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CYCLOTRON LABORATORY

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SAM M. AUSTIN, N. ANANTARAMAN, and J.S. WINFIELD

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Sam M. Austin, N. Anantaraman, and J.S. Winfield

National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

ABSTRACT: Charge exchange and inelastic scattering of heavy ions appear to offer significant advantages over nucleon projectiles for the study of spin-isospin strength in nuclei. This paper discusses studies performed to date and assesses the potential for further advances, including applications to astrophysics, with the new generation of heavy ion spectrographs. Coincident deteotion of gamma rays at the target location will permit experiments with seleotivity not available with lighter projeotiles. A brief description of the NSCL S800 spectrograph project is also presented.

INTRODUCTION

The study of colleotlve nuolear spin-isospin vibrations began with the discovery of the Gamow Teller Resonance (GTGR) in (p,n) spectra taken at 45 MeV.[1] A flurry of activity followed, fueled by the discovery that at bombarding energies above about 100 MeV, (p,n) spectra were dominated by the GT excitation and that the observed charge exchange cross section was closely proportional to the β deoay strength.[2] This made it possible to show that the low lying GT spin strength was quenohed to about 60% of its sum-rule value. Later, an analogous excitation, the giant inelastic spin resonance, was found in proton inelastic scattering.

Yet much remains to be done. Little is known about the behavior of other charge exchange resonances: for example, it is not clear whether the L=1 spin dipole resonance is quenched and there is no unambiguous evidence for the isovector spin monopole resonance. Nor is experimental information available on the GT matrix elements for electron capture transitions in the sd shell and in the Fe region needed in order to understand the evolution of type II supernovae and nucleosynthesis in supernova explosions.

One may ask: why heavy ions when nucleons have done so well? It is the purpose of this talk to address that question, to discuss what special advantages heavy ions may offer and what problems may arise in their use. Principal among advantages, is the potential that projectiles and ejectiles can be chosen whose quantum numbers uniquely select particular values of the spin and isospin. For example the (^{6}Li,^{6}He) reaction involves the transition $(1^+,T=0) \rightarrow (0^+,T=1)$ which guarantees a transfer of one unit of spin and isospin ($\Delta S=\Delta T=1$) provided that the reaction proceeds by a simple one-step process. The (^{12}C,^{12}B) and (^{12}C,^{12}N) reactions are similar. These heavy ion reactions therefore offer cleaner spectra, in principle, and since they involve charged particles in both the initial and final states, better resolution is often possible. Finally, heavy projectiles are strongly absorbed and should be more sensitive than other probes to transitions such as the spin-isovector-monopole for which the transition density has a node within the nucleus, as the destructive interference is avoided.

Before heavy ion reactions can be used for spin-spectroscopy several questions must be answered in the affirmative. These include:

(1) Do one step processes dominate the cross sections so a simple connection with GT strength can be obtained? And is a model, (e.g. DWBA) available to describe the reaction?

(2) Can one calibrate the reaction phenomenologically so that the detailed reaction model dependence is reduced?

(3) Is the signal observable above background?

(4) Are experimental facilities with the required characteristics available?

We proceed by reviewing the present state of experimental studies and their theoretical understanding. Most of the work described here was done by NSCL researchers. There has also been important recent work at Karlsruhe, GANIL, HMI, SARA, and Osaka.

We conclude that the situation is promising and that heavy ions may yield information complementary to that from nucleon induced reactions. However, it appears that experiments at higher energies than have been possible heretofore may be necessary to achieve this promise. In addition, it will be useful to take advantage of the unique quantum numbers of excited states in the ejectile nuclei. These states can be labelled by their decay gamma rays. When translated into equipment, accelerators capable of energies in excess of 100 MeV/nucleon and spectrographs with the bending power and resolution (certainly 10^{-4} or better) necessary to analyze the reaction products are required. In addition, coincident detection of gamma rays from the projectile or from the decay of the target nucleus will require sophisticated detection arrays around the target.

The (^{6}Li,^{6}He) Reaction

This reaction has been studied by a number of investigators (Winfield, et al., and references therein; Wirth, et al.).[3] Tests of the reaction mechanism lead to the conclusion that it is probably one step in nature at energies of 35 MeV/nucleon or above. An example of the selectivity of the reaction is the cross section for the excitation of the isobaric analog state in ^{14}N which would proceed by $\Delta S=0$ and is hence forbidden for (^{6}Li,^{6}He); this cross section is suppressed by a factor of 15 from that observed in (p,n) at the same energy per nucleon.

It was found that the cross section at the second diffraction maximum is closely proportional to the B(GT) strength observed in a number of nuclei, independent of A. However, although DWBA calculated cross sections are in good agreement with the strength and angular distribution at larger angles, they are significantly above the data near 0°. This discrepancy is not understood and casts some doubt on the use of (^{6}Li,^{6}He) for spectroscopy. This is particularly unfortunate, as the analog of this reaction, the (^{6}Li,^{6}Li(3.56 MeV)) reaction, would be of particular utility for the study of spin-isospin excitations in the inelastic channel.

The (^{12}C,^{12}B) and (^{12}C,^{12}N) Reactions

These mirror reactions have great potential for the study of GT strength in the β^+ direction. Since ^{12}N has only one stable state, the 1^+ T=1 ground state, the reaction spectrum is not contaminated by projectile excitation effects. Although ^{12}B has several bound states, it can still be used to study cross sections to isolated states when projectile excitation peaks can be resolved. The strategy we adopt is to use the (^{12}C,^{12}B) reaction, leading to states of known B(GT), to provide a calibration curve for these reactions. The (^{12}C,^{12}N) reaction can then provide a measure of GT strength in the β^+ direction, where the (n,p) reaction has generally poor resolution.

In order to establish the utility of these reactions as a spin probe we have performed a number of tests, some experimental and some in the nature of computer experiments. It was possible to assess the importance of two-step processes by measuring the ^{12}C(^{12}C,^{12}N)^{12}B reaction at 35 MeV/nucleon, where these processes dominate, and using this result to normalize an estimate of the two-step cross section. Comparison with calculations of the one step cross section showed that the reaction mechanism was one-step in nature at energies above about 50 MeV/nucleon.[4] Detailed calculations[5] verified this conclusion for the L=0 GT transitions.

DWBA calculations[6] showed (1) that most of the complicated amplitudes were small and did not disturb conclusions based on simple calculations; (2) that different effective interactions yielded similar cross sections; normalization differences cancel in the calibration procedure developed later; and (3) that cross sections of L=0 transitions are closely proportional to B(GT) values calculated with the same wavefunctions. This latter point is a fundamental requirement if these reactions are to serve for spin spectroscopy. The example of ^{26}Mg(^{12}C,^{12}B)^{26}Al at 70 MeV/nucleon is shown in Fig. 1; the proportionality requirement is fairly well satisfied, even for weak GT transitions such as these to states 4 and 5.

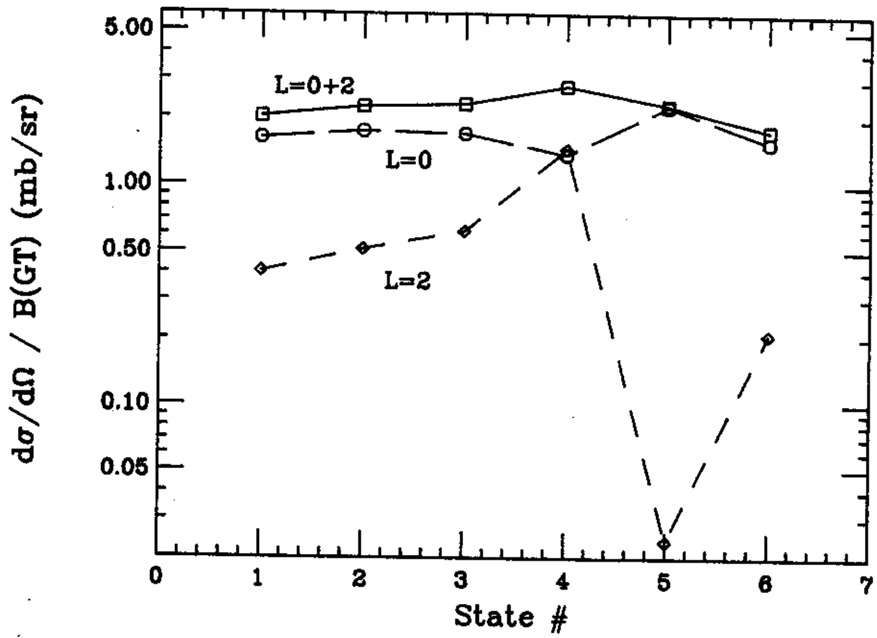

Fig. 1. Ratios of DWBA zero degree cross sections and B(GT) values calculated from full sd-shell wavefunctions [7] using the Franey-Love interaction for the six lowest lying 1^+ states in ^{26}Al.

The experiments described here were performed at GANIL by an MSU/GANIL collaboration. Reaction products from a 70 MeV/nucleon ^{12}C beam were analyzed by the SPEG spectrograph, yielding a resolution of 270 keV for (^{12}C,^{12}N) and 550 keV for (^{12}C,^{12}B). Data for the (^{12}C,^{12}B) reaction were taken on targets of ^{12}C, ^{26}Mg, ^{54}Fe, ^{58}Ni and ^{90}Zr; these reactions all include transitions for which B(GT) is known from β decay or from intermediate energy (p,n) reactions. The (^{12}C,^{12}N) reaction was then studied to obtain a measure of the β^+ (or electron capture) strength for ^{54,56,58}Fe -- these strengths are important to an understanding of the electron capture processes in supernovae.

The data exhibit several characteristic features. All angular distributions show important L=2 components, even at 0°. This L=2 strength is much larger than seen in (p,n) reactions at small angles, and is dominantly from the tensor force. Since the tensor interaction does not mediate β decay transitions we have chosen to subtract this L=2 strength before using these cross sections to obtain GT strengths. Fortunately, the L=0 and L=2 amplitudes have very distinctive shapes, making this separation unambiguous for sufficiently accurate data. These features are illustrated in Fig. 2, which shows an angular distribution for $^{26}Mg(^{12}C,^{12}B)$.

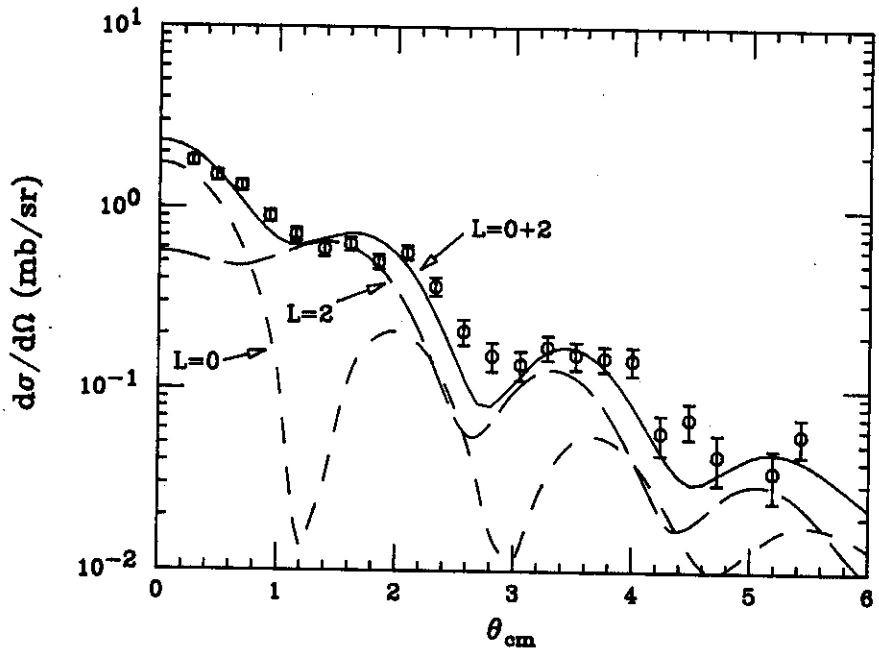

Fig. 2. Angular distribution for the reaction $^{26}Mg(^{12}C,^{12}B)^{26}Al(1^+$, 1.06 MeV) at 70 MeV/nucleon. The short dash curve is for L=0, the long dash curve for L=2, and the solid curve, the sum of the L=0 and L=2 contributions.

The angular distributions were compared to DWBA calculations done using the code FOLD based upon the momentum space techniques developed by Petrovich and his co-workers.[8] The 100 MeV t-matrix interaction of Franey and Love was used[9] and exchange was included for the central interaction. Effects of tensor exchange are expected to be small.[10]

For $^{26}Mg/^{26}Al$ we used the full sd-shell wavefunctions of Brown and Wildenthal;[7] for other nuclides, less complete wavefunctions were available. It was found that the relative L=0 and L=2 strengths depended somewhat on the details of the wavefunctions. Cohen-Kurath wave functions were used to describe the projectile and ejectile; a correction was made to account for the fact that these wavefunctions do not exactly reproduce the B(GT) for ^{12}B and ^{12}N.

The resulting cross sections were generally in good agreement with the measured cross sections, requiring renormalizations that were typically 30%, certainly in the range of the overall calculational uncertainties. In many cases the angular distributions were well described quantitatively. In cases where the agreement was poorer, it was generally possible to obtain good agreement by adjusting the relative strengths of the L=0 and L=2 contributions, i.e. by performing a multipole decomposition.

Given this situation, the following procedure was used to check the consistency of the extracted unit cross sections, the ratio of the cross section extrapolated to q=0 to the GT strength B(GT). First, calculations were made as outlined above, to provide L=0 and L=2 angular distributions. The relative strengths of these distributions were adjusted to yield the best least squares fit to the cross section, yielding the extrapolated L=0 cross section at 0°. In order to obtain the cross section corresponding to a total momentum transfer q=0, this cross section was multiplied by the ratio R of the L=0 cross section at 0°, calculated at Q=0 to that calculated at the actual -Q of the reaction (typically around 20-30 MeV). Dividing this q=0 cross section by the corresponding B(GT) leads to the calibration curve seen in Fig. 3. This curve can be used to obtain the B(GT) from the cross section measured for an unknown transition.

Preliminary attempts have been made to use this calibration curve and the results obtained for $^{56}Fe(^{12}C,^{12}N)^{56}Mn$ to extract B(GT) for transitions to the two lowest lying 1^+ states in ^{56}Mn and provide a check on the electron capture strengths used in supernova calculations. The calculations appear to agree better with the results of Brown[11]

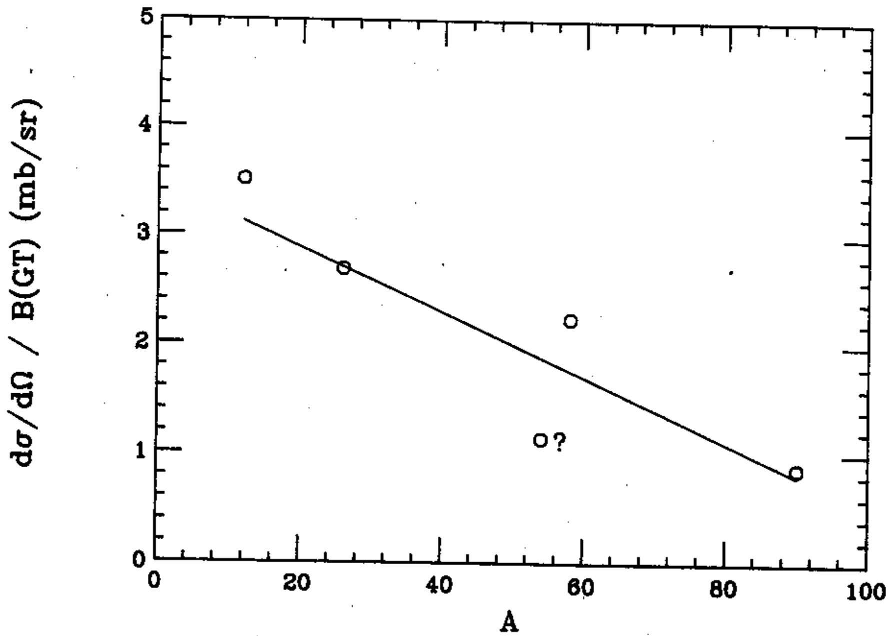

Fig. 3. Calibration curve determined from the ($^{12}C,^{12}B$) reaction on several nuclei as described in the text. The data for ^{54}Fe, marked with ?, are less complete than those for the other targets.

than with those of Bloom and Fuller.[12] However, the data for ($^{12}C,^{12}N$) generally have poorer statistics than the ($^{12}C,^{12}B$) results, and for the ^{54}Fe case, the L=2 strengths are rather large, so that the results are not conclusive. As we shall discuss in the next sections, measurements at higher energies may help to resolve this problem.

FUTURE DIRECTIONS

Higher Energies

Examination of future possibilities should include both improvements of existing procedures and development of new probes. It seems clear that higher energies will be necessary to reduce the uncertainties presently involved in heavy ion charge exchange reactions and to take advantage of their potential. There are two principal reasons for this conclusion. The first concerns the importance of successive transfer reactions which may obscure the direct charge exchange reactions in which we are most interested. Lenske, et al.[5] have shown that for transitions with L>0, successive transfer processes may be important for the $^{12}C(^{12}C,^{12}N)$ reaction unless bombarding energies are well above 100 MeV/nucleon. The second reason is that, for a given transition, the momentum transfer at 0° decreases as bombarding energy increases, increasing the ratio of L=0 to L=2 strength. For example. in the case of $^{26}Mg(^{12}C,^{12}B)^{26}Al(1^+_,$ 1.06 MeV) the ratio of L=0 to L=2 is 4 at 70 MeV/nucleon and 12 at 150 MeV/nucleon, all else being constant.

There are also some intrinsic disadvantages associated with the $(^{12}C,^{12}N)$ reaction itself. First is the large mass difference between ^{12}C and ^{12}N which contributes to the Q value of the reaction. Second is the relatively small matrix element connecting these nuclei. The $(^{14}C,^{14}N^*)$ reactions leading to the excited states at 2.31 MeV ($0^+_,$ T=1) and 3.95 MeV (1^+, T=0) allow one to select ΔS=0 and ΔS=1, respectively, but require that one tag the transition by the decay gamma ray. The log ft of the 3.95 transition is large. Unfortunately, ^{14}C beams are not available at any of the cyclotrons capable of sufficient energy.

The $(^6Li,^6Li(3.56$ MeV)) Reaction

This reaction provides a unique probe of the isovector spin response in the inelastic channel. Since the quantum numbers of the 3.56 MeV state are 0^+ T=1, $(^6Li,^6Li,(3.56))$ excites only ΔS=ΔT=1 transitions in the target nucleus. As such it contrasts with the (p,p') reaction. Although (p,p') has been used successfully to identify the giant inelastic spin resonance (1^+) in light and medium weight nuclei, it suffers the disadvantage that natural parity states are also strongly excited so that the ΔS=ΔT=1 states lie on a strong background. As a consequence, observation of higher multipoles is difficult.

The $(^6Li,^6Li,(3.56))$ reaction then has great promise, but with the additional complexity that it is necessary to determine that the reaction proceeded through the 3.56 MeV state. Fortunately, this state is the only particle stable state of ^6Li, so that observation of the

3.56 MeV de-excitation gamma ray, in coincidence with ^{6}Li, tags the reaction uniquely.

If application of this reaction is successful, it will be a unique probe of the isospin response for L>0. It should also permit improved measurements of the L=0 GT response. The ^{6}Li-gamma coincidence requirement, in addition to eliminating the ΔS=0 background, also eliminates the tail of the elastic peak which presently makes small angle (small q) measurements difficult.

FACILITY REQUIREMENTS

If one is to apply the techniques above, a basic requirement is beams of light ions with energies significantly above 100 MeV/nucleon and a spectrograph with sufficient bending power to analyze the reaction products. An overall energy resolution of about 10^{-4} is needed, as is a large spectrograph solid angle to provide reasonable event rates when it is necessary to tag the reaction products. Such a spectrograph should also permit the study of reactions with secondary beams.

It is also necessary to provide the capability for detection of gamma rays and charged particles produced in the target. For this purpose, space should be reserved around the target position to the greatest extent possible. Attention should be given to preventing spectrograph pivot arrangements from encumbering the target space and to the use of special small scattering chambers. This should be possible since the large radial aperture, about 10°, and the strongly forward peaked nature of the reaction cross sections will often obviate the need to change spectrograph angles during an experiment.

The S800 spectrograph designed for the NSCL should meet most of these requirements; we next give a brief description of this device.

NSCL S800 SPECTROGRAPH

The S800 spectrograph is a vertically bending QQDD device, with a bending power of $800Q^2/A^2$ MeV/nucleon. It employs superconducting dipole and quadrupole magnets operating in an iron dominated field region. Special efforts have been made to reserve space around the target chamber to facilitate the use of gamma ray and particle detectors. The S800 is located at the most distant part of the NSCL experimental area and can be fed by secondary beams produced by the NSCL A1200 fragment separator. Fig. 4 shows a schematic view of the

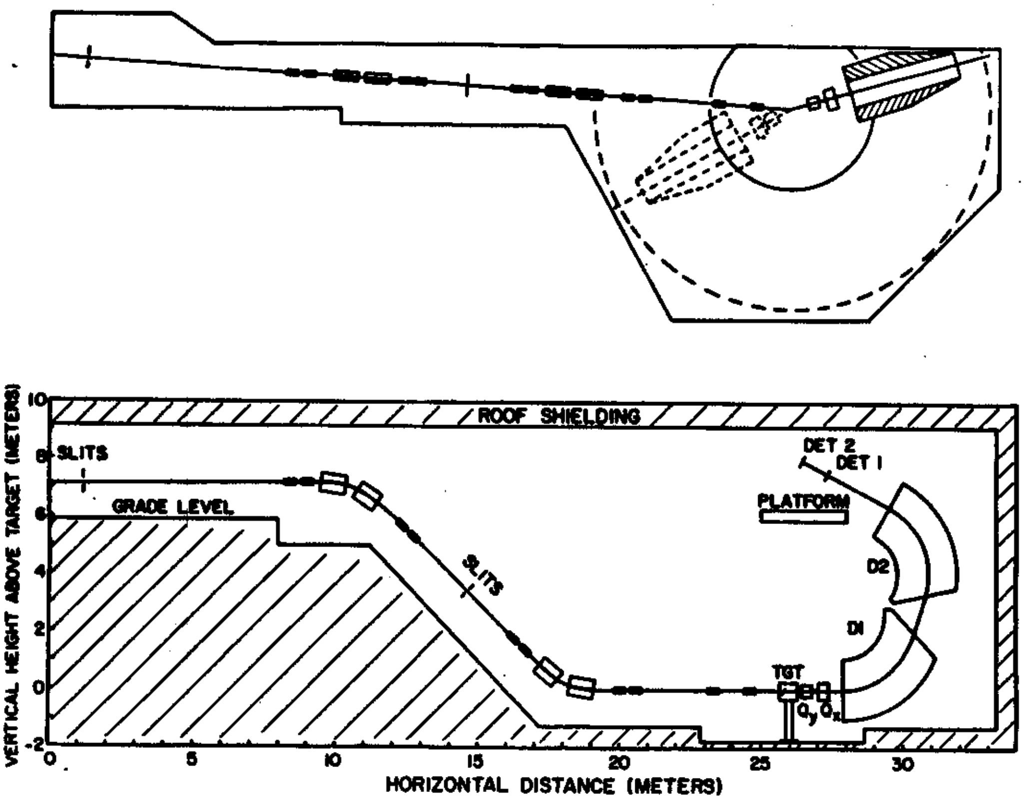

Fig. 4. Schematic view of the NSCL S800 spectrograph. The large rectangles in the beam preparation lines are dipole magnets and the small rectangles are quadrupole doublets.

spectrograph; some of its salient characteristics are given in Table 1. The spectrograph pit and the dipole steel already exist. However, funding for the completion of the spectrograph will probably not be available before late 1991.

Table 1. S-800 spectrograph specifications.

ENERGY RESOLUTION:	$\Delta E/E = 10^{-4}$ WITH 1mm RADIAL OBJECT SIZE FOR BEAM ANALYSIS SYSTEM
ENERGY RANGE:	$\Delta E/E$ = 10%
SOLID ANGLE:	Ω = 10-20 msr
RESOLVING POWER:	D/M = 12.3
RADIAL DISPERSION:	D = 9.1 cm/%
RADIAL MAGNIFICATION:	M = 0.74
AXIAL DISPERSION:	R_{34} = 0.88 mm/mr
ANGULAR RESOLUTION:	$\Delta\theta \leq$ 2 mr (TOTAL OF BEAM PLUS SPECTROGRAPH CONTRIBUTIONS)
FOCAL PLANE SIZE:	50 cm (RADIAL) X 15 cm (AXIAL)
FOCAL PLANE TILT:	28.5°
MAGNETIC RIGIDITY:	$B\rho$ = 4T-m
DIPOLE FIELDS:	B = 1.5T(ρ = 2.7 m)
DIPOLE GAP:	D = 15 cm
DIPOLE SIZE:	3.5 m LONG X 100 cm WIDE (75° BEND) QTY OF 2
WEIGHT OF DIPOLES:	70 TONS EACH
QUAD SIZES:	#1) 20 cm ID X 40 cm LONG #2) 35 cm X 17 cm X 40 cm
DETECTOR REQUIREMENTS:	TWO 2-DIMENSIONAL DET., 1m SEPARATION #1) 50 cm X 15 cm #2) 62 cm X 16 cm RESOLUTION: RADIAL 0.2 mm AXIAL 0.4 mm

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