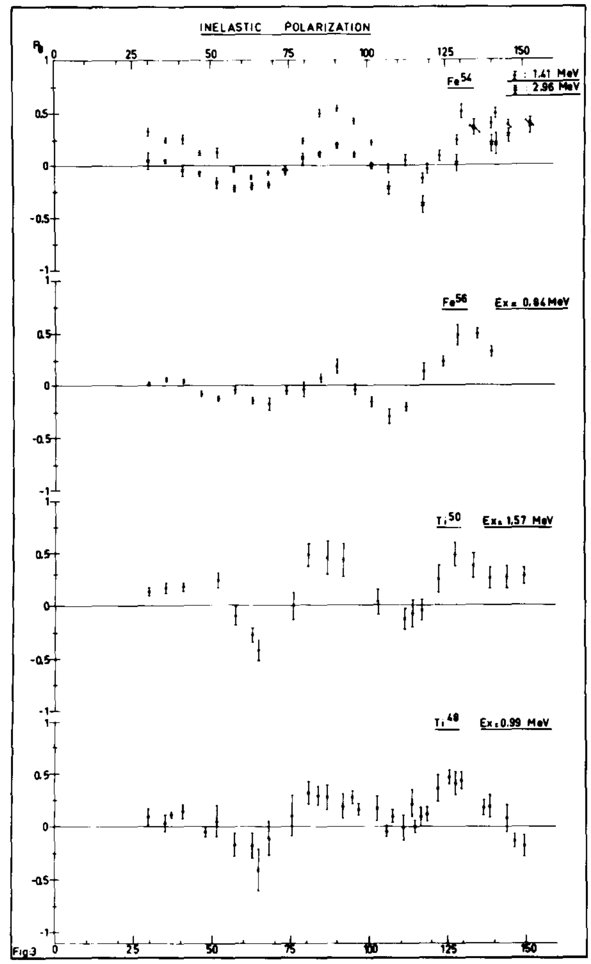
## PANEL DISCUSSION

THIRION: I would like to make two comments. The first is connected with energy resolution requirements. The aim is usually to be able to separate clearly the final energy levels. That may sometimes require a resolution of one, or at most a few, keV. I would like to emphasize that magnetic analysis, for the incident beam as well as for the secondary particles, is a suitable answer to this problem. The usual drawbacks of slow counting rates or delayed information can be overcome; we will hear later of some developments at Ann Arbor and Oak Ridge. As an example, let me present to you a spectrum of




inelastic 24.5-MeV proton scattering on $^{208}$Pb obtained at Saclay (Fig. 1). It was obtained with a locating spark chamber 20-cm long (Charpak type), placed along the focal plane of the secondary analyzer. The counting rate is 100 per second and the resolution is 25 keV. Although this last value is not exceptional, it can probably be improved; the convenience and efficiency of the set-up is worth mentioning.

The second comment concerns the experiments with polarized beams. Cyclotrons have unexpectedly been first to use polarized ion sources. As we can deduce from the past days, polarized beam currents as high as 0.01 μA can be expected in a very near future, one tenth of that value being available now at Birmingham. Such performances are due to the exceptional ability of AVF cyclotrons to capture and accelerate so much of the injected beam. An example of the extremely remarkable possibilities thus opened can be seen from what we are already able to observe with beams of 2 x $10^3$ particles per second. Figure 2 shows the asymmetries obtained in inelastic scattering of 18.5-MeV polarized protons, the final levels being 2+ levels in all cases. The interesting fact is that the curves exhibit large differences. A macroscopic model would predict a universal curve. One may then conjecture that the differences are due to detailed nuclear structure, such as different shapes in the form factors. If true, that would allow us more insight of the nuclear wave functions. That is certainly very important; the use of polarized beams will provide us, I hope, detailed and essential information.




PARKINSON: The Chairman asked me yesterday if I would say just a few words about our magnet system, and the resolution we obtain. I don't have any slides of our results to show, so I won't be disturbed if you say "cum grano salis."

You may recognize this sketch of our system; it was shown at the Los Angeles conference, see Fig. 1. After the cyclotron source there are two beam preparation magnets, a scattering chamber, and three 180° reaction-product magnets.

All five are n = 1/2 magnets. Note that the sum of the radii of the two 110° (200-cm) magnets is equal to the sum of the radii of the three 180° (133-cm) magnets. That is very important.

Also, we prefer to talk about the resolving power, R, rather than the resolution. For our system, with 1-mm slits, this is 8 x $10^3$. It means that we would have 2.5 kV energy spread at 20 MeV. I think the resolving power is more significant than resolution because resolution depends upon the line shapes, intensities, and so on. We prefer to use the Rayliegh criterion.

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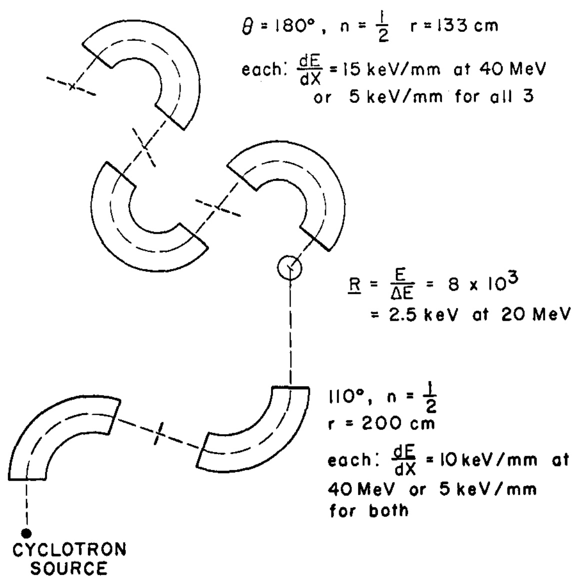


Let me just make three quick comments about the system: first, the resolution and ease of operation of the beam preparation system; second, the resolving power of the reaction products analysis system; and, third, a remark about the intensity of the beam on the target.

It is possible to do excitation functions in energy steps of only a kilovolt or so, with an energy spread on the target of only 2 to 4 kilovolts. For example, at 14.25 MeV (I use that number only because there happens to be a resonance in $^{12}C(p, p)$ at that point, the resonance being something like 4 to 6 kV wide), it is possible to run over this resonance in steps of about 1 kV with a 1.8-kV energy spread on the target, for 1-mm slits. It is very simple and very quick to change the energy in this kind of step, since it is only necessary to change the frequency of the proton moment for this second magnet.

The second point about the reaction products analysis and the resolution: because the ion optics are reasonably good, and in fact match the beam preparation system, the resolution in all practical cases, is determined almost entirely by the target. While we have not made a serious effort to obtain the optimum, Conzett did mention the 6 to 8 kV half-width of the peak in aluminum ground-state doublet at 21-MeV proton energy. This is an important point, incidentally. This was a half-width of something like 6 to 8 kV, and I want to emphasize that this was a completely non-uniform aluminum leaf target, which should contribute something like 9 to 10 kV to the total width. This is not a contradiction in numbers, but rather it points up the question of line shape width and resolving power, which is so well understood, in fact, by the atomic and molecular spectroscopists.

The third and final point has to do with the beam on the target. At full resolution, let's talk about $10^4$, the beam current is small. In our case we get typically anywhere from 20 to 100 nA, and very seldom 100 nA. This is actually a factor of 10 lower than we should be able to realize with our present facility, but we know where this factor of 10 comes from, and we hope to do something about it.

But my point is that in spite of Tuesday's discussion, if I take Blosser's numbers for the current that you can get from a source before a space charge begins to set in, then in my opinion the ion source really is the limiting factor in obtaining a good current at high resolution. For example, with a resolving power of $10^4$ this current would be something on the order of a microampere. So that I think that really the ion source is going to be the limiting thing if you want more current when you have high resolution.

LIVINGOOD: I would like to comment on Dr. Conzett's suggestion, that one can double the duty factor of a cyclotron by injecting into both the dee and the dummy dee. I am afraid that's a fallacy which has trapped many people in the past, including myself! If you think about it, you are only going to get one batch of particles out of the cyclotron per cycle. No matter how you inject them, either you won't get them at all, or they will add to the mixture of energy.

In an old-fashioned synchrocyclotron which had an open ion source, particles could be accelerated into this dee or that dee, whenever it is negative. Half a cycle later the particles leave this dee and head for that one, which is the same moment when particles are leaving the ion source and starting for this one. So they are in time together. They may be a half a cycle behind, in energy one dee energy behind each other. In a synchrocyclotron the phase stability will allow them to get mixed up, and they will catch up in time, but they will come out with different energies.

In a modern cyclotron if one injects into both dees, the particles leaving for the dummy dee will be off center so they won't get out of the system at all.

CONZETT: Does everybody agree?

VOICES: Yes.

CONZETT: I am glad I only suggested that the possibility be looked at!

EISBERG: I speak with reference to a point Conzett made about this class of experiments, such as (p, 2p) experiments, involving the detection of two or more particles in coincidence. Many people feel that this class of experiments in the 100- and 200-MeV range will be among the most fruitful experiments done on these new machines. I certainly support Conzett's statement to the effect that duty factor is the really important experimental machine criterion for these experiments, because they are always going to be accidental-coincidence limited. We hope that ultimately machine people will produce machines that do have the theoretical, realizable limit of duty cycle, whatever that is. But even when that happens, the experiments are still going to be accidental limited, and experimentalists are still going to want a month running time, and they still are going to be running at a very reduced beam, because of the problem of accidentals. It seems then that the logical thing to do, since the machine's beam is not being fully used, is somehow or other to split the beam into two, or three or more, separate beams. Separate bombardment areas could then be used at the same time, to provide really efficient use of the machine, and get a lot of physics done per year.

There was a reference made to this yesterday by Vogt. It seems very easy to do, if you are accelerating negative ions. You can perhaps get simultaneous beams out of different energies from the machine. If you don't want to do that, though, you can split external beams, negative ions or positive ions, in several ways.

I found recently that beam splitters had been built at the 60-inch cyclotron at Berkeley and at the MIT Van de Graaff, but they were never used because the experimentalists didn't cooperate. They wouldn't get together, because they didn't have to. Some of us are feeling much more cooperative than we used to--because we have to! I really think that it is very feasible to anticipate scheduling one month in which there are several low-intensity, high-duty cycle beams available for different bombardment areas while different groups do different correlation experiments at the same time.

THIRION: Thank you. I think you are perfectly right.

BENT: Little has been said about the use of AVF machines to accelerate heavy ions. Would one of the speakers comment on whether any of the groups are now doing this, what the future possibilities are, and how AVF cyclotrons will compete with large tandem Van de Graaffs for acceleration of heavy ions?

Conzett: At Berkeley all machine time is essentially sold in accelerating protons, deuterons, helium-3, and helium-4; but on the other hand we are in the fortunate position of having a heavy-ion linear accelerator. So, in fact, nobody has really come to ask us about accelerating heavy ions.

THIRION: This is not quite an answer! Would somebody like to answer this question about heavy ions?

LIVINGSTON: I am sure that AVF cyclotrons are practically a perfect vehicle for accelerating heavy ions. There are some limitations, however, on the heavy ions which can be conveniently accelerated. These were touched upon yesterday in the Omnitron talk. If you use an internal ion source, you are limited to the species of ion which the ion source will put out. This, in general, is 3+, 4+, or 5+ heavy ions. Of course, at Oak Ridge we have accelerated 3+ nitrogen very successfully for a long time.

I think that the great interest nowadays, however, is in going to very highly stripped very heavy ions, which the ion source of the AVF cyclotron really cannot produce directly. We need an external system to create the ions in a highly stripped condition and inject them into the cyclotron. This is an area which really should be thought about a good deal, right now. I am personally quite interested in what is the best way to get high currents of these very heavy ions. My own personal thinking is that maybe something other than the AVF cyclotron may be the best way to do it. The AVF cyclotron is very good, but it does have limits.

SUZUKI: I would like to comment on the duty cycle of the beam, especially on the duty cycle of meson beams, since the lifetime of the mesons are about the same as the time duration of beams. We have very great difficulty with time-dependent experiments, for example, measurement of neutron asymmetry following the $\mu^-$ capture, lifetime of $\mu^-$ in materials, $\pi$ lifetime, and so on, even if we have very, very weak beam compared with meson factories, and even if we have 50% overall duty cycle at Carnegie Tech. Control over duty cycle of meson facilities is very important.

HOLMGREN: What we were talking about this morning in most of the papers here is roughly 5% of what happens when a high-energy nucleon, such as the nucleon between 100 and 200 MeV, strikes a nucleus. If you look at the typical spectrum (sketching the spectrum from right to left) you find a little wiggle out here for the elastically-scattered group, and then maybe a couple of other little wiggles for a few inelastic-scattered groups, and then a large continuum. I want to emphasize this point of duty cycle, because the single-particle spectra that you achieve can be obtained very well with the high-energy-resolution poor duty-cycle machine. But that only tells you about these five or so little groups way out here, which is 3 to 5% of what happens in the large continuum that many of us are interested in. To investigate what happens here you can look at the single-particle spectrum, but whatever theory you come up with is pure guesswork, and there are as many guesses as there are theorists working on this area.

The only way to look at this area is to measure more parameters associated with each event. The typical thing to do is to look at two particles in coincidence. This is typically an experiment where you put counters at two angles and measure the energies of the two particles. Again this is fine; however, even that may not suffice to answer all of the questions. There are a few of us who have been doing even triple-coincidence experiments, looking at three particles. As a matter of fact, we just finished an experiment looking at four particles coming out of a single nuclear reaction, measuring all of their energies.

But, let me go back to these two-particle type coincidences. We look at an experiment where we have an energy $E_1$, $E_2$ for these two particles at these two angles. In this reaction all events are concentrated along some sort of a circle, or closed line, in a two-dimentional energy spectrum. Now we are talking about beam bursts, which may be 5 to 10 nanoseconds in length. The energy range covered here is very wide. The time of flight from the target to one of these detectors is typically 5 to 15 nanoseconds. That means, because of the wide range of energies here, that normally the range of time of flights is so wide that it has not been practical, up to now, to really look at these things with resolving times better than the resolving time corresponding to the beam bursts. There was no point, then, in building a coincidence circuit that was much better than 10 or 15 nanseconds.

With the advent of large computers, and data-processing systems, it is now feasible to measure the time relationship for every event on this two-dimensional energy spectrum. This means requiring at least three parameters for even the two-particle events, that is, the energies of the two particles and the time; possibly identifying the particles, which may require two more parameters. That is up to five parameters. To start doing more complex experiments you can rapidly enlarge this. You may be measuring each of these parameters in something like 100 to 500 bins. So, you see, this experiment becomes very complex.

This type of experiment could not be done until the large data-processing systems arrived. Now, electronics and solid-state detectors are clearly capable of measuring coincidences down in the sub-nanosecond range; it becomes really practical to start increasing the duty factor of these machines. Maybe 90% of the physics, probably 90% of the machine time, for these higher-energy machines will be involved in these types of studies. Therefore, the value of the machine will go up in proportion to the duty factor.

FOSS: Many people realize that flat-topping the rf is a good way to improve the duty cycle. All they need is a good way to flat-top the rf!