SECTOR-FOCUSED CYCLOTRONS FOR NUCLEAR PHYSICS RESEARCH

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Ever since the discovery of the nucleus by a scattering experiment, high-energy collisions and nuclear reactions have been successfully employed to get information about nuclear properties. Nuclear size and density, nuclear deformation, the energy levels of light nuclei and the level densities of heavier ones, the mechanism of nuclear reactions, and the behavior of individual nucleons and clusters, all these are examples of the kind of information that can be obtained with high-energy particles. A variety of ingenious accelerators were invented for this purpose, with energy capabilities from a few tenths of an MeV to tens of GeV. This large dynamic range of 10^5 is not everywhere dense; some energy regions were touched only lightly in the race to the top.

We will concern ourselves here with research programs made possible by the new sector-focused cyclotrons in the 20-100 MeV range. Accelerators in this class have maximum proton energies between 30 and 80 MeV, and they can accelerate other particles such as deuterons, α-particles, and heavy ions (N, O, and perhaps Ar) to commensurate energies. Most of them have an adjustable magnetic field and RF system which makes them variable-energy machines. The region which they cover is just beyond the reach of fixed-frequency cyclotrons or modern tandem electrostatic accelerators, and well below the meson threshold.

What makes this region attractive? Between 20 and 100 MeV the effect of the Coulomb barrier diminishes in importance, and many energetic threshold restrictions of desirable reactions are lifted. Practically limitless possibilities open up: pickup of nucleons or clusters, stripping, transfer of several nucleons from one ion to another, the emission of several particles in the same reaction, etc. On the other hand, the energy is still low enough so that one can hope to get excellent energy resolution in the incident beam without great difficulty, a matter of great importance, and one which becomes increasingly worrisome as we go from 100 to 1000 MeV.

For nuclear physics research between 20 and 100 MeV sector-focused cyclotrons have the following desirable characteristics:

1. High intensity and duty cycle
2. Variable energy
3. Choice of particle

(*) Operated for the USAEC by Union Carbide Corporation.

To this should be added a characteristic they do not possess -- good energy resolution, which must be grafted onto the accelerator in the form of high-resolution magnetic analysis. This is usually done at the expense of beam intensity.

With this tool we now look for the crucial experiments to be performed in nuclear physics, and find none. Indeed, if we look for a nuclear theory we find only a very inadequate one, in terms of the protons and neutrons which constitute the nucleus and the forces between them. Instead we are faced with a number of nuclear models, each of which is successful in its own domain, and the optimistic view that with enough accurate experimental data the various models will coalesce and that a satisfactory nuclear theory will emerge. Actually, the situation is not so bleak; in their own fields the models are quite good, and must insight has been gained since one of the early models likened the nucleus to a drop of water. Incidentally, even a picture this crude can explain why U^{235} fissions when it absorbs a slow neutron and U^{238} does not.

Direct Nuclear Reactions

The direct reaction is likely to be the most popular field of study for AVF cyclotrons in the immediate future. Here we deal with stripping reactions such as (d, p), (d, n), (He^3, d) and their inverse, the pickup reactions (p, d), (p, t), (d, Li^6), etc. In such reactions the incoming particle is considered to interact with only one or two particles (or holes) in the target nucleus, while the rest of the nucleus acts as a spectator and influences the reaction in a quasi-elastic way. A very successful description of direct reactions has been achieved in the last few years by means of the distorted-wave Born approximation. The matrix element T, for a stripping reaction A(d, p)B is

$$T = \left\langle \chi(p)\, \Phi(B) \,\middle|\, V(np) \,\middle|\, \chi(d)\, \Phi(r_{np})\, \Phi(A) \right\rangle$$

where the χ's are distorted-wave functions of the incident deuteron and the final proton, and the nuclear structure information is obtained from the relations between $\Phi(A)$ and $\Phi(B)$. The proton and deuteron relative motions are described by optical model wave functions.

Because the DWBA theory describes the direct interaction mechanism correctly, we can extract nuclear structure information from the experimental results. This means that, in shell model language, one can obtain quantum numbers of the nucleons in the valence shell of the nucleus, similar to the determination of electron quantum numbers in an atom which are deduced from an analysis of its spectrum. Many people think that the collection of nuclear spectroscopic data is the most important task for the physicist today, and a very large sector-focused cyclotron installation, at the University of Michigan, will be primarily devoted to this kind of research.

The DWBA theory makes use of the nuclear optical model to describe the motion of the incident and outgoing particles in a direct reaction. According to the optical

model the nucleus can be represented as a complex potential whose depth and radial extent are defined by about five adjustable parameters. To determine these parameters we measure angular distributions of particles scattered elastically from a nucleus, and to gain insight into the model this must be done with various particles at many energies. It is probably correct to say that a large AVF cyclotron installation could be kept busy for many years just measuring elastic scattering of various particles to high precision, and thus determining optical parameters. Nuclear physicists would applaud such a venture, although it is not likely to materialize because it is considered such dull work, and is difficult at the same time. Polarization and total reaction cross-section measurements also supply essential data for the optical model.

For the study of direct interactions we need very precisely defined incident energies of the projectile, preferably of the order of 10 keV, and a detection system which can identify and measure the energy of the product particle. In addition, it is becoming increasingly important to measure the direction of any γ-rays which may be emitted in the reaction. To this end it is desirable to have as low a background as possible in the room where the reaction is taking place, and a long duty cycle. Variable energy is not a prime necessity for these reactions, but the availability of various projectiles is a definite advantage, since one can study pairs of inverse reactions such as (d, p) and (p, d) or (He^3, p) and (p, He^3).

The study of direct reactions is a good example of the interdependence of nuclear models. The DWBA theory is needed to get shell-model information about nuclear structre, but DWBA in turn needs optical model parameters. The hope is that in the future the shell model itself can be used to derive the parameters of the optical model.

Collective and Statistical Models

Another successful description of the nucleus is the collective model. In place of the shell-model orbital picture, the nucleus now is endowed with rotational and vibrational degress of freedom, analogous not to the atom but to the molecule. Band structure is postulated and, indeed, observed in many heavier nuclei. Deformation from sphericity becomes an important nuclear property, and is well described by the collective model. At present the best way of studying this model is by inelastic scattering, and especially Coulomb excitation. In the latter it is the Coulomb field of the passing projectile which causes the target nucleus to become excited; in the case of even-even nuclei we get the characteristic transitions to the members of the rotational band 2^+, 4^+, 6^+ ....., and states as high as 10^+ have been observed with heavy-ion Coulomb excitation. A high nuclear charge of the projectile enhances the transition probability for Coulomb excitation, while at the same time the large electrostatic potential barrier diminishes the confusing consequences of nuclear-force interactions between the nuclei. In Coulomb excitation the interaction is

electromagnetic and can be calculated with high precision. The experimental results then yield pure nuclear structure information. In this way remarkable insight into collective aspects of the nucleus has been gained.

Experimentally, for Coulomb excitation one does not need very good energy definition. On the other hand, low background in the experiment area is imperative, as is a long duty cycle. A variety of heavy ions as projectiles is most desirable; it would be worthwhile to have a beam of iron nuclei of several hundred MeV for this purpose. With such ions, for example, one could study Coulomb excited fission of heavy nuclei, and otherwise add to our knowledge of photonuclear processes.

The shell model and the collective model are useful for the ground state and low lying states of nuclei, especially if pairing forces, distorted potentials, and other refinements are introduced. The optical model too is a very successful potential representation of the nucleus as a whole. The structure of nuclei at very high excitation, above 10 to 20 MeV, however, requires yet another picture, the statistical model.

What concerns us here is the spacing of nuclear energy levels, how this varies from one nucleus to another, what function of the excitation energy it is, and how it depends on the level spin. Stated simply, the experiments involve measuring energy distributions and angular distributions of particles emitted in a compound nucleus reaction. In addition, one can measure total cross-sections and ratios of isomeric states in residual nuclei. The AVF cyclotron is particularly useful here because of the flexibility in particle energy and species. Thus, one can produce the same compound nuclei at the same excitation in two different reactions, where the only distinguishing characteristic is the amount of angular momentum involved. For example, if we make the compound nucleus Ag^{105} at 44 MeV excitation with oxygen or nitrogen bombardment of Y^{89} or Zr^{91} respectively, the maximum angular momentum will be $\ell = 15\ \hbar$ for oxygen and $\ell = 10\ \hbar$ for nitrogen. This is calculated for a sharp cutoff nuclear model, and is only approximately correct. However, the qualitative difference is certainly correct, and illustrates the point that one can obtain a 50% change in angular momentum simply by switching particles.

New techniques have been developed in the past year which permit the direct measurement of lifetimes of nuclear reactions. In particular, the lifetime of compound nucleus reactions, of the order of 10^{-20} sec at high energies of excitation, is being successfully pursued. The ability to produce compound systems in many different ways, possessing different amounts of angular momentum, should provide fertile ground for investigations of this sort.

Experiments dealing with the statistical model require precise information about that fraction of the reaction under study which proceeds by a compound nucleus mechanism as opposed to direct processes. With heavy ions as projectiles it is frequently easy to make this distinction, since the emission of one or two particles

is not likely to result from any simple direct process.

With some exceptions, the beams required for statistical model work do not have spectacular energy resolution, but variable energy and a wide choice of particles are essential.

Clusters, Heavy Ions, etc.

So much for the more orthodox lines of nuclear research which will probably constitute the major part of the AVF cyclotron programs. It is also likely to provide the bulk of the information sought by theorists who construct nuclear models.

Nuclear problems, however, can be cast in many different ways. For example, there is now increasing interest in the so-called cluster model. In this picture nuclei consist of a stable core surrounded by clusters of deuterons, tritons, α-particles, etc. Various experiments indicate the presence of such structure. Perhaps the most fruitful line of research to pursue in this connection is the study of correlations in three-particle reactions. For example, (p, pα), (α , 2α), and other similar reactions must be investigated in detail. Thus if, say (p, pt) has a much larger cross-section than (p, p He^3) we have reasonably convincing evidence that the nucleus contains a triton cluster and no He^3 cluster. Further, if the correlation of the outgoing proton and triton indicates that we are dealing with a sort of quasi-elastic scattering, we have additional corroboration of the cluster structure. Correlation experiments are very time consuming. Here the high beam intensity, and as long a duty cycle as can be managed, are of the greatest importance. On his part the experimenter will have to provide fast circuitry and multiparameter analysis to take advantage of the full capabilities of the machine.

The nuclear surface is also receiving increasing attention currently. Almost all the techniques available shed some light on this problem: scattering, polarization, direct interactions, etc. One specialized field worth mentioning in this connection is the study of nucleon-transfer reactions between complex nuclei. Although the experiments are difficult, they have already shown that neutron reduced widths can be extracted from the results by means of a semi-classical transfer theory due to Breit.

It was a common notion among physicists that good energy resolution is not required at energies above 20 MeV. After all, so the argument ran, at these energies, levels overlap, direct interactions predominate, and since they take a short time there can be no dramatic changes in cross-sections over regions smaller than a few MeV. This is wrong for two reasons: 1) good energy definition is required to resolve levels in direct interaction experiments, and 2) it has been demonstrated that cross-sections fluctuate strongly at excitations of 30 MeV, with a characteristic width of about 100 keV (Fig. 1).

The ever-present nucleon-nucleon interaction will undoubtedly form an important portion of AVF-cyclotron research. The polarization, spin-spin correlation, and similar parameters for p,p and n,p scattering must be measured to high precision.

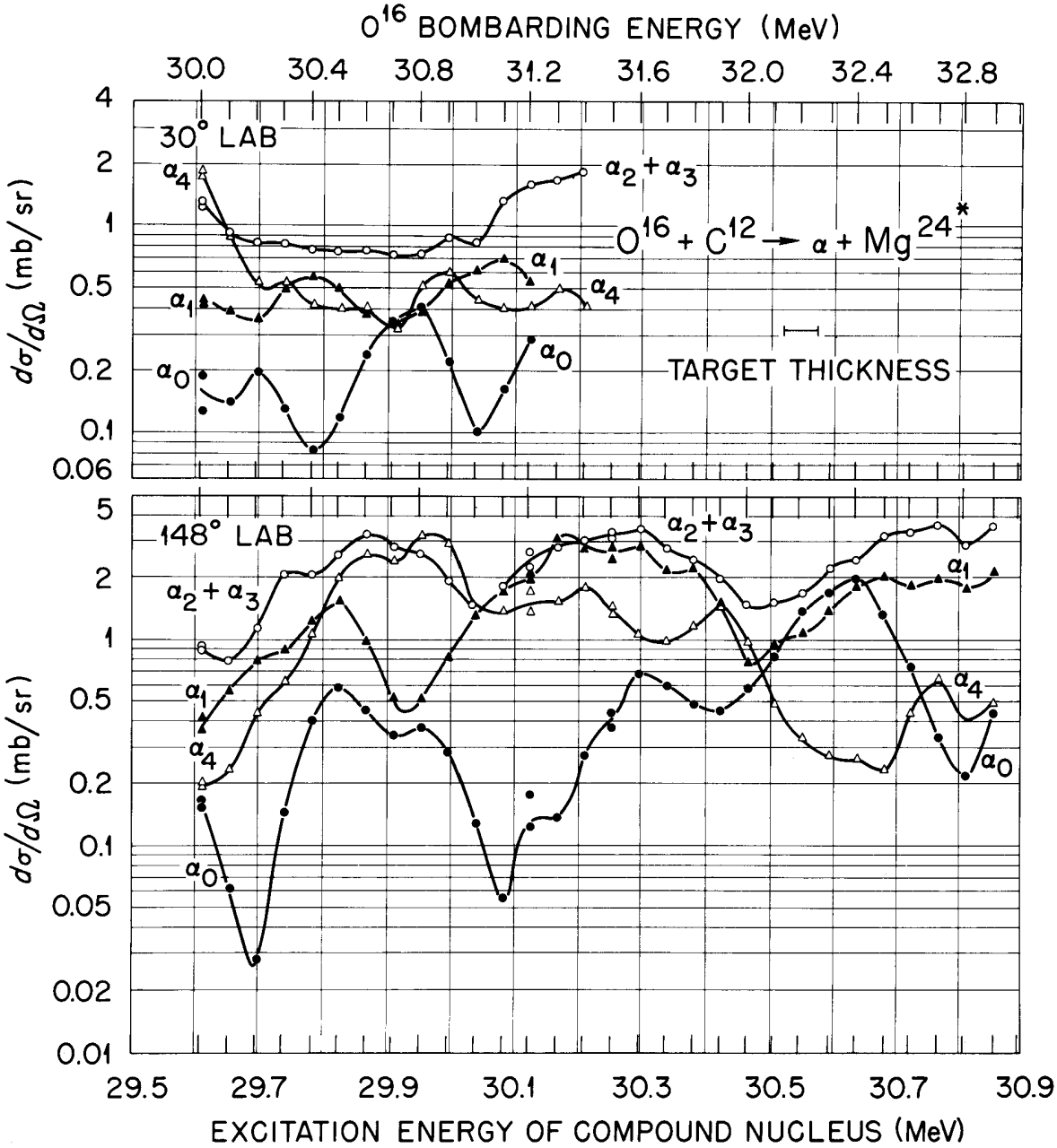

Fig. 1. Excitation functions for α-particle groups from the reaction $C^{12}(O^{16}, \alpha)Mg^{24}$. The excitation in the compound nucleus Si^{28} is about 30 MeV.

For the n-n interaction, complicated experiments depending on final-state interactions are needed; e.g., d(n, 2n)p, t(d, 2n)He^3.

It is possible to continue in this vein and outline experiments in all fields of nuclear physics. Instead we turn now to work actually in progress, though only in its earliest stages, on two AVF cyclotrons which fall into the 20-100 MeV region.

Some early results from the Berkeley 88-Inch Cyclotron were communicated by B.G. Harvey, and concern the measurement of elastic and inelastic scattering of

65 MeV α particles from C, N, and O. Particularly, in the O^{16} case 13 inelastic levels have been identified. The mechanism apparently is the promotion of single nucleons from the p shell to the higher shells, and the results seem to be in excellent agreement with the predictions of the shell model. There is apparently no evidence for the promotion of clusters of nucleons by (α, α') reactions. The beam characteristics for this experiment are as follows. Energy resolution after analysis is 140 keV full width at half maximum, the full angular convergence of beam is 0.2°, the beam is 0.5" high and .08" in the radial direction, its intensity is ~ 0.5 μA but several microamperes are obtainable.

At UCLA the internal beam produces 38 MeV neutrons, which in turn are collimated for scattering experiments about 7 meters from the cyclotron. If one may extrapolate present information, a 20 μA circulating beam will result in ~ 6×10^6 neutrons/sec-cm^2 in the experiment area. The new sector-focused cyclotrons in the 20 to 100 MeV region promise great things. Now the tools have been provided, it is up to the experimental and theoretical physicists to use them to best advantage.

DISCUSSION

TENG : It is not clear to me how one goes from these nuclear models to the final nuclear theory, based on first principles you talked about. Even assuming that we have all the nuclear-level assignments and all the model parameters of the optical, collective, and statistical models, where do we go from there?

ZUCKER : There is an attempt in this direction, a rather successful attempt in some ways, the Bruckner theory which tries to construct a nucleus from protons and neutrons. Unfortunately, at the present time the Bruckner theory is good for an infinite nucleus, and that is not very realistic since the surface of the nucleus is, in many cases, most of it. But that kind of theory is what is needed, and there are people working on it. I'm not sure that this is really the approach that will eventually yield the answer, but I think this is the approach which will be taken in the next few years, until the next development happens.

SCHMIDT : You seem to suggest that it may be wise for one particular group to concentrate on a machine which would be designed for a particular type of work.

ZUCKER : I didn't really mean a machine, I meant a group of physicists. A machine in itself is nothing, it is the people who work on it that count. I think if some group could be persuaded to study the optical model in great detail and very painfully, it would be very valuable.

JONKER : I would like to ask if you could discuss the prospects of doing time-of-flight work with an AVF Cyclotron, e.g., neutrons in the energy range 15-20 MeV.

ZUCKER : To do this kind of work one has to throw away something like 9 out of every 10 RF pulses. Then time-of-flight work becomes feasible, since the pulse width is approximately 2 ns. Flight paths of some meters are necessary.

STAFFORD : Could we pursue this a little bit further? What's the length of your neutron bunch?

ZUCKER : Well I really don't know what kind of RF length you can get with these machines. One reported yesterday was rather long, something like 25 ns. There is, however, no reason why you shouldn't be able to get 2 ns bunches, but 25 ns is too long for this kind of work. From the reports of the phase slip yesterday it would seem to me rather obvious that you could get much less than 90° phase acceptance.

STAFFORD : I think it's worth pointing out that the linear accelerator can do quite considerably better than that, just because of the inherent time structure in the machine; you can expect neutron bursts with a resolution of say 0.5 ns, or perhaps slightly more.

LIND : We have observed neutron bursts which have a time width of 3 ns. You did not mention the problem of the discrepancy between theory and experiment that has arisen in connection with the (p, α) polarization work that came out of the Minesota results at 30 MeV, I believe, and the whole question of nuclear-nucleon interactions?

ZUCKER : I think it's a little early to say anything about that because the phase-shift calculations should be good. If the discrepancy really exists, I just really don't know where to go, or what the theorists will invent to get out of the hole. They'll invent something.

STAFFORD : That discrepancy certainly exists. It's been confirmed up to 50 MeV with p-helium polarization measurements.

TICKLE : In your discussion of Coulomb excitation you mentioned that a good resolution is not necessary. I might point out that it can be helpful because there is another way you can do the experiment, and that is look at the inelastic particles. So, if you have good resolution you can look at the elastic group plus the inelastic groups and by comparison of the two get the cross-sections for the Coulomb excitation directly.

ZUCKER : Surely, but that is useful only for well separated states. However, the big push is in the higher levels, multiple excitation; there you get into something like 20 or 30 kV. Also it is important to know just how cascades proceed. As far as I know, it is better to do conversion spectrometry on gamma rays and get high resolution that way, at the cost of intensity. Not too much is being done by inelastic scattering for that reason.

SCHMIDT : One cannot have "poor" resolution and at the same time satisfy other requirements of an otherwise "poor" resolution experiment, as for example reduction of background radiation from slits, etc.

ZUCKER : You're quite right.