NUCLEAR INSTRUMENTS AND METHODS 111 (1973) 425–430; © NORTH-HOLLAND PUBLISHING CO.

AN ARRAY DETECTOR FOR THE SPECTROSCOPIC STUDY OF REACTIONS PRODUCING ^{8}Be AND ^{8}Be*

J. G. CRAMER+, K. A. EBERHARD, N. R. FLETCHER†, E. MATHIAK, H. H. ROSSNER and A. WEIDINGER††

Sektion Physik der Universität München, West-Germany

Received 9 March 1973

A multi-detector counter for detecting ^{8}Be particles in ground and excited states is described. The counter consists of seven rectangular Si(Li) detectors 8.9 mm by 22.6 mm, closely positioned, so that the central angles of the detectors are 5° apart plus an eighth detector placed at a non-adjacent position. The breakup cone of the ^{8}Be→α+α reaction is normally such that the ^{8}Be ground state is detected only by one of the six pairs of adjacent detectors, while reactions leading to the excited state at 2.9 MeV or at 11.4 MeV are detected in most of the 28 pairs of detectors. Techniques for the separation of events and the reduction of data are discussed.

1. Introduction

Interest in the study of alpha-particle transfer reactions has led several groups to investigate reactions involving the production and subsequent decay of the particle-unstable nucleus ^{8}Be in its ground state. The methods of detecting and identifying this reaction product have been either the measurement of alpha-particle coincidences in a pair of closely spaced detectors[1]) or the use of a counter-telescope in which the passage of two alpha-particles from ^{8}Be resembles ^{7}Li [2]). The disadvantages of attempting to study quantitative spectroscopy with a three-body final state are fairly apparent, but there are also some definite advantages to reactions of this type. Among these are spectroscopic considerations[3]), unambiguous identification of the particle type and state of excitation, and the simple elimination of elastic scattering with stopping foils so that very forward angles can be studied.

In this paper we will describe a multiple-detector system which has been employed for studying reactions producing ^{8}Be not only in its ground state but also in its excited states at 2.9 MeV and 11.4 MeV. As will be shown below, these excited state reactions are clearly distinguishable from the ground state ^{8}Be reactions through the kinematics of the ^{8}Be breakup. This is a significant advantage over heavy ion reactions with two-body final states, where mutual excitation of the two reaction products can lead to much confusion in the interpretation of energy spectra. Further, while the widths of the ^{8}Be excited states are very broad, this does not markedly affect the resolution with which states in the residual nucleus can be distinguished since the total energy of both alpha-particles is measured in each case.

2. Detectors

The solid-state particle detectors used in the counter array were rectangular in shape to permit a minimum separation between adjacent active areas. Slabs of silicon were cut to a size of 10 mm by 24 mm and lithium drifted to give depletion depths of about 700 μm [4]). These were then mounted in holders with an aperture for each detector of 8.9 mm by 22.6 mm in a closely spaced configuration with adjacent active areas separated by ~3.5 mm. The angular spacing of adjacent detectors is 5°. A photograph is displayed in fig. 1, showing one detector dismantled to illustrate the basic design[4]), while the other seven detectors are in position for use. During the experiments an aluminium foil was placed in front of the detectors in order to stop the elastically scattered heavy ion beam while allowing the breakup alpha-particles to pass into the detector.

The coincidence detection efficiency for adjacent detectors for ^{8}Be (g.s.) was calculated to be 12% of the detector-pair solid angle for a ^{8}Be energy of 50 MeV and 14% for 30 MeV. For non-adjacent pairs only ^{8}Be* is detected in this energy region due to the small breakup angle for ^{8}Be (g.s.). The efficiency for ^{8}Be* (2.9 MeV) detection is approximately 1/30 to 1/100 the

Supported in part by the Bundesministerium für Bildung und Wissenschaft.

+ Permanent address: University of Washington, Seattle, Wash. 98195, U.S.A.

† Permanent address: Florida State University, Tallahassee, Fla. 32306, U.S.A.

†† Present address: Institut de Physique Nucléaire, Université Paris-Sud, 91 Orsay, France.

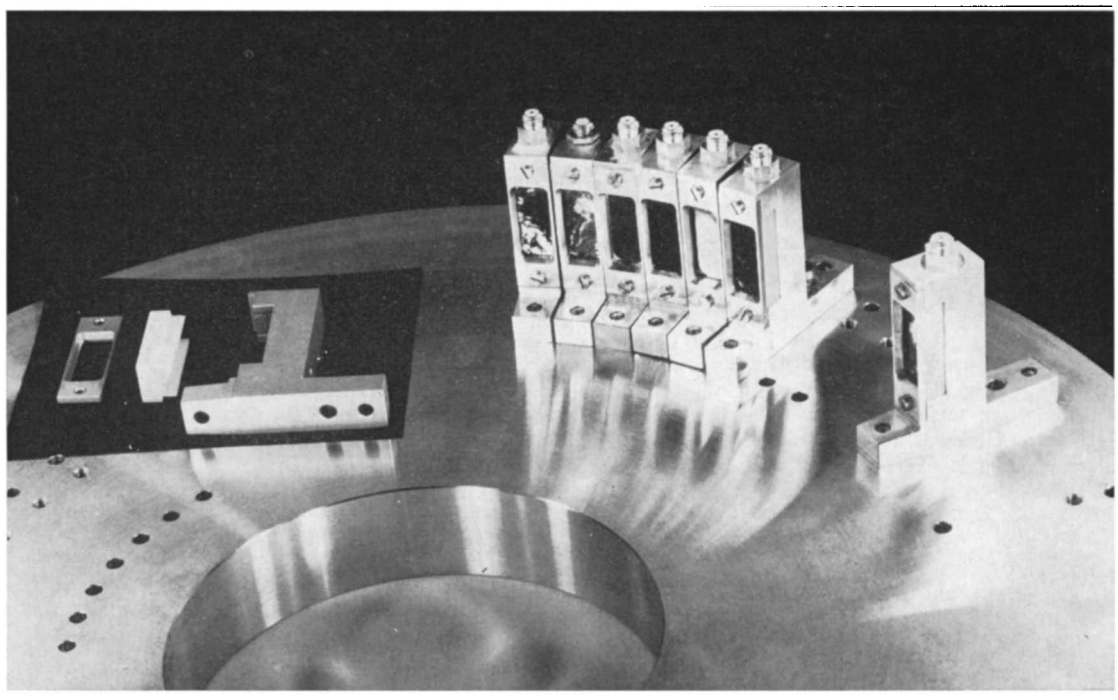

Fig. 1. Photograph of the detector array.

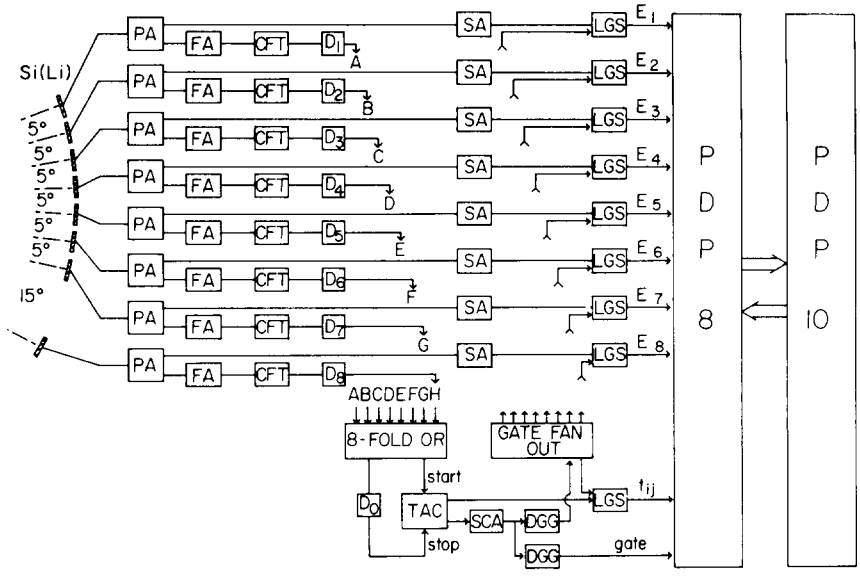

Fig. 2. Block diagram of the electronics with the notation: PA = preamplifier, FA = fast amplifier, CFT = constant fraction trigger, D_i = delay, SA = spectroscopy amplifier, LGS = linear gate and stretcher, TAC = time-to-amplitude converter, SCA = single channel analyzer, DGG = delay gate generator.

value for ^{8}Be (g.s.) detection efficiency, depending on the relative position of the coincidence counters. An accurate efficiency calculation for the detection of ^{8}Be* is in progress. In the present application, however, such a calculation would be difficult to interpret in many cases since often some of the breakup alpha-particles from ^{8}Be* are actually stopped in beam stopping foil because of their low energy. This phenomenon will be illustrated in section 5.

The energy spectrum for ^{8}Be-particles is formed by

summing the digitized pulse heights of two coincident alpha-particle pulses after appropriate energy calibration. The energy resolution in such a ^{8}Be energy spectrum is determined primarily by the kinematic effect, and partly by energy straggling in the beam stopping foil and by the non-uniformity of the foil. The observed energy resolution was about 400 keV.

3. Coincidence identification of ^{8}Be events

In the present case the handling of coincidences between pairs of detectors produces problems not usually encountered in the multidetector coincidence systems because the coincidence of each detector with every other detector is of interest. Since an eight detector system has 28 possible coincidence pairs it is clear that special attention must be given to the problem to avoid unnecessary electronics complication. This problem has been solved by mixing the fast signals from the eight detectors after each has been suitably delayed and then using the mixed signal to provide both a start and a stop signal for a time-to-amplitude converter (TAC). The mixed signals for a true coincidence event will contain the successive pulses, the first starting and the second stopping the TAC. An event is recorded on magnetic tape as the digitized energy and time signals and the ADC number in which the corresponding pulses were analyzed when the TAC supplies a gate signal to the gate fan-out and to the PDP-8.

A block diagram of the data acquisition system is shown in fig. 2. The nominal values of the delays, D_i for $i = 1$–8 are given in the table in fig. 3. The table of relative time delays, t_{ij}, in fig. 3 shows the nominal time between the start pulse from detector i and the stop pulse from detector j. It is important that the OR circuit employed in mixing the time signals has a paired-pulse resolution which is much less than the delay intervals used which were 10 nsec in the present case. A total time spectrum, as represented by the output of the TAC, resulting from ^{12}C bombardment of a ^{58}Ni target containing carbon and oxygen impurities is shown in the upper portion of fig. 4. The most intense peaks in the spectrum correspond to coincidence events in adjacent detectors which have a high efficiency for detection of ^{8}Be(g.s.). Upon replay of the magnetic tape data a time spectrum for a single pair of detectors can be generated, as illustrated in the lower portion of fig. 4.

It should be noted that a true fast coincidence signal from detectors i and j may be accompanied by a single event in detector k sufficiently close in time that all three energy signals are admitted to the PDP-8 while the gates are open. In such a case the time replay spectrum for events in energy ADC's numbered i and k could show an accumulation of time events at time t_{ij}. By setting a window on t_{ik} and replaying the energy data this particular type of accidental coincidence for detector pair i–k is eliminated. Such events are still available for the summed energy spectra in branches i and j, whereas in the conventional multi-plexed ADC system they are eliminated completely.

t_{ij} table (nsec)

i	D_i (nsec)
1	0
2	10
3	30
4	70
5	120
6	200
7	300
8	440

i \ j	1	2	3	4	5	6	7	8
1	0	10	30	70	120	200	300	440
2		0	20	60	110	190	290	430
3			0	40	90	170	270	410
4				0	50	130	230	370
5					0	80	180	320
6						0	100	240
7							0	140
8								0

Fig. 3. Tables of the nominal values for the delays, D_i, and for the relative delays, $t_{ij} = D_j - D_i$, for all pairs of branch inputs to the TAC.

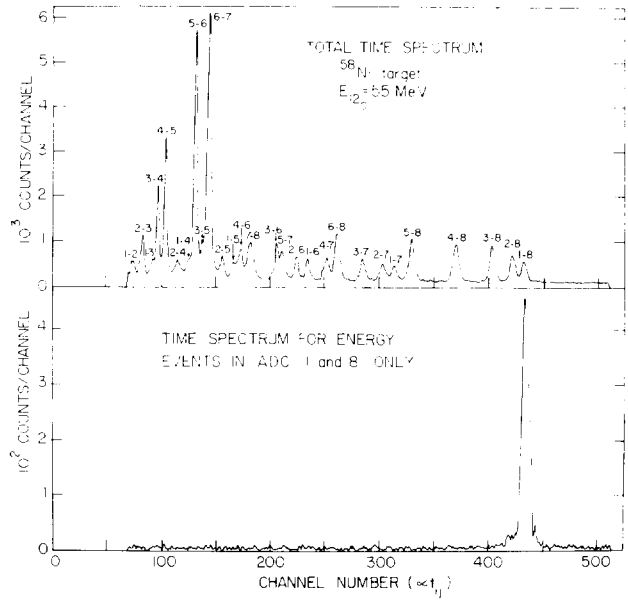

Fig. 4. Time spectra from the time-to-amplitude converter. Upper spectrum is for all possible pairs of an eight branch system with detector number pair shown above the appropriate peak. Lower spectrum is for events in branches 1and 8 only.

4. Kinematic identification of ^{8}Be events

The kinematics of three-body reactions in general[5]) and of reactions involving ^{8}Be final states in particular[1]) have been discussed in detail elsewhere. We will illustrate here some of the kinematic features as manifested in the application of the present system to the ^{12}C(^{12}C, ^{8}Be)^{16}O reactions.

The results of kinematic calculations for a single pair of adjacent detectors and for a variety of excitation energies in the final nucleus, ^{16}O, are shown in fig.5.

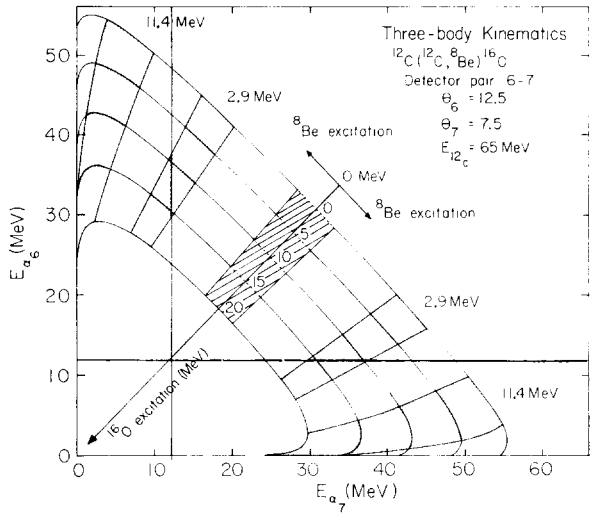

Fig. 5. Three-body kinematic loci of possible alpha-particle energies for the reaction ^{12}C(^{12}C,$\alpha\alpha$)^{16}O at E_{lab} = 65 MeV for detector angles of 7.5° and 12.5° and for oxygen excitation energies of 0, 5, 10, 15, and 20 MeV.

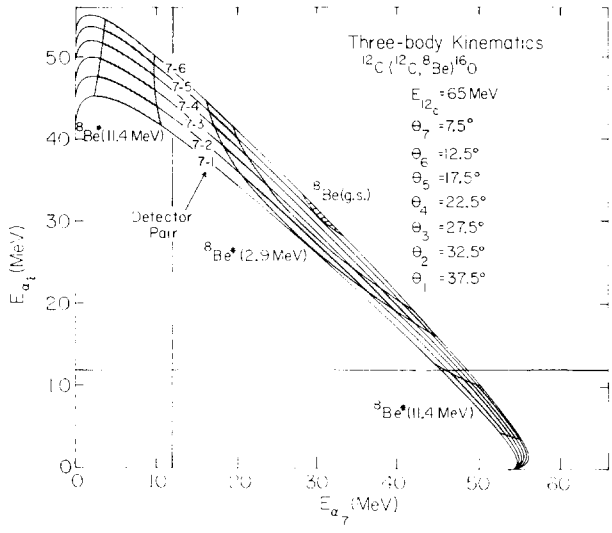

Fig. 6. Three-body kinematic loci of possible alpha-particle energies for a variety of detector pair angles.

The coordinates are the energies of two alpha-particles from a ^{12}C(^{12}C,2α)^{16}O reaction. The contours represent ^{16}O at excitation energies of 0, 5, 10, 15, and 20 MeV. The lined region corresponds to a region of events having ^{8}Be in its ground state. The shaded areas correspond to regions for ^{8}Be in excited states at 2.9 MeV and 11.4 MeV. The width of the lined region is dominated by the energy spread for alpha-particles due to adjacent detectors subtending the entire ground state breakup cone. The widths of the shaded regions are dominated by the energy widths of the states in ^{8}Be. Clearly an event identified by fast time coincidence and the energies of the two alpha-particles would determine the excitation of both the ^{8}Be and ^{16}O final nuclei. Alpha-particles of energy below about 11 MeV are stopped in the beam stopping foils. This cutoff is shown by horizontal and vertical straight lines in fig. 5. It is apparent that the 11.4 MeV state of ^{8}Be is not observed under these conditions and that the observed yield of ^{8}Be* (2.9 MeV) is greatly reduced for ^{16}O excitation above 10 MeV.

In fig. 6 the results of kinematic calculations for ^{16}O in its ground state and for several pairs of detectors are shown. This figure further illustrates that ^{8}Be(g.s.) is detected only in an adjacent pair. It also appears that some of the ^{8}Be* (11.4 MeV) state may be observed; however, for the most part the non-adjacent detectors record ^{8}Be* (2.9 MeV) events only.

For each event detected with the present system at a pair of detector angles θ_1 and θ_2, two kinetic energies T_1 and T_2 are observed which characterize the event. The parameters of real interest, however, are the excitation energies in the ^{8}Be system (E_{12}) and the residual nucleus (E_n), and the effective angle θ_{12} at which the ^{8}Be "particle" was emitted. In this next section we will consider the kinematical analysis which will allow the determination of these quantities of interest from the observables.

The known quantities that we have at our disposal, in addition to those above, are the beam, target, and detected particle masses A_b, A_t, A_1, A_2 (in MeV), the Q-value Q_0 of the reaction producing two alphas and the unexcited residual nucleus, and the beam energy T_b. We have the following relations:

$$E_{12} = A_{12} - A_1 - A_2 \tag{1}$$

$$E_N = A_0 - A_B - A_T - E_{12} \tag{2}$$

$$\theta_{12} = \tan^{-1}[(P_1 \sin\theta_1 + P_2 \sin\theta_2)/(P_1 \cos\theta_1 + P_2 \cos\theta_2)], \tag{3}$$

where

$$A_0 = [(A_B+A_T)^2+2A_T T_B]^{\frac{1}{2}} \quad (4)$$

$$A_{12} = [W_{12}^2-P_{12}^2]^{\frac{1}{2}} \quad (5)$$

with

$$W_{12}^2 = [(T_1+A_1)+(T_2+A_2)]^2 \quad (6)$$

$$P_{12}^2 = P_1^2+P_2^2+2P_1P_2\cos(\theta_1-\theta_2) \quad (7)$$

$$P_1^2 = T_1(T_1+2A_1) \quad (8)$$

$$P_2^2 = T_2(T_2+2A_2). \quad (9)$$

Thus we can calculate E_{12}, E_N, and θ_{12} from the known and observed quantities in the reaction.

It should be noted that the two shaded regions on the kinematic locus in fig. 5 in which reactions leading to the 2.9 MeV excited state of ^{8}Be are localized correspond in general to two different values of θ_{12} since P_1 and P_2 are quite different for the two regions. Therefore the two ^{8}Be* (2.9 MeV) regions detected with a given pair of counters correspond to different angles of emissions of the ^{8}Be* particle.

5. Application of the method to the reactions ^{12}C(^{12}C, ^{8}Be)^{16}O

The (^{12}C, ^{8}Be(g.s.)) and (^{12}C, ^{8}Be* (2.9 MeV)) reactions on the target nuclei ^{12}C, ^{16}O, ^{28}Si, ^{40}Ca, ^{54}Fe, and ^{58}Ni have been studied by the present method[6]), and a detailed report of the results will appear in forthcoming publications[7]). Here we wish only to illustrate the kinematic identification of ^{8}Be ground state and excited state energy spectra as obtained by the present method using a ^{12}C target.

The ^{8}Be energy spectrum formed by the summation of coincident pulses in a detector pair with reaction angles of 7.5° and 12.5° is shown in fig. 7. The events recorded are predominantly ^{8}Be in the ground state since for adjacent detectors the detection efficiency for ^{8}Be* (2.9 MeV) is only a few percent of the ^{8}Be(g.s.) efficiency. Even that small percentage will be completely eliminated during replay data reduction by accepting only summed events from the lined region of a plot similar to fig. 5. The spectrum of fig. 7 is dominated by the states of ^{16}O which make up the 4-particle – 4-hole rotational band built on the $J^\pi = 0^+$ state at 6.07 MeV excitation, confirming the result of an earlier published spectrum obtained by the E-ΔE counter telescope method[2]).

An energy spectrum of ^{8}Be "particles" in the 2.9 MeV excited state, as obtained by pulse height summation of coincident events in detectors at angles of 17.5° and −7.5°, is shown in fig. 8. In this case, even though the central angle of the detector pair is 5°, the actual mean angles for the ^{8}Be* directions are approximately 2° and 8°, corresponding to the two different angles θ_{ij} and θ_{ji} discussed in section 4. Again as in the spectrum for ^{8}Be(g.s.), the spectrum is dominated by the states in ^{16}O corresponding to the 4p-4h band, a result not obtainable by the E-ΔE counter telescope method. The yield for the ground state of ^{16}O, however, seems to be greatly enhanced. Such an enhancement is probably a result of partial elimination of ^{8}Be* yield

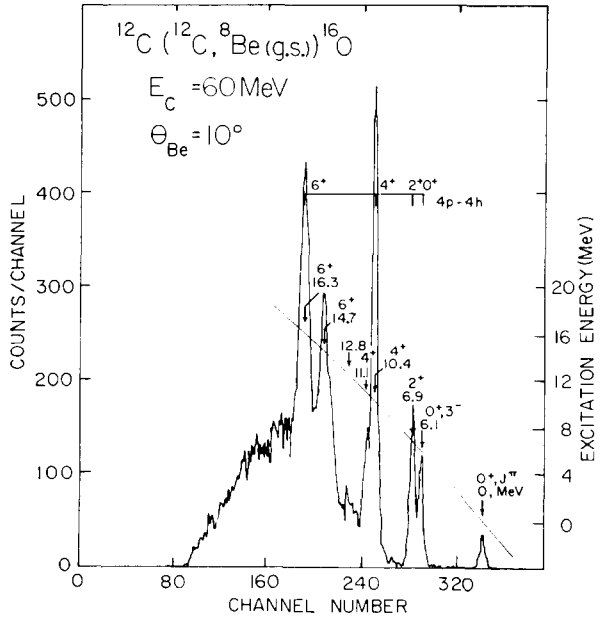

Fig. 7. Energy spectrum of ^{8}Be "particles" in the ground state from ^{12}C+^{12}C at E_{lab} = 60 MeV and θ_i = 7.5°, θ_j = 12.5°.

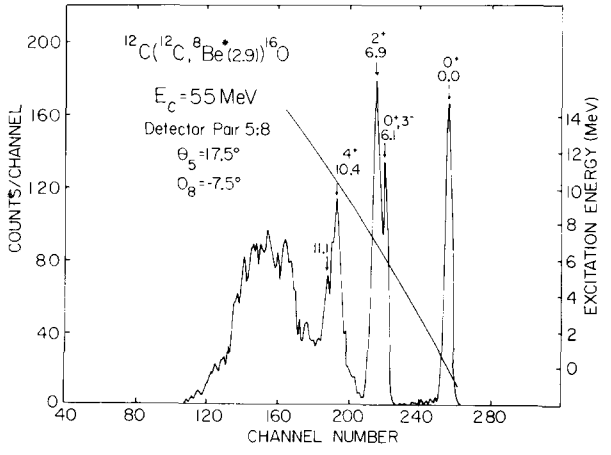

Fig. 8. Energy spectrum of ^{8}Be "particles" in the 2.9 MeV excited state from ^{12}C+^{12}C at E_{lab} = 55 MeV and θ_i = 17.5°, θ_j = −7.5°.

for excited ^{16}O states by absorption of alpha-particles in the stopping foil. This effect becomes apparent upon inspection of the results illustrated in figs. 5 and 6 calculated at $E_{lab} = 65$ MeV, whereas the spectrum of fig. 8 was measured at $E_{lab} = 55$ MeV.

In conclusion it has been illustrated that the present method represents a technique of high efficiency whereby mutual excitation events in nuclear reactions can be uniquely identified. In the reactions $^{12}C(^{12}C, ^{8}Be^{*}(2.9\ MeV))^{16}O^{*}$ the selectiveness is readily apparent but cross sections are difficult to extract because of the problem of calulating the detection efficiency for the decay of the 2^+ state of $^{8}Be^{*}(2.9\ MeV)$ properly and because of the use of absorbing foils in front of the detectors. In recent runs[8]) absorbing foils were used for detectors at very forward angles only, thus making possible the measurement of spectra for the $^{8}Be^{*}$ (2.9 MeV) state over the entire range of excitation energy in the corresponding residual nuclei.

The authors would like to thank Dr W. Henning and his collaborators for their assistance with the 80 cm scattering chamber. One of the authors (N.R. F.) wishes to acknowledge the combined financial assistance of the Florida State University, the University of Munich and the Fulbright Commission during his stay at the University of Munich.

References

[1]) R. E. Brown, J. S. Blair, D. Bodansky, N. Cue and C. D. Kavaloski, Phys. Rev. **138** (1965) B1394; G. Goldring, I. Plesser and M. W. Sachs, Phys. Rev. **160** (1967) 827; M. B. Greenfield, J. L. Artz and N. R. Fletcher, Bull. Am. Phys. Soc. **17** (1972) 489; Ph. Martin and T. R. Ophel, Nucl. Phys. **A194** (1972) 491; N. R. Fletcher, J. G. Cramer, K. A. Eberhard, E. Mathiak, H. H. Rossner and A. Weidinger, Bull. Am. Phys. Soc. **17** (1972) 920.

[2]) G. J. Wozniak, H. L. Harney, K. H. Wilcox and J. Cerny, Phys. Rev. Letters **28** (1972) 1278.

[3]) D. Robson, Comments Nucl. Particle Phys. **5** (1972) 16.

[4]) Si(Li) slags and basic detector design supplied by Ms. S. Kellenbager, University of Washington, Seattle, Wash.

[5]) D. P. Boyd, P. F. Donovan and J. F. Mollenauer, Phys. Rev. 188 (1969) 1544; W. J. Braithwaite, Computer Phys. Commun., in press.

[6]) J. G. Cramer, N. R. Fletcher, K. A. Eberhard, E. Mathiak, H. H. Rossner and A. Weidinger, Bull. Am. Phys. Soc. **17** (1972) 920.

[7]) J. G. Cramer, K. A. Eberhard, N. R. Fletcher, E. Mathiak, H. H. Rossner, J. Stettmeier and A. Weidinger, to be published.

[8]) K. A. Eberhard, E. Mathiak, U. Meyer-Berkhout, H. H. Rossner and J. Stettmeier, to be published.