OPTIMIZED USE OF A CYCLOTRON FOR HIGH RESOLUTION STUDIES OF NUCLEI*

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ABSTRACT

The effectiveness of an accelerator in nuclear physics research hinges heavily on the energy resolution which can be obtained in actual experiments. Contributions to the resolution from the energy spread and incoherent phase space distribution of the beam, the kinematic effects in the nuclear reaction proper, the energy loss in the target, and the aberrations, must all be included. Optimization for one or the other of these factors is in some cases at the expense of a broadening in other contributions and a compromise point is actually the choice for minimum line width. A manually adjusted optimization system has been in use for some time in our laboratory and has given momentum resolutions of 1 in 20,000 in a variety of test situations and of 1 in 10,000 on a rather regular basis in extended runs. A second generation optimization system is being developed which will make more extensive use of the computer both for calculating best values and for on-line control of system elements.

INTRODUCTION

Particle beams are an essential tool in the study of nuclear phenomena. Practically all of the information on nuclear systems is obtained from measurements of the scattering of particles by nuclei and the emission of ensuing electromagnetic radiation. Nuclei exist in "energy states" which live for varying times and whose properties are generally widely different. Thus our ability to extract the information required for a better understanding of nuclei is intimately tied to our ability to resolve various nuclear states.

When investigating nuclear properties with charged particle beams, we recognize two distinctly different situations in high resolution studies. In the first, the nuclear states of interest belong to the compound system formed by the merging of the incident projectile and the target nucleus. Such processes give highly excited states for the given system of nucleons, and it is the total energy spread in the beam at the target which controls the resolution. Electrostatic accelerators are best suited in such instances, but excellent results can be obtained with cyclotrons by selecting a fraction of the total beam with the required energy spread.[1] At MSU, for example, we have done experiments of this type with a resolution of 1 keV in beams with energies of 5 MeV.

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In the second type of experiment with charged particles, the nuclear properties are those of the residual nucleus and range in energy from the lowest (ground) state to all other excited states with limitations imposed only by the conservation of energy requirements. For example in the reaction $^{209}Bi+^{1}H \rightarrow ^{208}Bi+^{2}H$, where the deuterons are observed in the focal plane of a magnetic spectrograph, it is the properties of the energy states of the ^{208}Bi nucleus which are being investigated. We will call experiments of this type "charged-particle spectroscopic experiments". It is in this type of experiment that the use of cyclotrons which we now describe has been optimized and that a variety of highly significant results are now being obtained in nuclear experiments.

The factors which affect the resolution in charged-particle spectroscopic experiments have been previously discussed.[2] The phase space density of the ion source of the accelerator sets the ultimate limit.[3] Positive-ion cyclotrons have a large advantage in phase space density over accelerators where the initial acceleration uses negative ions. In their paper, Blosser et al.,[2] treat the cyclotron, beam analyzing system, and magnetic spectrograph as a single system and review the factors which determine the overall performance. In this paper, we restrict our comments to a discussion of the results of calculations which permit the experimenter to set the various parameters of the experiment close to optimum values so that final settings can be quickly reached by a manual optimization procedure. Since most of the beam which is accelerated is used on target and since the results already obtained in our laboratory represent improvements by factors from 2 to 5 over those obtained with other systems, the cyclotron-spectrograph combination must certainly at present be viewed as the choice instrument for this type of nuclear research.

The parameters which can be selected and/or adjusted in a particular cyclotron-spectrograph experiment are as follows:

1) the incident beam energy
2) the total energy spread on target
3) the target thickness
4) the spectrograph solid angle
5) the coherent energy dispersion on target
6) the position of the spectrograph focal plane
7) the shape of the incoherent phase space area

The incident energy (1) is chosen by the experimenter taking into account many factors; among the most important are the Q-value of the reaction, the range of excitation energies to be investigated, and the ease of analysis of the resulting angular distributions.

The total energy spread on target (2) can be limited by means of slits in an analyzing system but depends very much on the particular accelerator. At MSU, the analyzing system is typically set to limit the energy spread to 0.08% of the beam energy and since this is comparable to the energy spread in the total extracted beam,

most of the extracted beam is used on target. This efficient use of the accelerated beam is in large part due to the internal phase selection slits and the accurate stabilization of the magnet and rf system of the cyclotron.[4]

For target thickness (3), a value as large as will not limit the resolution is chosen for most high resolution experiments. Use of an on-line resolution meter in the focal plane of the magnetic spectrograph[2] gives quick information about the quality of the target. This contribution to the resolution is frequently misinterpreted especially where target inhomogeneity is significant. We have observed significant variations in resolution from target to target, sometimes with targets of greater average thickness giving better resolution.

The spectrograph solid angle (4) is also in general chosen as large as possible, except in experiments where the yield of reaction particles varies so rapidly with angle that a large angular acceptance results in an unacceptable degree of averaging of the angular distribution. (The beam spot size also influences the range of angles observed and, in some instances must also be made small.) Typical values at MSU have been 1° and 2° for the radial and axial spectrograph acceptance apertures.

Thus we have for a given reaction chosen the first four parameters; the remaining operation is to fix the coherent energy dispersion on target (5) the position of the spectrograph focal plane (6) and the shape of the incoherent phase distribution (7) to give best resolution.

To qualitatively understand the effect of the incoherent radial phase space distribution (radial emittance) we refer first to Fig. 1, which shows the base line width in keV derived from a radial emittance of 0.8 mm-mrad as a function of the ratio of the axes of the ellipse. The width shown is the sum of the incoherent spot size times the magnification plus the incoherent divergence times the kinematic ($dE/d\theta$). It is clear that the ratio of x_i'/x_i which gives

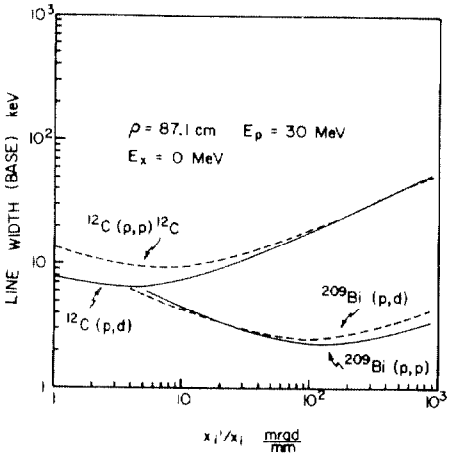

Fig. 1 Contribution of incoherent phase space area of the beam on the resolution for various reactions. A value for that area of 0.8 mm-mrad in the shape of an ellipse is assumed.

best results varies significantly with reaction kinematics, e.g. heavy vs. light targets and polar vs. equatorial angles. In constructing a beam system, it is thus advantageous to be able to vary the shape of this radial phase space distribution independently of the energy dispersion of the beam at the target position. Changing quadrupoles which follow the analyzing magnets does not accomplish this, since quadrupoles alone change dispersion and magnification in a locked way.[5] An independent change can be effected however if quadrupoles ahead of the analyzing system are used to shift the location of the object point of the analysis system; with this technique target dispersion and spot size can be independently set to optimize resolution for a particular reaction on a particular nucleus. Using this technique the magnification is set to give the x_i'/x_i which minimizes the line width for the particular reaction.

It remains to pick the dispersion of the beam on target and the position of the spectrograph focal plane. As is well known the contribution to the resolution coming from the kinematic energy shift $dE/d\theta$ can be compensated by an appropriate shift of the spectrograph focal plane away from the design position. The basic phenomena is simply that a particle scattered at a smaller (larger) angle from the target than a reference particle has a higher (lower) energy and therefore bends less (more) in the spectrograph magnet than the reference particle and therefore crosses the reference particle trajectory for our geometry sooner (sooner) than would be the case if the energy were the same as that of the central ray. If both the magnet and the energy change $dE/d\theta$ are linear, the shift in the crossing point is independent of the initial angle and hence a point object goes to a point image irrespective of the value of $dE/d\theta$. The image is displaced however from the image location for $dE/d\theta=0$. The solid curves in Fig. 2 show calculated values of this displacement for (p,p) and (p,d) reactions on Carbon and Bismuth. (A negative shift means that the focal point moves toward the magnet.)

The coherent energy distribution of the beam on target gives rise to a similar optical phenomena. A ray with higher (lower) energy comes from the left (right) of the target relative to the central ray and bends less (more) in the magnet therefore crossing the central ray at a displaced point relative to the design focal plane. Again, if the dispersion on target dE/dx and the magnet are linear, all rays corresponding to a given energy loss in the target will cross at a point and in this way the dashed curves in Fig. 2 are obtained. The phenomena is different from the kinematic effect however in that varying the value of the dispersion shifts the complete curve and therefore the dashed curve can be made to intersect the solid kinematic curve at some desired, "most interesting" excitation. This excitation will then be the point of minimum line width in the spectrum. In Fig. 2 for example, the dispersion values have been picked in each case to make the dashed curves and the solid curves intersect at zero excitation. This choice is however completely arbitrary and the crossing could have been placed at any other excitation by an appropriate choice of

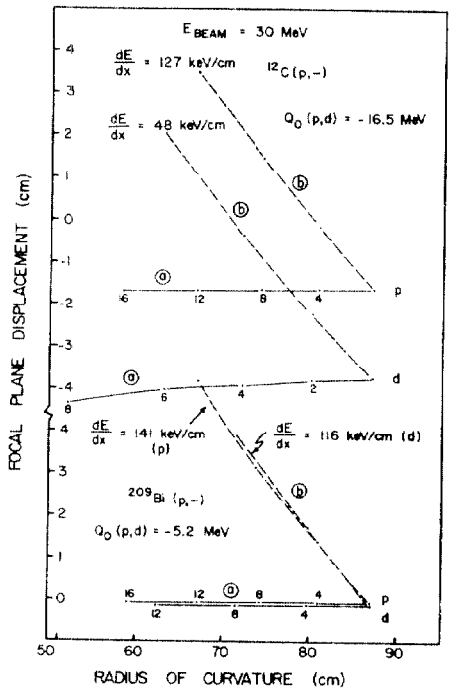

Fig. 2 Calculated focal plane displacement for optimum resolution (a), dispersion compensation (b), and kinematic compensation (c). The value of energy dispersion on target shown are those which give the smallest line width for the ground state reaction.

dispersion. The system is said to be "dispersion matched" at this crossing point i.e. at the ground state for the case shown. With such calculations the value of the dispersion and the position of the focal plane at the best resolution point are set.

Away from the best resolution point the optimum location for the focal plane is determined by considering how the line width broadens as one moves away from the kinematic and dispersion crossing planes i.e. away from the solid and dashed curves of Fig. 2. This widening is shown in Fig. 3. In the approximation that the width contributions from dispersion and kinematics add linearly, the best focal plane position will always be either the kinematic plane or the dispersion plane depending upon whether the convergence angle is larger at the kinematic crossover or at the energy crossover. For the case of the Enge magnet the kinematic broadening normally dominates as is shown in Fig. 3 which is a typical situation. If a more accurate addition law is considered, the best focal plane position will be somewhere between the kinematic crossover and the dispersion crossover but for the Enge magnet normally very close to the kinematic curve reflecting the basic characteristics presented in Fig. 3. Figure 3 also shows contributions from the incoherent phase space distribution as well as the sum of all of these three contributions (the dashed curve).

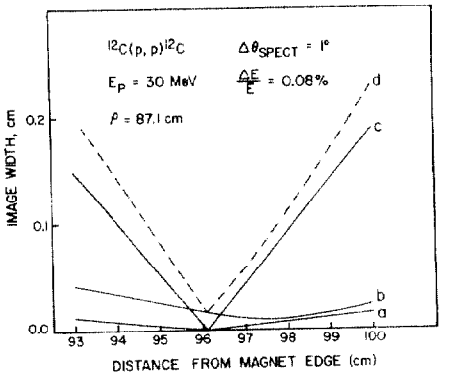

Fig. 3 Contributions to the calculated line width from the energy dispersion (a), the radial phase space area (b), the kinematic (divergent ray) effect (c). The sum of these is the dashed curve (d). The distance from the magnet is measured along the central ray.

To display the effect of a larger incoherent radial phase space we have calculated optimum settings after increasing by a factor of three the energy spread on target, the incoherent radial divergence and the incoherent radial spot size. The resulting settings differed little from those displayed in Fig. 2. The overall results for the line width were of course affected and were a factor of three worse than in the previous set of parameters. The parameters thus obtained provide an initial set of values and the on-line tuning procedure of Blosser et al.[2] yields almost invariably a significant improvement in the overall resolution. The final values of the parameters after this tuning are however close to the calculated ones reflecting the delicate character of such precise resolution. Part of the difficulty in simply setting up the best condition may be due to the difficulty of setting the quadrupole magnetic fields to the high degree of precision required using only shunt currents as guides. The representation of the spectrograph as a linear element also has its limitations. The large number of elements involved in the system makes it unlikely that the final on-line tuning procedure can be eliminated.

The most convincing evidence that such a procedure works can be seen in some nuclear data measured at MSU. One example is the deuteron spectrum from the reaction $^{209}Bi(p,d)^{208}Bi$ shown in Fig. 4.[4] The overall resolution is 5 keV (FWHM) with an incident beam energy of 35 MeV. The residual nucleus ^{208}Bi has an odd number of protons (83) and of neutrons (125), and therefore a rather high level density of low-lying states. It is easy to observe in the spectrum the multiplet structure resulting from the coupling of the odd $h_{9/2}$ proton with the various neutron "holes" characterized by quantum numbers $p_{1/2}$, $f_{5/2}$, etc. The resolution achieved in that experiment has allowed a significant advance of our knowledge of ^{208}Bi. At the same time, the promise that an additional improvement of a factor of three in resolution holds is inescapable, and would

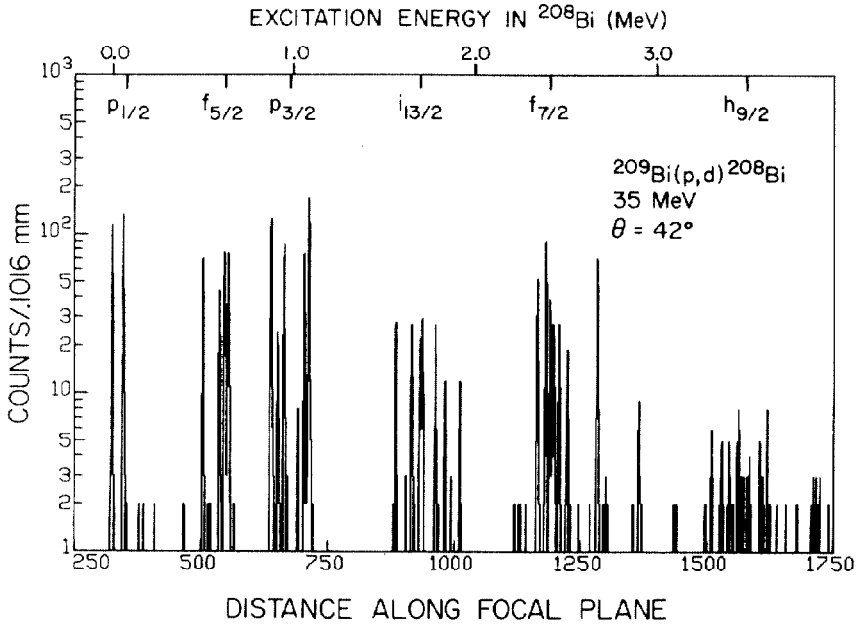

Fig. 4 Energy spectrum of deuterons from the $^{209}Bi(p,d)^{208}Bi$ with 35 MeV protons. The energy resolution is 5 keV. The single particle states of ^{207}Pb are labeled on the upper part of the drawing as $p_{1/2}$, $f_{5/2}$ etc. The multiplet structure in the spectrum is easily observed.

be achieved with our present beams by the use of a spectrograph of three times greater resolving power such as in the (Q,3D) design.

REFERENCES

1. E. Kashy, G.F. Trentelman, and R.K. Jolly, Proc. of Fifth International Cyclotron Conference, Sept. 1969, p. 380 Butterworths, London (1971).

2. H.G. Blosser, G.M. Crawley, R. deForest, E. Kashy, and B.H. Wildenthal, Nucl. Instr. and Methods, 91, 61(1971).

3. B.L. Cohen, Rev. Sci. Instr. 33, 85(1962).

4. H.G. Blosser, Proc. of the Fifth International Cyclotron Conference, Sept. 1969, p. 257 Butterworths, London (1971).

5. E.D. Courant, Particle Accelerators 2, 117(1971).

6. W.A. Lanford, G.M. Crawley, H.G. Blosser, and E. Kashy, BAPS 17, 462(1972); to be published.

DISCUSSION

FLOOD: I was curious if you had thought about what the future course of this high-resolution work is and how long before you can be mapping the topography of the nucleus, or do you know what energy spread is necessary?

KASHY: We actually have given some thought to this. If we had a spectrograph whose resolving power was a factor of three or four higher than our present one, we know that our present beam quality will allow us to go down to the 1 keV level. Now 1 keV in charged particle work is considerably different from 1 keV in γ-ray work. There is no Compton effect and no Compton background. So I believe if we could get down to the 1 kV level, we could map the nucleus for a large part of the periodic table very close to the neutron threshold.

FLOOD: Are there data systems that could display this as a map rather than as a spectrum? I am talking about a picture that I can look at and say, that is a nucleus.

KASHY: Instantly or what?

FLOOD: No, at all. I don't think it has been done at all, or maybe it has.

KASHY: The picture which I showed is a map of the nucleus in some type of language--in this case energy language.

FLOOD: I mean a topographical map.

KASHY: Oh, a topographical map. Well, you know, there are nuclear models. There are so many properties of nuclei that I do not believe there is going to be a single picture which will let you say, aha, this is a nucleus and there are its properties.

FLOOD: I mean is there such a thing as a proton microscope? Is it a reality in the future if this kind of resolution continues, or not?

KASHY: Does anybody know? I don't know, I cannot answer.

PARKINSON: Not at these energies.