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Applications of Millimicrosecond Spectroscopy to Neutron Polarization Studies — Method and Results

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It is clear that millimicrosecond neutron spectroscopy has an important role to play in connection with neutron polarization studies in several ways. Thus, if one wishes to determine the polarization of one of several neutron groups produced in the target of an accelerator such methods are invaluable if not essential – particularly if one's interest is not restricted to the most energetic or ground-state group. Such use of the method is illustrated by some work already reported at this conference by Dr. SCANLON on behalf of the workers at Harwell. That work is concerned with the limiting case in which the discrete groups corresponding to excitation of single states in the residual nucleus merge into a continuum. We have reported results previously for two groups from the reaction $Li^7(p, n)Be^7$ [1][1]).

Another case where such methods are clearly useful is that in which one studies polarization in the spectrum of inelastically scattered neutrons. This is a topic of interest from the point of view of theories of nuclear reactions and some information on this item will be presented in what follows.

Less obvious, because it is buried in the quantitative details, is the fact that the pulsed-beam time-of-flight technique is very advantageous even for the study of ground-state neutron groups – the case of special interest in connection with development of the optical model. Most of the new results to be presented are in this category.

There are various possibilities for incorporating millimicrosecond neutron spectroscopy in an arrangement for the study of neutron polarization. The first slide (figure 1) illustrates the arrangement we have chosen. Its most distinctive feature is the fact that the scatterer is very close to the target, in contrast to the usual arrangement which places it close to the detector. The motivation for this choice is that one can, with this plan, do spectroscopy on the products of the neutron-producing reaction

[1]) Number in brackets refers to Reference, page 324.

and on the products of the scattering process simultaneously, and it requires only a trivial modification of our usual arrangement for the study of elastic and inelastic neutron scattering – namely, the displacement of the scatterer and of the detector pivot away from the zero-degree direction. The choice of 35° from the proton direction was typical of the reaction angles used in this study.

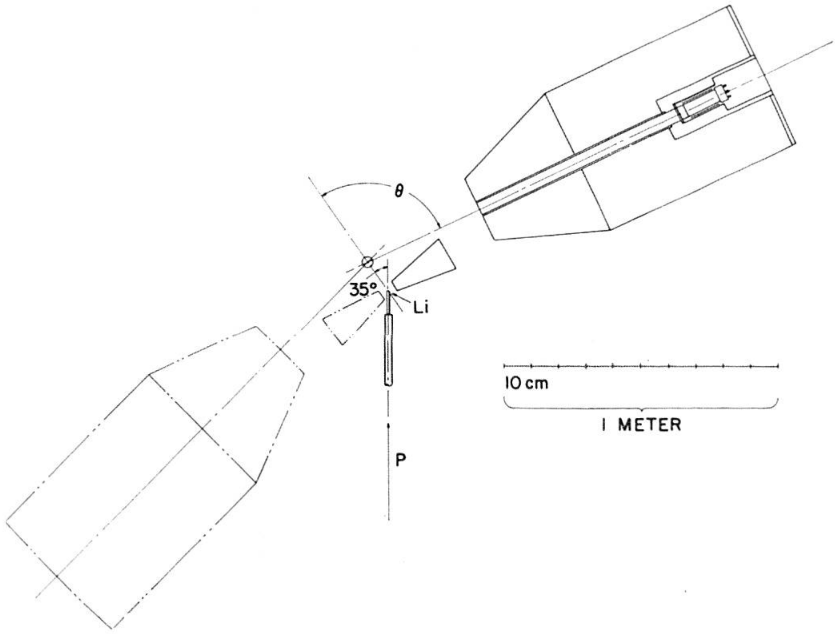


Figure 1

This arrangement is particularly vulnerable to two sources of spurious asymmetry. One is transverse displacement of the proton beam which results in a spurious left-right asymmetry due primarily to a corresponding shift of the zero-degree scattering angle; and the other is the effect associated with the shielding wedge, whose function is to shield the detector from the direct flux from the target. When the detector and the wedge are in the 'right' position the wedge is more strongly illuminated by the neutron flux from the target than when it is in the 'left' position. This gives rise to the possibility that neutrons scattered from the wedge and then scattered again from the scatterer will be more numerous on the right side than on the left side.

The effect of transverse displacement of the proton beam was dealt with in the following way. The beam was sufficiently well focused that it could be transmitted effectively by an aperture of only 2 mm diameter placed close to the target. To check on the positional stability of the beam within this 2 mm aperture the zero-degree neutron scattering direction was determined very frequently, usually between each left and right observation. The procedure for determining zero-degrees follows the plan described in a paper by Clement, Boreli, Darden, Haeberli, and Striebel, which will be referred to henceforth as Clement *et al.* This procedure involves measuring the transmission of the sample at small angles in the neighborhood of zero-degrees, and the center of symmetry of the transmission pattern is taken to be zero-degrees. The sensitivity claimed for this method by Clement *et al.* of $\pm$ 1/4 of a degree has been confirmed by our experience. In our measurements this angular uncertainty corresponds to an uncertainty in the asymmetry of about 0.01 for forward angles, and less for back angles.

The effect of the wedge in producing spurious asymmetries due to double scattering effects could in fact be observed under sufficiently aggravated conditions. These aggravated conditions correspond to the use of a heavy metal wedge at small scattering angles. By using a polyethylene wedge, however, and restricting the range of observation to angles of 50° or larger, the effect of the wedge was such as to produce substantially less than 1% spurious asymmetry.

Since there is no built-in self-monitoring in this arrangement, accurate monitoring of the neutron flux irradiating the sample on corresponding left and right runs must be done with good accuracy, preferably to 0.1% or better. The next slide (figure 2) illustrates the monitoring arrangement.

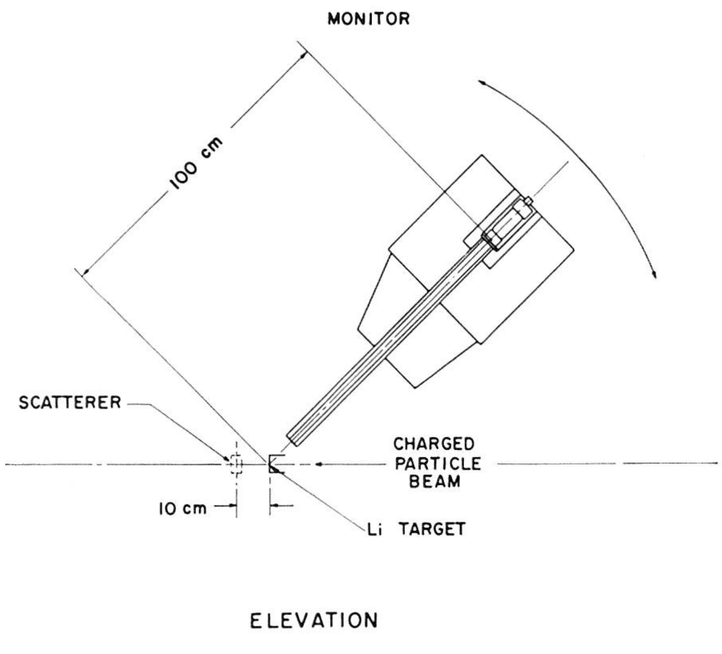


Figure 2

This is an elevation view in the plane of the proton beam and shows the monitoring detector, which is an anthracene scintillator, in its shield and collimator. The essential feature of the arrangement is that with the aid of tight collimation the field of view of the monitor detector is restricted to a small volume in the vicinity of the neutron-producing target. Thus it is insensitive to the presence of the sample and to the position of the wedge.

The next slide (figure 3) is a photograph which illustrates the arrangement in three dimensions, combining the views of the first and second slides. In the photograph a solid sample is shown in place on a wire which normally supports three samples and may be moved remotely. The next slide (figure 4) illustrates the arrangement which was used when the samples were in the form of compressed gases. Two of the spherical vessels shown contain He^4 and He^3 at pressures of 350 atmospheres, and the third vessel is an evacuated dummy for background subtraction purposes. The large boxes at the corners of the framework are gauges which continuously monitor the pressure in the filled vessels.

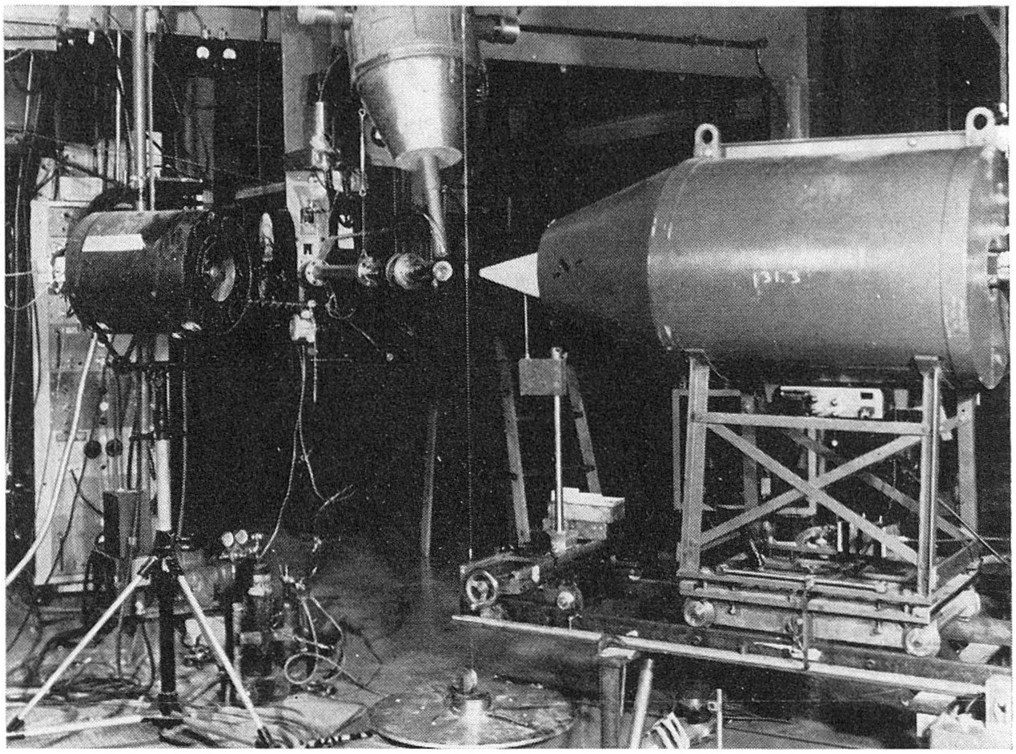


Figure 3

Table I is a summary of the essential performance parameters of the system under the conditions for which most of the measurements which will be reported here were taken.

The accelerator used for this work was the large Los Alamos VAN DE GRAAFF fitted by J. L. MCKIBBEN with a terminal pulser of the deflection type.

Let me note parenthetically that I regard the performance characteristics indicated in table I as representative of a state of affairs which can be very radically improved by straightforward procedures, and that one can readily attain the performance indicated by the numbers in parentheses in table I. There are a number of places at which effort is now being directed toward achieving the performance indicated by the numbers given in parentheses, and I think it quite likely that such improvement will have been accomplished before the year is out.

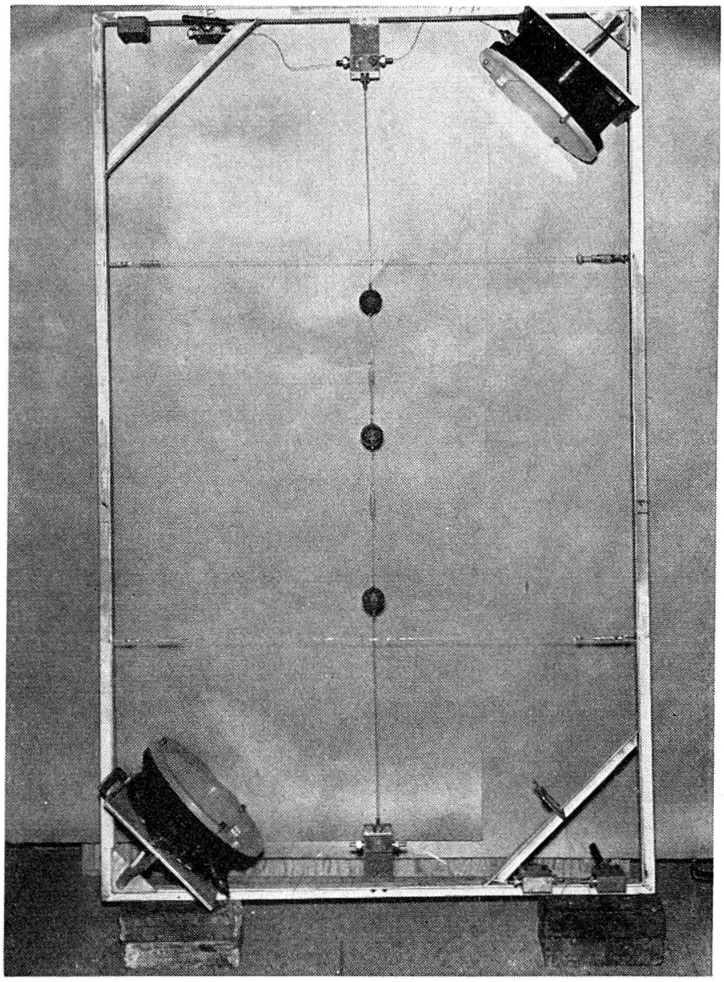


Figure 4

The next slide (figure 5) shows a time spectrum which is typical of those obtained in the course of this work, and illustrates the present state of our technology. The conditions under which this time spectrum was obtained are indicated on the slide. The neutron source was the $Li^7(p, n)$ reaction giving a ground state group of 2.09 MeV at 35°, and a second group about 10% as strong at about 1.6 MeV. The scatterer was a sample of titanium. Time increases from right to left. The gamma-ray line is due to de-excitation of Ti^{48} excited to its first state at 1.0 MeV. We then see elastic scattering due to the strong and weak neutron groups, and finally an inelastic neutron line due to the main group from the target. The width of the inelastic line is dominated by the spread in neutron energy due to the target thickness, which was 160 keV. The width of the elastic line is due primarily to the burst duration. This figure indicates we can resolve effectively a neutron group within 500 keV of the 2 MeV ground state group.

Table I

Average Current	1 μA	(10)
Duty Cycle	0.01	(0.001)
Elastic Line Width at Half Max	4.5 ns	(2)
Target-Scatterer Distance	8–12 cm	
Scatterer-Detector Distance	1.2 m	
Signal-Background Ratio	$\sim$ 3	
Counting-Rate	10–40 s^{-1}	

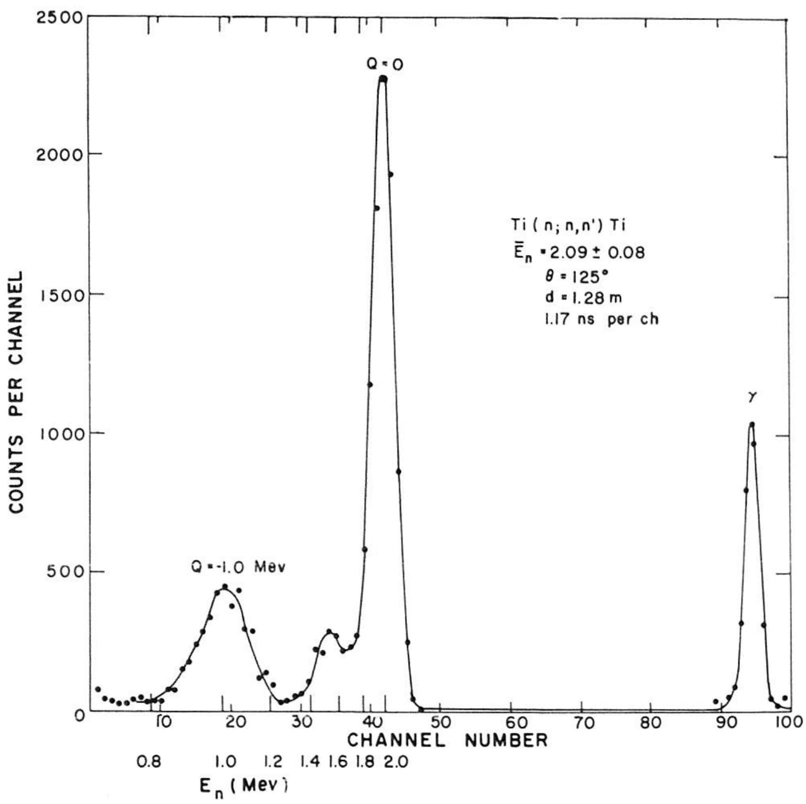


Figure 5

So much for the general features of our method. We turn now to the discussion of the results.

Our first endeavour was to attempt to find a neutron source strongly polarized, at least as prolific as any of those now known, and preferably of an energy substantially higher than 1 MeV, which is the energy of the earlier comprehensive study of CLEMENT *et al.* Following the suggestion of J. MARION, we have investigated the ground state neutron group from the reaction $Be^9(p, n)B^9$ which exhibits a strong resonance at 4.5 MeV proton energy. The rather discouraging results are illustrated in the next slide (figure 6), which indicates we have explored this reaction at 45° for proton energies from 4.5 to 5.3 MeV, using carbon as an analyzer, and the values of polarization calculated from the phase shift analysis of MEIER, SCHERRER, and TRUMPY. The polarization obtained is substantially less than that available from the $Li^7(p, n)$ reaction and the neutron yield is also down. We therefore determined to undertake a systematic investigation of polarization effects at the highest energy at which our previously reported investigation [1] had shown that the $Li^7(p, n)$ reaction gives substantial polarization. As indicated in the summary given by Professor HAEBERLI earlier at this conference, this energy is in the range of 2 MeV neutron energy, and a systematic investigation of polarization effects in neutron scattering has been carried out at that energy for about 30 nuclear species ranging in mass from deuterium to U^{238}.

$Be^9(p, n)B^9$ $\theta' = 45°$				
E_p(MeV)	E_n(MeV)	$P_1 P_2$	P_2	P_1
4.49 ± 0.11	2.39	-0.034 ± 0.015	-0.75	0.045 ± 0.02
4.69 ± 0.10	2.58	$+0.078 \pm 0.013$	-0.85	-0.091
4.90 ± 0.10	2.77	$+0.093 \pm 0.015$	-0.97	-0.095
5.30 ± 0.09	3.16	$+0.06 \pm 0.02$	-0.95	-0.101

Figure 6

As a preliminary step the polarization of the $Li^7(p, n)$ source was remeasured by the same procedure which had been used before, – that is, by scattering from a compressed gas sample of He^4. Our result for this measurement of $35 \pm 3\%$ compares well with our earlier published result of 38 ± 3. In the subsequent slides the values of polarization observed in scattering are based on the value 0.38, or the observed value of the asymmetry, ε, only is given. In the latter case the corresponding polarizations are obtained roughly by multiplying the observed values of the asymmetry by three.

One may usefully distinguish four mass intervals (hereafter referred to by Roman numerals) as characterized by special features of theoretical interest. In group I, which comprises the very lightest nuclei, the chief point of interest is the possibility of obtaining clues with respect to the nucleon-nucleon force itself. In group II are the nuclei whose scattering properties may be interpreted in terms of the excitation of one or two resonances in the compound nucleus. Group IV, which includes the medium-weight and heavy nuclei, is characterized by the excitation of a very large number of states in the compound nucleus and lends itself to description in terms of cross-sections averaged over levels, by the optical model, and by statistical theories of nuclear cross sections such as the Hauser-Feshbach theory. Group III, which is intermediate in mass between groups II and IV is also intermediate with respect to the number of levels excited in the compound nucleus and may be expected to exhibit strong fluctuation effects, that is, a strong and irregular dependence of scattering properties on mass number and on the mean energy and energy spread of the incident neutron beam.

The results in group I have been given for deuterons in earlier work and by previous speakers, and the results obtained on T and He^3 (this was work done in collaboration with J. D. SEAGRAVE and J. E. SIMMONS) were reported at last year's London Conference on the Few Nucleon Problem. They will also appear shortly in the Physical Review. These results may be summarized very simply by saying of all of them that very little polarization is observed. I regard this as our most striking result on polarization to-date. There is a cleancut break with respect to polarization effects at the boundary between mass 4 and mass 5 systems (referring now to the mass of the compound systems) although p-wave effects are equally prominent at an energy of a few MeV for systems of mass 3, 4, and 5. The role of spin-orbit or tensor force in producing a split of p-wave phase shifts is very large for the mass 5 system but is very much smaller for the mass 3 and 4 systems. This is a striking effect which may have a significant unified interpretation, but there is none available at present to the best of my knowledge. I commend this observation to the serious attention of the theorists.

In the mass II region we have observed polarization in scattering from B^{10}, B natural, Be^9, C^{12}, and Mg^{24}. Here our main motivation for the present has been to look for large polarization effects in the hope that we might find a nucleus suitable for use as an analyzer in our energy range. The largest effect was obtained with carbon, and the results for the polarization of carbon as a function of angle are shown on the next slide (figure 7). Also shown on that slide are the results calculated from the data of MEIER *et al.* at the nearest energies available in their analysis. It is clear that the sin 2θ term is the dominant one in describing the polarization as in the results of MEIER *et al.*, but is substantially reduced in magnitude. It is regrettable that we do not have a comparison with the predictions of WILLS *et al.* which do extend into our energy region, and that our energy coincides with a resonance in C^{13}, so that the analyzing efficiency in carbon is changing rapidly in the energy interval which corresponds to our energy spread. By a crude integration over the relevant energy interval for the prediction of WILLS *et al.* we can say, however, that our result is consistent with WILLS *et al.* to about 15%.

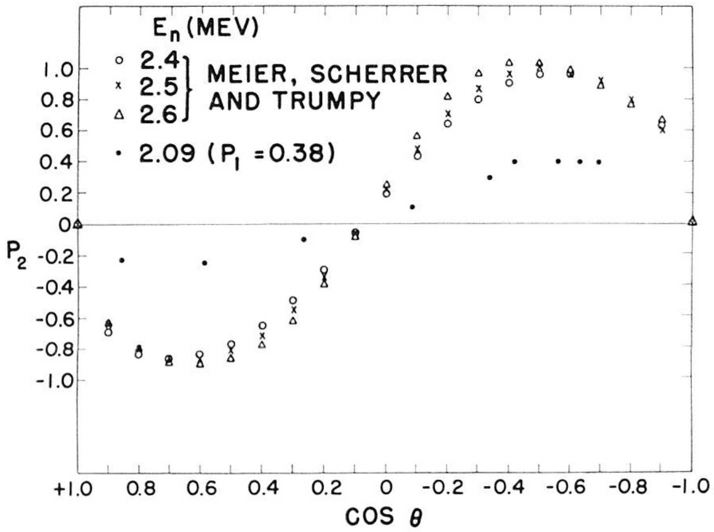


Figure 7

The next pair of slides gives the results obtained for inelastic scattering corresponding to excitation of the first levels in Fe^{56} and Ti^{48} and are, I believe, the first data available on polarization in inelastic neutron scattering.

The first of these slides (figure 8) is for iron. The upper portion of the slide shows the angular distribution of the inelastically scattered neutrons corresponding to the 850 kV level, and the lower portion shows the observed asymmetry. The isotropy of the inelastically scattered neutrons implies the absence of polarization and the experimentally observed result is consistent, within the limits of statistical uncertainty, with the prediction of no polarization. Previous results of LEVIN and myself on inelastic scattering in this nuclide in this energy range have shown, however, that the anisotropy and asymmetry about 90° of inelastically scattered neutrons is rapidly varying with bombarding neutron energy. Hence, the isotropic result, which is consistent with the Hauser-Feshbach prediction of symmetry of about 90°, must be regarded as fortuitous. This interpretation of our result is consistent with the results shown in the next slide for titanium (figure 9) which is similar in mass number to iron and similarly even-even in its predominant isotope. Here we observe substantial asymmetry about 90° in the inelastic scattering, and the possibility that there is indeed a non-zero polarization of as much as 10%.

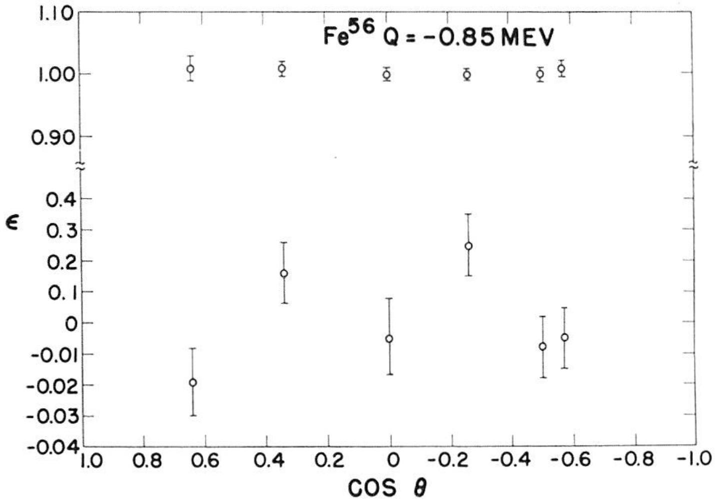


Figure 8

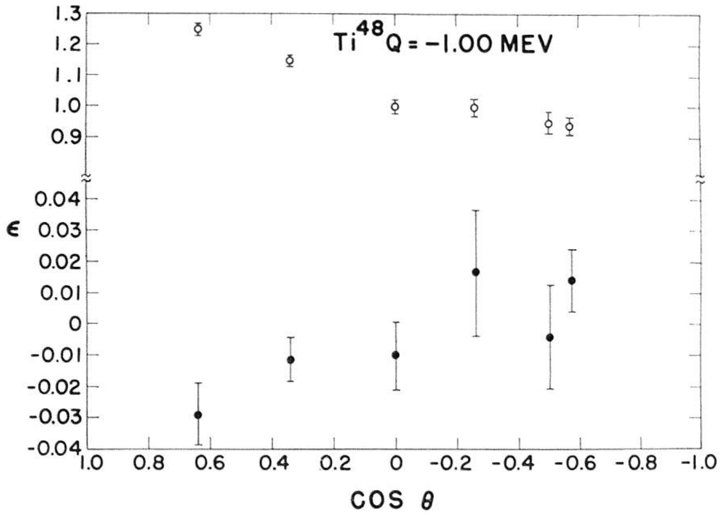


Figure 9

The chief point I want to make here is that at our energy of 2 MeV titanium and iron may be regarded as group III nuclei, that is, nuclei which exhibit marked fluctuation effects associated with the excitation of levels of the compound nucleus which do not satisfy in detail the so-called statistical assumption of the Hauser-Feshbach theory of inelastic scattering, which implies zero polarization.

We come now to the results on elastic scattering for nuclei in groups III and IV. Before giving our results at 2.09 MeV it will be useful to show a slide (figure 10) of the results of CLEMENT *et al.* at 980 keV. In this work the sign of the polarization convention is not the Basel one, and for comparison with the subsequent slide the sign has been reversed. Let me call your attention to the following two salient features. First, for mass numbers larger than 150 or so, the polarization is positive in the forward direction, decreases at 90°, and essentially vanishes in the back direction. Secondly, we notice a broad negative maximum in the polarization at 90° for nuclei in the neighbourhood of mass 100. This was first pointed out for 400 keV data in the paper which pioneered in this general field, namely, the paper of ADAIR, DARDEN, and FIELDS.

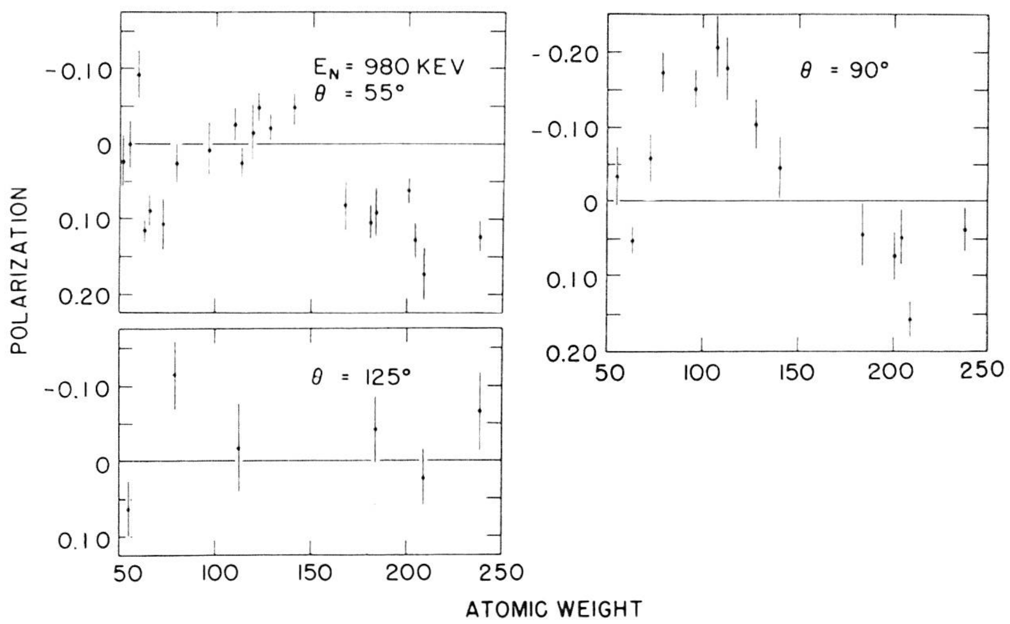
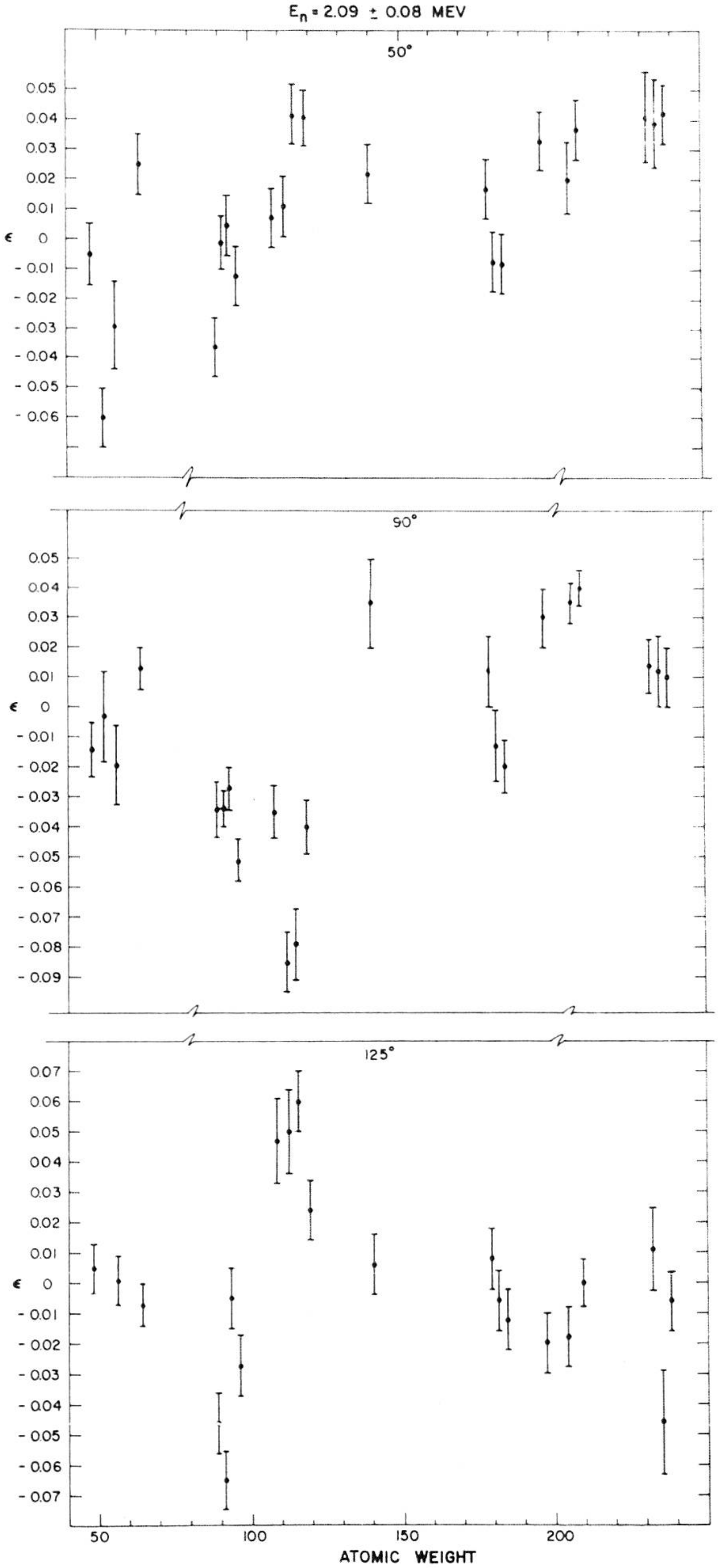


Figure 10

The next slide (figure 11) shows our recent results at 2.09 MeV for 22 nuclei of atomic weight 48 and above, for scattering angles of 50, 90, and 125°. These results do not include corrections for multiple scattering and for unresolved inelastic scattering corresponding to excitation of levels within 500 keV of the ground state, but the corrections will be small and in such a direction as not to modify any of the comments we shall make about the results.

First, we notice, as for the lower energy data, the trend toward diminishing positive polarization for the heaviest nuclei as we go toward the back direction. Secondly, we see again the broad negative maximum at 90°. A new and striking feature, however, is the sharp reversal of the direction of polarization in the back direction in the neighbourhood of mass 100. The paucity of back-angle data at the lower energy precludes



E_n = 2.09 ± 0.08 MEV
50°
0.05
0.04
0.03
0.02
0.01
ε
0
- 0.01
- 0.02
- 0.03
- 0.04
- 0.05
- 0.06
90°
0.05
0.04
0.03
0.02
0.01
ε
0
- 0.01
- 0.02
- 0.03
- 0.04
- 0.05
- 0.06
- 0.07
- 0.08
- 0.09
125°
0.07
0.06
0.05
0.04
0.03
0.02
0.01
ε
0
- 0.01
- 0.02
- 0.03
- 0.04
- 0.05
- 0.06
- 0.07
50
100
150
200
ATOMIC WEIGHT

Figure 11

any statement as to whether this effect may not in fact be present also at lower energies.

In sum we see now a pattern of smooth variation among what we feel entitled to call group IV nuclei, with respect both to mass number and energy over a fairly wide range. This result encourages the belief that an optical model fitting of these data can be accomplished. JOHN WILLS at Los Alamos is undertaking to do this. I regret that there are no results to report on this endeavour as yet, but the new data reported here are only a few weeks old. Hopefully, at our higher energy the role of compound elastic scattering, whose evaluation plays a troublesome role in an optical model fitting, is substantially less than in the earlier data taken at lower energy.

It is worth pointing out that it was expected that the reduction of compound elastic scattering would give us substantially higher polarizations than have been observed at lower energies. In this hope we have been somewhat disappointed. The maximum polarization observed of about 27% is not much larger than the maximum of about 20% reported by CLEMENT *et al.* although our expectation of increased polarization has been confirmed.

One special point of interest in these data concerns four adjacent nuclei in the neighbourhood of mass 100, namely, Ag, Cd, In, and Sn. In each of these cases the sign of the polarization changes twice as one goes from 50° to 125°, indium being the most striking case because of the large (greater than 20%) effects observed at each angle. According to the maximum complexity rules of SIMON and WELTON this result implies that there must be a strong contribution of partial waves of l equals 2 or more to the scattering. On the other hand CLEMENT *et al.* have ascribed the structure in the neighbourhood of mass 100 to the effect of splitting of a giant p-wave resonance in this mass interval. The persistence of this structure over a factor of more than 4 in energy, and the clear evidence now that d-waves or higher are important at mass 100 at 2 MeV suggests that another interpretation may be required for a systematic description of the mass 100 effect.

Previous speakers have referred to considerations due to RODBERG which suggest that the polarization in elastic scattering should follow the derivative of the differential scattering cross section. There are too few of the latter data available at 2 MeV to be useful for a check of this matter.

A final point concerns the group III nuclei. In figure 11 the three lightest nuclei shown are titanium, chromium, and iron. At 50° Cr stands out with a polarization of 18%, while the result for the others is small or negligible at all angles. It is tempting to interpret this result as part of the pattern exhibited in the inelastic scattering and in the data reported earlier at this conference by FERGUSON on elastic scattering at 1.6 MeV and below for similar nuclides. Since few levels are being excited in the residual nucleus, compound elastic scattering is probably strong; and since the level density in the compound nucleus is inadequate to satisfy the statistical assumption of HAUSER and FESHBACH, we are justified in expecting an erratic pattern of polarization effects in the compound elastic scattering.

One would hope for the future that a polarization investigation might be carried out at 4 MeV where BJORKLUND and FERNBACH have had such gratifying success in fitting total and differential scattering cross section data. Such a study will be enormously facilitated by the advent of the improvements in millimicrosecond neutron spectroscopy alluded to earlier.

In conclusion I should like to acknowledge with special thanks the stimulating effect of a visit with Professor HUBER here in Basel in 1952 which directed my interest toward polarization studies.

REFERENCE

[1] L. CRANBERG, Phys. Rev. *114*, 174 (1959).