MEASUREMENTS OF (p,α) REACTIONS ON SOME LIGHT NUCLEI AND THE THEORY OF THREE NUCLEON TRANSFER REACTIONS

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ABSTRACT

Some (p,α) reactions on light nucleus targets have been studied by the measurement of the differential cross section. A standard method using one counter and also a telescope system for the measurement and identification of the alpha particles is described. The DWBA with local energy approximation is developed and used to analyze the experimental data. A method for the calculation of the theoretical triton pickup spectroscopic factor is described in detail and the comparison between experimental and theoretical values is made. The absolute differential cross section for the reaction $^{19}F(p,\alpha)^{16}O$ is reproduced. There is evidence for the need of a process other than a direct triton pickup in order to explain the backward peaking in the angular distribution of the reaction $^{12}C(p,\alpha)^{9}B$ over a range of beam energies. The angular distribution of this reaction is however fitted rather well except for such a backward peak. For $^{7}Li(p,\alpha)^{4}He$, the shape in the angular distribution is reproduced fairly well by considering the symmetrization of the two alpha particles in the exit channel.

A systematic way of using the DWBA method and the validity of the local energy approximation by means of a square-well are mentioned. It seems to be possible to predict the partial cross section of a (p,α) reaction at

different beam energies by normalizing the theoretical value at one energy.

CHAPTER 1

INTRODUCTION

Since the first artificial nuclear transmutation was successful in 1932,[1] the (p,α) reaction has been continuously carried out to study different nuclei. The energy of the bombarding protons has also been increasing from 100 kev order upward. In fact, one may say that the story for the variation of the bombarding particle energy is synonymous with the development of the particle accelerators.

The accumulated results at lower energies have been studied rather extensively, but there have not been too many data at the 40 to 50 Mev region for (p,α) reactions. It was therefore our intention to extend the measurement for these reactions into this energy region and to study and understand the properties of the nuclear reaction mechanism.

Historically, dispersion theory was first developed to explain the experimental aspects of angular distributions in the early days by considering one- or several-level resonant process. However, when the energy was increased to several Mev, the angular distributions were in general highly asymmetric, and were either backward-peaked or forward-peaked or both. The pure compound nucleus process could not explain these results satisfactorily. This was at the time when the direct reaction mechanism was being developed and had explained some (d,p) and (p,d) reactions rather successfully. In a similar way, the triton pickup was naturally assumed for a (p,α) reaction and did in fact explain some experimental results rather reasonably. The further step was tried ofignoring the compound nucleus formalism and introducing different modes into the direct reaction scheme. By varying the mixing percentage of the contribution of each mode it was possible to account for the backward peaking. This did not, however, have much physical reality since it is very difficult to think of a direct reaction that depends on the bombarding energy very sensitively. It was then suggested that at some energy range, say, 10 Mev, both the compound and direct processes could be comparable. It might be that the coherence among the several different processes could provide an explanation and interpretation of the experimental results. But such calculations would be rather difficult and ambiguous. So far, there has not been a successful theory to combine these two reaction mechanisms in a useful way.

At higher energies, as in our case, the direct reaction should be predominant. The physical situation is therefore much simplified and the direct nuclear reaction should be logical to describe the experimental results. Thus, the remaining question is how can one select a particular mode out of several possible processes within the direct reaction scheme, and still guarantee that one is doing a right thing. One could, in principle, include all possible modes simultaneously, but the actual calculation would be terribly complicated even with the fast electronic computer. In fact, there is no complete theory for this situation yet. The latest mode of direct reaction so-called DWBA, can only handle one process at a time, generally the stripping or pickup process. Until such time as each of the direct reaction modes has been calculated in this energy range, the situation is not clear, and any choice is somewhat subjective. There is some evidence that the amplitude for triton pickup decreases less as the energy is raised than the other processes, so that it may be the main one to survive at our energies.

We will therefore develop a triton pickup theory for (p,α) reactions and attempt to analyze some experimental results. For this purpose, three reactions were investigated, each of which has its own particular physical structure. These are $^{19}F(p,\alpha)^{16}O$, $^{12}C(p,\alpha)^{9}B$ and $^{7}Li(p,\alpha)^{4}He$. The first reaction should favor a triton pickup; the second reaction should have some contribution of heavy particle stripping since ^{12}C is a well-known α-nucleus. For the third one, both the pickup and heavy particle stripping make an equal contribution due to the indistinguishability of the two outgoing alpha particles.

Chapter 2 will describe the experimental method and the instrumentation. The experimental results are summarized in Chapter 3. The direct reaction theory using a triton pickup process is developed in Chapter 4. Chapter 5 will give the interpretation and analysis of the experimental results. Finally, a concluding remark is reserved for Chapter 6.

CHAPTER 2

EXPERIMENTAL INSTRUMENTATION AND TECHNIQUE

2.1 Detection and Discrimination of Alpha Particles.

When a proton beam bombards a target nucleus, in addition to the elastically scattered protons, any nuclear reactions can be induced as long as the physical conservation laws hold and no selection rules are violated.

Thus for a standard experiment, one has to be able to discriminate the alpha particles, for example, from all other particles before the energy spectrum at a particular angle is measured. The detection of alpha particles will be described first and then followed by the technique for discrimination of different particles.

2.1-A Detector

The alpha particles from the (p,α) reactions were registered by some suitable semiconductor counters. Both lithium drift and surface barrier silicon detectors were used. In addition, several thin or transmission detectors of different thickness were also used in the later part of our experiments for the purpose of particle identification.

The lithium drift detectors* used in our experiments

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* Manufactured by SIMTEC.

had a depletion depth of 1 mm, sensitive area of 100 mm^2 and window thickness of 0.2 micron. The collection time was 100 nanosecond or less. The resolution was about 60 kev for 5.5 Mev alpha particles.

Since the surface barrier detectors were found more convenient to use, several silicon detectors* of 150 and 400 microns occasionally replaced the lithium drift detectors at the backward angles where the alpha particles had lower energy than at the forward angles. The advantages of the surface barrier detectors are: a) no cooling is required, b) better resolution and c) thinner window thickness, which is especially important for the alpha particles when their energy is relatively small so that the energy loss through the window thickness becomes serious.

The surface barrier silicon detector of 150 microns mentioned above was also used as a thin detector when the particle identifier was used. In addition to this, we also used a 30-micron transmission detector obtained from Jugoslavia.**

Finally, a silicon detector*** of thickness 600 microns was used as a monitor for calibrating the absolute differential cross section.

It should be pointed out here the difficulties we had with the lithium drift detectors.

1) <u>Thermal Effect:</u> Although the manufacturer

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* Purchased from ORTEC.

** Institute of Nuclear Science, Boris Kidrich.

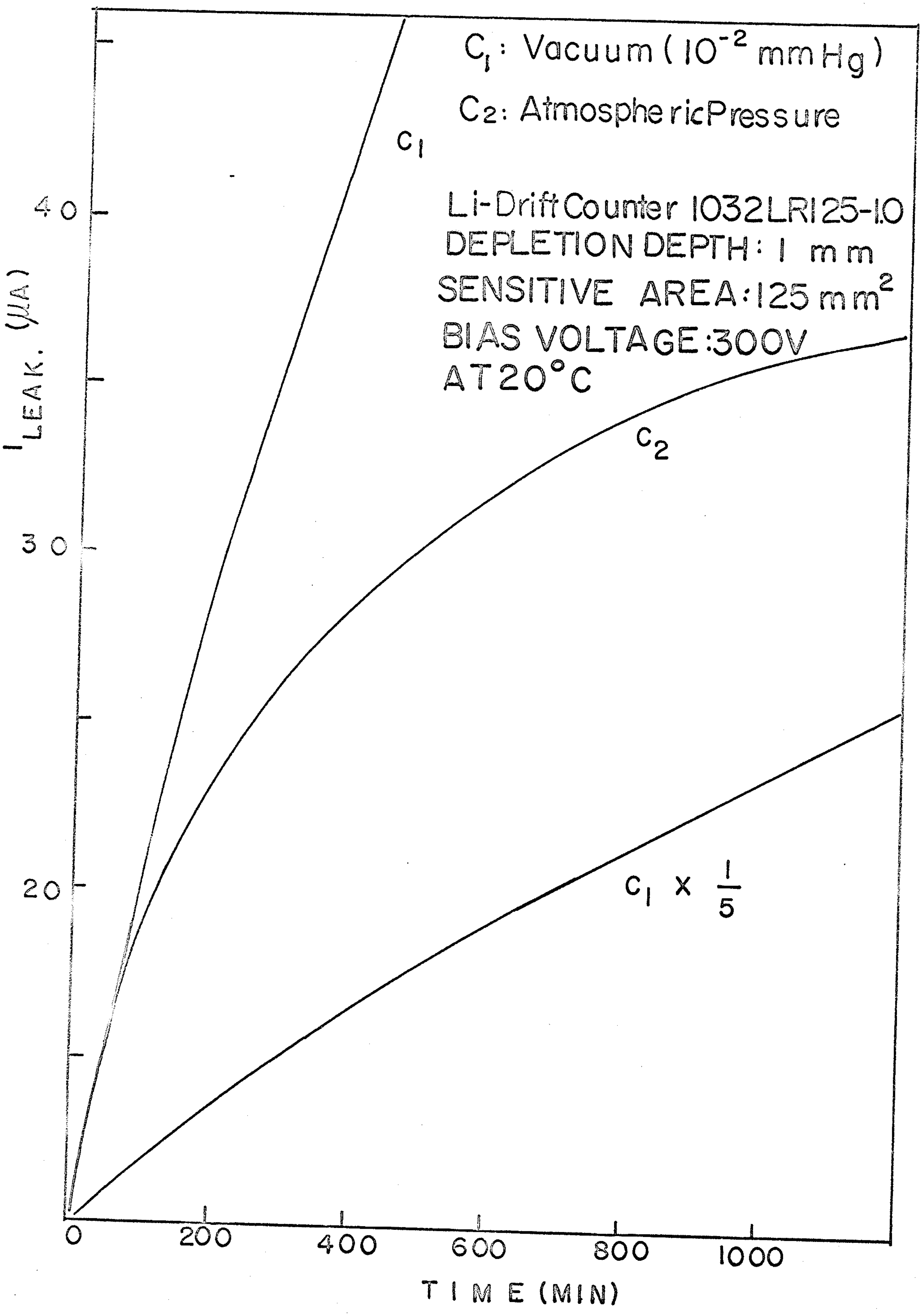
***RCA standard semiconductor diode.

recommended that the lithium drift detectors could be operated at room temperature indefinitely, we found out that the leakage current increased with biasing time, and depended on the pressure at which the counter was operating. A typical result is shown in Figure 2.1. The leakage current increases almost linearly with time when biased in a vacuum of about 10^{-2} mm Hg, but tails off at atmospheric pressure. This effect may therefore be accounted for by the accumulation of Joule heat developed by the small yet sizable leakage current.

Since the noise of a diode varies with the square root of the leakage current, one has to make it as small as possible to obtain better resolution. We used, therefore, a thermo-electric cooling device to reduce the temperature from room temperature to about $-10^{\circ}C$. The current was found smaller by a factor of 10 and had a better time stability than that without cooling. The arrangement for such a device is shown schematically in Figure 2.2. The counter was mounted inside a copper holder which was thermally connected to the cold side of a thermo-electric cooler to keep the detector temperature as low as possible. A close fitting teflon ring was used to locate the counter in a geometrically defined position. A circular opening of diameter of 0.18 inch at the center of the front side facing the target defined the solid angle subtended by the detector as seen from the target. In this way the counter was also shielded from picking up the stray r.f. generated by the cyclotron.

Figure 2.1

Li-drift detector leakage current measurement. The curve C_1 represents the leakage current variation of time in a vacuum of 10^{-2} mm Hg and curve C_2 is the result obtained at atmospheric pressure.


C1: Vacuum (10^{-2} mmHg)
C2: Atmospheric Pressure
Li-Drift Counter 1032LR125-1.0
DEPLETION DEPTH: 1 mm
SENSITIVE AREA: 125 mm^2
BIAS VOLTAGE: 300V
AT 20°C
C_1
C_2
$C_1 \times \frac{1}{5}$
$I_{LEAK.}$ (μA)
40
30
20
0
200
400
600
800
1000
TIME (MIN)

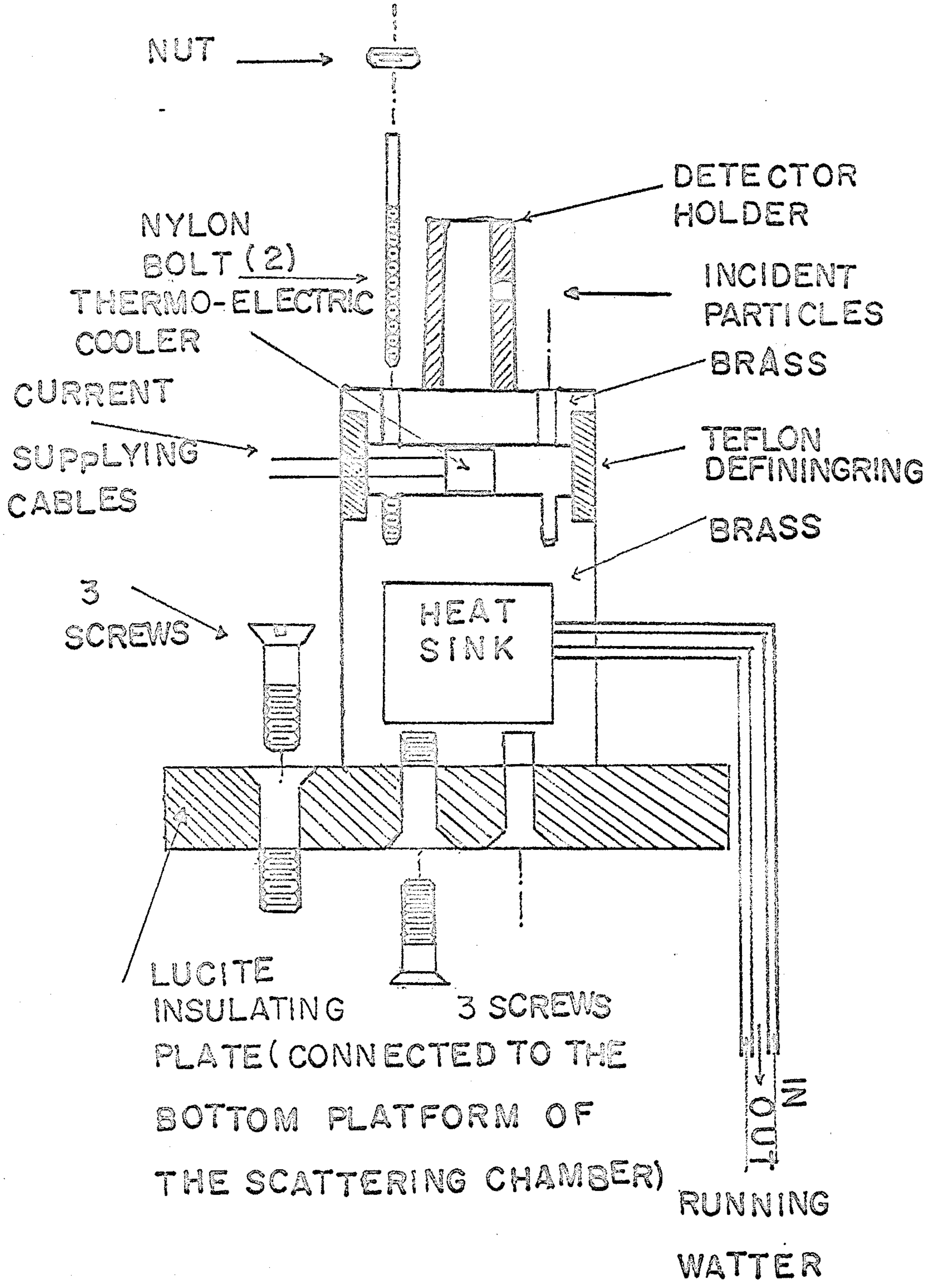


FIGURE 2.2 SCHEMATIC DIAGRAM FOR THE THERMO-ELECTRIC COOLING SYSTEM

2) Radiation Deterioration: When the lithium drift detector was still new, it could be run through one measurement without any noticeable deterioration. However, after having been exposed to radiation for some time, a defect of the counter was observed when it had been continuously biased for several hours in a particular measurement. The resolution became worse than at the beginning of the run and was found to be mainly due to the increased window thickness of the detector. This effect was particularly apparent when the detector was left unbiased overnight or for a longer period of time. The thickness could be reduced by increasing the bias voltage. However, this would correspondingly increase the leakage current which made the resolution of the detector worse. For a total exposure to the flux of protons of about 2.3×10^8 cm^{-2}, the window became so thick that the 5.5 Mev alpha particles were unable to penetrate it.

An attempt was made to rediffuse the lithium ions by warming the counter at 100°C for 24 hours, according to the suggestion of the manufacturer. But no improvement was obtained. Thus we thought that the lithium drift detector should be biased continuously after being exposed to a certain amount of radiation.[2,3]

A difficulty for the surface barrier detectors was also observed. In this case the counters became suddenly open circuited without noticeable dead layer or leakage current increasing. This effect might also be caused by radiation damage as was believed for the lithium drift detector, but it was more likely to be mechanical damage due to the repeated evacuation of the scattering chamber and mechanical handling.

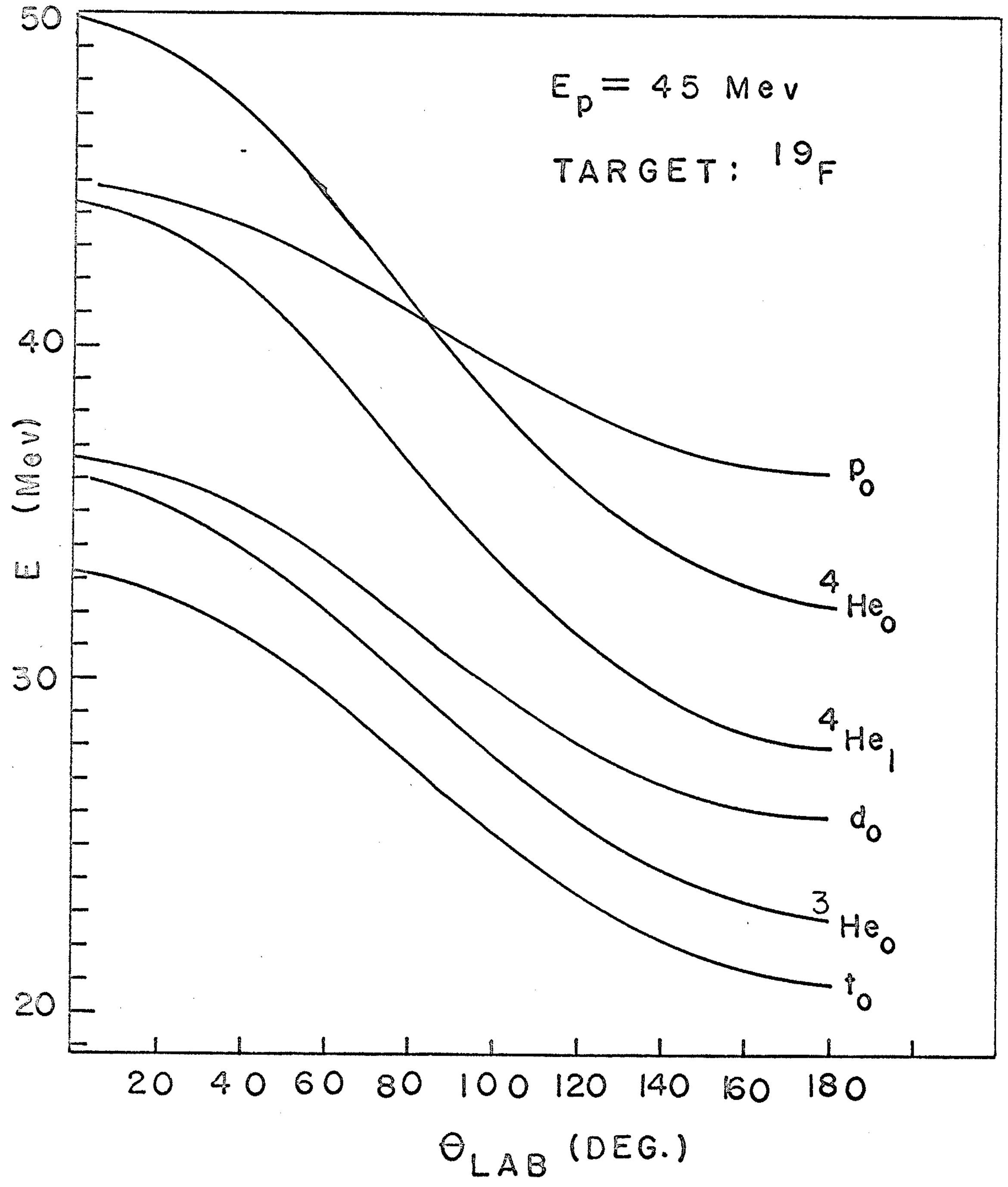
2.1-B. Discrimination of Alpha Particles.

1) One-counter system.

The Q-values of (p,α) reactions from the targets of light nuclei are in general larger than that of $(p,{}^3He)$ by about 10 Mev or more. This can be seen from Figures 2.3a, 2.3b and 2.3c, where the kinetic energies of the elastically scattered protons, the d_o, t_o, ${}^3He_o$, α_o and α_1 from the reactions induced by 45 Mev protons in targets of ${}^{19}F$, ${}^{12}C$ and ${}^7Li$ are shown for comparison. The curves were calculated by a two-body kinematics program written foran IBM 1620 computer and then later run on an IBM 360/65 computer. Appendix 2A will give the complete reprint of this program. The subscripts 0 and 1 in Figures 2.3 represent the ground state and the first excited state, respectively. It is clear that the ground state group of the alpha particles has larger kinetic energy than that of all ${}^3He$ at all angles but it is overlapped by some charge-one particles. However, these can be eliminated by using a detector that is thick enough to stop all alpha particles (and hence all ${}^3He$ in our case) but sufficiently thin so that most of the energetic charge-one particles can get through without losing all their kinetic energy. Thus, for example, when a 1 mm silicon detector

Figure 2.3a

Kinetic energies of lighter products in proton induced reactions from ^{19}F.



$E_p = 45$ Mev
TARGET: ^{19}F
50
40
30
20
E (Mev)
20
40
60
80
100
120
140
160
180
Θ_{LAB} (DEG.)
p_0
$^4He_0$
$^4He_1$
d_0
$^3He_0$
t_0

Figure 2.3b

Kinetic Energies of lighter products in proton induced reactions from ^{12}C.

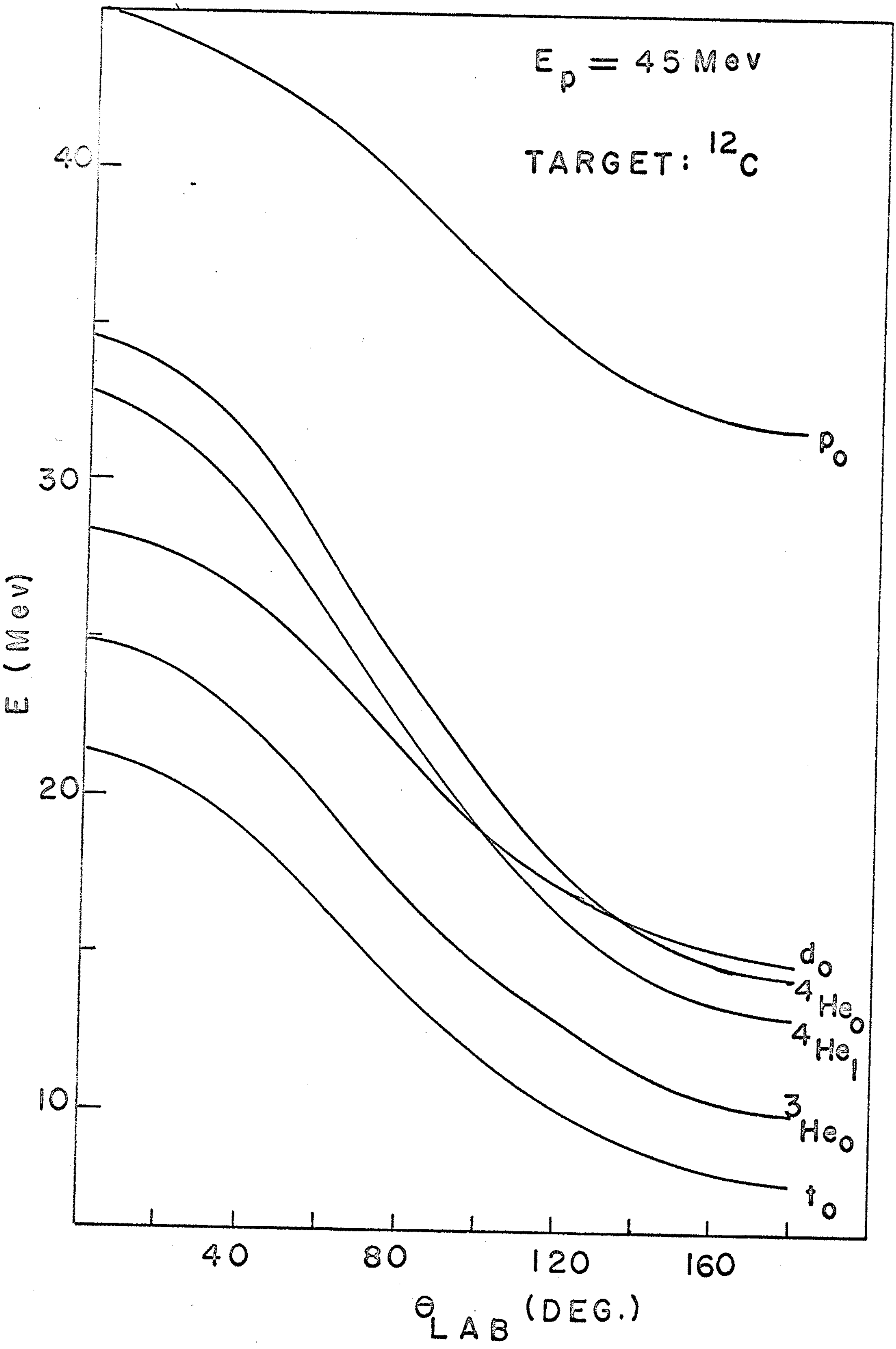

$E_p = 45$ Mev
TARGET: ^{12}C
40
30
20
10
E (Mev)
40
80
120
160
θ_{LAB} (DEG.)
p_0
d_0
$^4He_0$
$^4He_1$
$^3He_0$
t_0

Figure 2.3c

Kinetic energies of lighter products in proton induced reactions from ^{7}Li. Ground state group of alpha from $^{16}O(p,\alpha)$ is also shown.