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INFLUENCE OF CYCLOTRON BEAM PROPERTIES ON EXPERIMENTS*

Invited Paper

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Abstract

The importance and relationship of cyclotron beam characteristics to various experiments are discussed, and examples of some of the influences are given. The beam properties considered include phase-space density, energy, energy-spread, energy-variability, energy stability, and duty factor.

Introduction

Prior to 1960, most researchers doing nuclear physics experiments with the external beams from conventional cyclotrons accepted the 0.7 to 1% energy spread, the fixed energy, and the relatively unknown emittances and (microscopic) duty factors. These properties were taken to be characteristic of cyclotron beams, and I, for one, recall that in the mid 1950's we were happy just to have an externally transported beam at the Crocker Laboratory 60-inch machine.

The past five years have seen a truly amazing development of the cyclotron in terms of capability and versatility as a nuclear research instrument. It can now extend to much higher energies the very precise experiments with proton and deuteron beams that have been characteristic of the tandem van de Graaff accelerator, whereas the He^3 and He^4 beams are, in addition, considerably more intense than those available from the rival machine. These circumstances have required us to examine in some detail the relationship between the beam properties and the design of the more complicated and more precise experiments which can be done.

Beam Properties

The beam properties to be discussed are energy, energy stability, energy spread, energy variability, duty factor, and phase space density—which of course encompasses both intensity and quality. I have chosen examples to illustrate the importance of these characteristics mainly from the research results from the Berkeley 88-inch cyclotron, since these have been most available to me; but similar results have been forthcoming from other sector-focused cyclotrons as well as from upgraded conventional machines, such as, for example, that at the University of Washington.

Energy

Several advantages of the higher energies are straightforward. Large amounts of highly neutron-deficient radioactive isotopes have been produced by (α,xn), where x is 5, 6 or higher. Investigations of the nucleon-nucleon, p-d, p-He^3, p-α, He^3-α, and α-α interactions have been or will be extended to previously unexplored regions. Also, new and very interesting reactions can be studied; examples are the $C^{12}(He^3,He^6)C^9$ reaction,[1] designed to measure the mass of C^9, and the $Mg^{26}(\alpha,He^8)Mg^{22}$ reaction[2] which was used to determine the mass of He^8. Figure 1 shows a He^6 spectrum from the first reaction. The reaction threshold is about 40 MeV, so 65-MeV He^3 ions were used to provide sufficient energy to the outgoing He^6 particles that particle identification with a $(dE)/(dx)$ - E counter telescope was simplified. Figure 2 shows a He^8 spectrum from the second reaction, initiated with 80 MeV alpha particles since the threshold energy is about 45 MeV.

Energy Stability and Energy Spread

Instability and spread in beam energy limit the final energy resolution available, for example, in an experiment which uses semiconductor detectors and does not fix precisely the incident beam energy by stringent magnetic analysis. Also, such a magnetic system would suffer beam intensity fluctuations caused by input energy drifts. Parkinson and Tickle[3] have recently reported measured proton linewidths (FWHM) of 7 keV at 21 MeV from the $Al^{27}(d,p)Al^{28}$ reaction. This beautiful example of an overall resolution of 0.033% cannot yet be matched by semiconductor detectors, but the rapid developemnt of this truly revolutionary particle detector has provided very remarkable results at Berkeley. For example, experimental resolutions slightly better than 0.1% have been achieved with alpha particles up to 90 MeV[4] and with 29 MeV protons.[5] In the latter case after correction for the 0.07% beam spread, a 0.04% contribution from a thin vacuum window, and a 0.03% electronic noise spread, the detector contribution amounted to 0.05%. Figure 3 shows, as an example of the utility of such a detector, a spectrum of protons scattered elastically and inelastically from Ni^{58} (Ref. 6). The triplet of levels near 4.5 MeV had not been resolved in previous work.

Energy Variability

The controlled energy variability (once one has the higher energies) is very likely the most important development of the sector-focused cyclotron. In a very real sense, each energy setting, in steps of a few MeV, corresponds to having a separate conventional cyclotron from the point of view of nuclear physics research. Many nuclear scattering and reaction processes are quite strongly energy dependent, and only by investigating and seeing this energy dependence can theory be checked and corrected. Investigations of resonance phenomena and threshold effects, previously almost exclusively in the domain of the van de Graaff accelerator, can now be extended to the higher energies. Figure 4 shows excitation functions at two angles in elastic alpha-alpha scattering.[7] During some 70 hours of data collection the cyclotron energy

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was changed about 120 times. The sharp resonance structure near 34 MeV corresponds to two states of Be^8 at excitations of 16.6 and 16.9 MeV. Here, data were taken at energy intervals as small as 40 keV. These data demonstrate, also, the importance of the small beam energy spread, about 0.1%. For comparison, the data from a previous experiment[8] is shown. The beam spread of over 2% (about 800 keV), which was due in part to the use of absorber foils for reducing the energy, washed out the sharp resonance behavior. It is worth remarking that in an experiment such as this, where there is little or no resolution requirement imposed by the need to separate lines corresponding to various states of a residual nucleus, the experimental resolution is controlled by the beam energy spread and target thickness alone. That is, the detector records counts as a function of the energy of the intermediate or compound system, and that number is independent of the detector resolution. Figure 5 shows an example of the importance of both the higher energy and the variable energy cpabaility. The data points show the proton polarization induced in proton-alpha scattering between 20 and 63 MeV. The solid curves are values calculated from phase-shift analyses[9] of all the available data. Investigations of this interaction have been of particular interest because the proton-alpha combination is the simplest nuclear system that involves spin—a spin 1/2 system, so that it should be most amenable to analysis and interpretation. We now believe that we have a unique description, in terms of phase shifts, of that interaction from zero to 63 MeV. It took about 12 years to go from zero to 17 MeV, while the region above 17 MeV has been spanned in about two years, with the exception of earlier data from Minnesota[10] at 40 MeV. Differential cross section data between 20 and 28 MeV were taken at the Colorado cyclotron,[11] and the Berkeley polarization results shown in Fig. 5 were obtained in about 8 days total running time spaced out over a period of a few months. Such is the tremendous utility of the variable energy cyclotron.

Duty Factor

The effect of duty factor on experiments has been discussed at the previous three conferences on sector-focused cyclotrons, and in reading over the Proceedings, I detected something less than complete agreement on that subject. For simplicity, let us agree to discuss only the microscopic duty factor, which is imposed by the fact that beam pulses arrive with the rf time structure. For example, at 10 MHz, corresponding to an rf period of 100 nsec, the 88-inch cyclotron external-beam pulse length may be 10 to 15 nsec, giving a 10-15% duty factor. The question of whether or not each rf cycle provides a beam pulse is answered by Fig. 6. It shows the output pulses from a semiconductor detector[12] placed in the external beam, taken at the resonant frequency f_0 and at frequencies displaced by Δf in kHz. The 6 μsec sweep time covers 60 rf periods, and close examination of the picture reveals that there is beam in each rf cycle. This beam was modulated at about 0.5 MHz on resonance. By moving slightly off resonance it was seen that the modulation was mainly in the leading part of the beam with the lagging part, seen with $\Delta f = -3.0$ kHz, being stable.

Consider then at $f_0 = 10$ MHz an experiment to detect two outgoing particles, or a particle and a gamma ray, in coincidence. Let us start with a coincidence resolving time τ of 15 nsec and a beam pulse length T of slightly longer duration. Assume that pulse pileup effects in the detectors limits the singles counting rates to something like 10^4/sec, which averages one particle detected per 10^3 beam pulses. If the real to accidental coincidence ratio $r = R/A$ is, say, something like 100, then the duty factor question is not of much concern. If, however, the cross section $d^2\sigma/d\Omega_1 d\Omega_2$ and the detector solid angles $\Delta\Omega_1$ and $\Delta\Omega_2$ are small, as they usually are, one might have a ratio r near unity. Since the accidental rate A is proportional to $(N_1 N_2 \tau)/D$, where N_1 and N_2 are the average singles rates and D is the duty factor, it can be reduced by increasing the duty factor while maintaining the same average beam intensity. Thus, a coincidence experiment with τ less than T that is limited by the real to accidental ratio r, and not by other factors such as pileup and beam intensity, can be improved in direct proportion to the improvement in duty factor. Unfortunately, energy-analysis of the beam seems to reduce the duty factor, but it would be interesting to inquire if that correlation is absolute. On the other hand, coincidence experiments are not yet demanding the highest energy resolutions. Hopefully, the successful development of axial injection of ions at Birmingham and its very recent test application at the Berkeley 88-inch machine promises potential improvement in duty factors. I would like to suggest the possible use of a two-sided inflector, looking in elevation view like a pitched roof with a 90° apex angle, located at the center of the cyclotron. The axially injected ion beam might then be swept back and forth to either side of the inflector at the dee frequency. The resultant alternate injection first into the dee and then the dummy (or second) dee could, in principle, provide an immediate factor of two increase in the duty factor.

Phase Space Density

Finally, the effect of beam quality on an experiment can be illustrated by a simple example. As indicated schematically in Fig. 7, both the beam width and convergence or divergence introduce a spread of scattering angles between θ_1 and θ_2. The resultant kinematical energy spread depends on the masses of the initial and final state particles, the initial energy, the reaction Q value, and the angle θ. In Fig. 8 the shaded area represents the horizontal effective source emittance (phase space area) of an external beam of alpha particles from the Berkeley 88-inch cyclotron, a source 2 mm wide with a full divergence angle near 30 mr. (These phase space areas are drawn as rectangles only for simplicity.) The various rectangular areas A to D are calculated to correspond to kinematical energy spreads of 0.1% introduced separately by the indicated beam width and divergence, for elastic scattering of particles of mass M_1 incident on nuclei of mass M_2. Obviously, much of the phase space area is useless for high resolution experiments on light nuclei with incident alpha particles,

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

for example. Beam energy-analysis does, of course, reduce the phase space area, and even though we do not have a good measurement of that for the analyzed beam, the following numbers are useful. For the 65-MeV alpha particle beam, some 50 μA can be provided with horizontal and vertical emittances of 50 and 70 mm mr respectively. This corresponds to 14 μA/mm^2 mster. After being energy-analyzed to 0.1% and collimated to a horizontal emittance of about 5 mm mr (very nearly the area B in Fig. 8) and a vertical value of 10 mm mr, some 3.5 μA was available. This corresponds then to 70 μA/mm^2 mster, so the central phase space density was a factor of five larger than the average density, and that is most encouraging for those experiments that require the highest quality beams.

In summary, I think that the sector-focused cyclotron has exceeded most researchers expectations in terms of versatility and overall performance as touched upon here. If you should ever attain duty factors approaching 100%, it might be slightly unfortunate since there would then be virtually nothing left to criticize.

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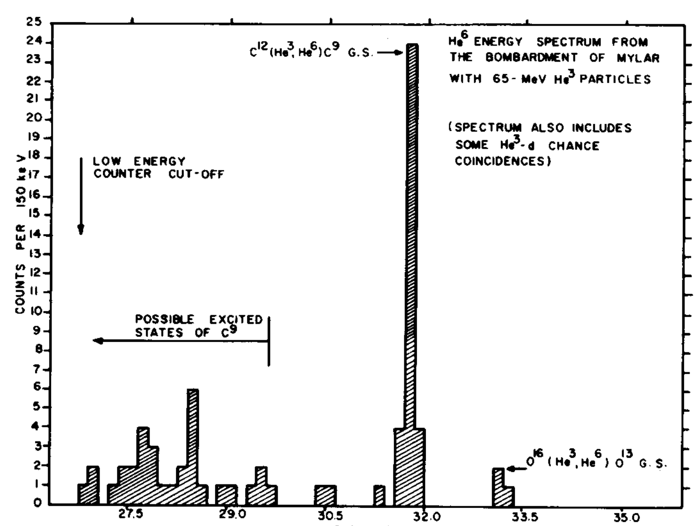

Fig. 1. An energy spectrum from the reaction $C^{12}(He^3, He^6)C^9$ taken near $\theta_{lab} = 12°$.

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

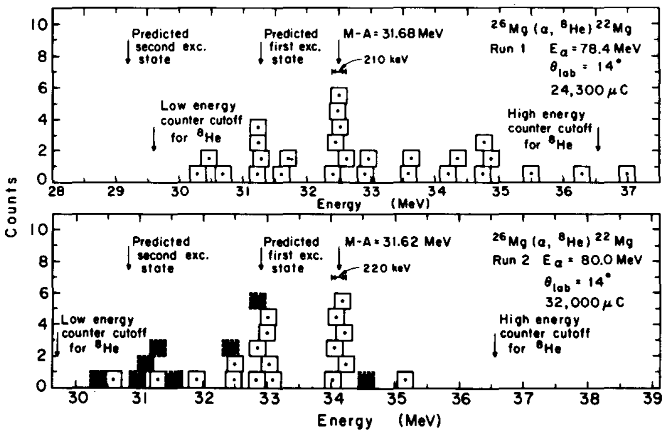

Fig. 2. Energy spectra from the reactions $Mg^{26}(\alpha,He^{8})Mg^{22}$ at $\theta_{lab} = 14^{o}$. The block width of each count corresponds to the expected full width of a He^{8} peak, and the central dot represents the exact energy of each event.

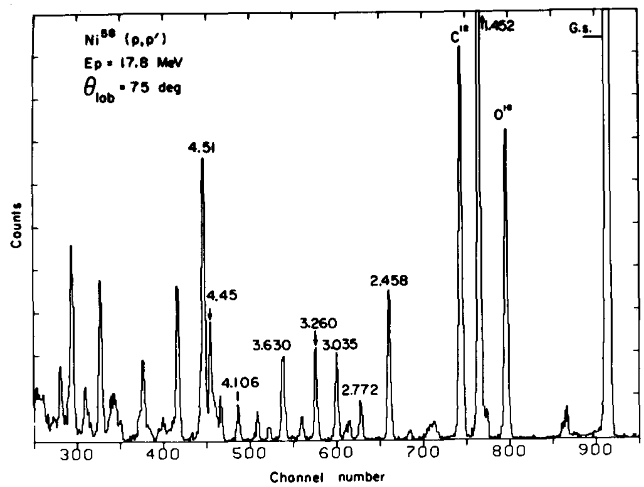

Fig. 3. Energy spectrum of protons scattered from Ni^{58} at $\theta_{lab} = 75^{o}$ with the incident proton energy $E_p = 17.8$ MeV.

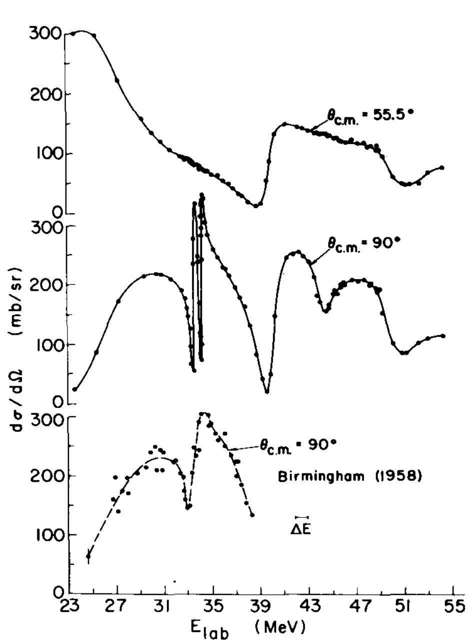

Fig. 4. Excitation curves for $\alpha - \alpha$ elastic scattering at $\theta_{cm} = 55.5^{o}$ and 90^{o}. Data from Ref. 8 is shown below.

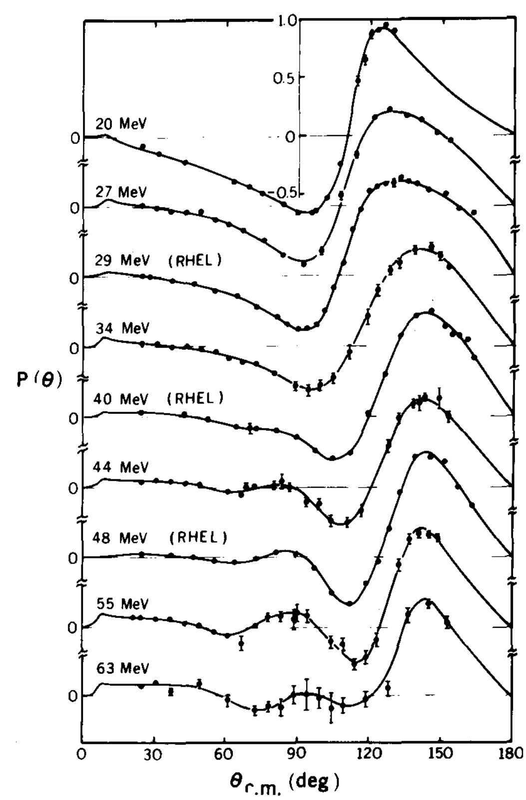

Fig. 5. Experimental and calculated results of $p\text{-}He^{4}$ polarizations between 20 and 63 MeV. The Rutherford High Energy Laboratory (RHEL) data is from Ref. 13.

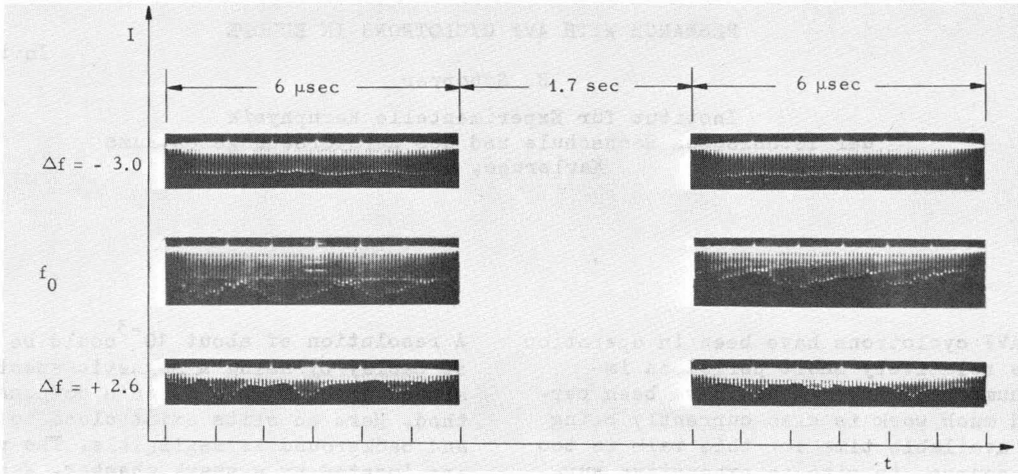

Fig. 6. Detector response to external beam pulses pulses over some 60 rf cycles. The resonant frequency was f_0 = 9986.6 kHz. Changes in the beam modulation envelope under small frequency changes Δf are evident.

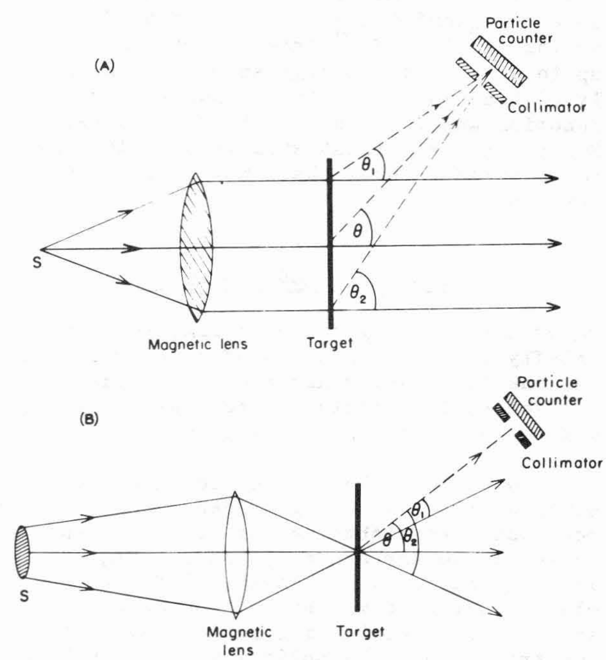

Fig. 7. Schematic diagram of typical experimental arrangement. (a) For system providing parallel beam from point source, the angle observed can vary between θ_1 and θ_2 due to the extended beam area on the target. (b) Similarly, for a small area beam on the target from an extended source the angle observed can vary between θ_1 and θ_2 due to convergence of beam at the target position.

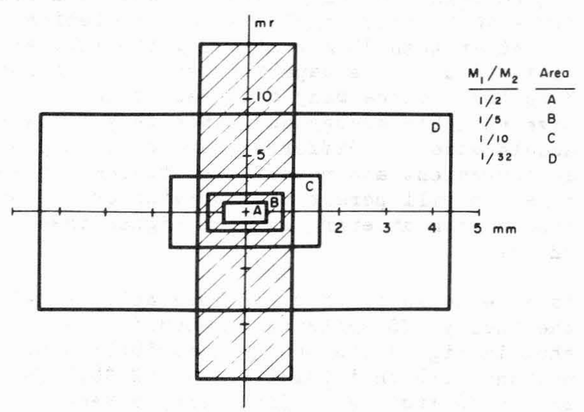

Fig. 8. The shaded area represents the external beam phase space area (or source emittance) for an alpha-particle beam from the Berkely 88-inch cyclotron. The areas A to D represent the useful areas for certain experiments as explained in the text.

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