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Comments on (n, charged particle) Reactions at E_n = 14 MeV

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COMMENTS ON (N,CHARGED PARTICLE) REACTIONS AT E_n = 14 MEV

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ABSTRACT

The study of charged particles produced by bombarding materials with 14 MeV neutrons is important for the development of fusion reactors and for biomedical applications as well as for the basic understanding of nuclear reactions. Several experimental techniques for investigating these reactions are discussed here. The interpretation of the data requires the consideration of several possible reaction mechanisms including equilibrium and preequilibrium particle emission and, for light nuclei, sequential particle emission, final state interactions, and the effect of resonances.

I. INTRODUCTION

By the term "(n,charged particle) reaction" we mean those reactions of neutrons with nuclei that result in light charged particles, namely protons, deuterons, tritons, ^{3}He and ^{4}He. For 14 MeV neutrons incident on typical target nuclides, several of these reaction channels are possible. For example, the ^{56}Fe (n,charged particle) reactions at 14 MeV include the (n,p), (n,n'p), (n,d), and (n, alpha) reactions, each with significant cross sections, and the (n,t) and (n,^{3}He) reactions with smaller cross sections. The emitted charged particles have energies from about 1 to 14 MeV. Thus it is expected that the required measurement techniques, the theoretical analyses, and the effects in applications are broad-ranging.

Although these reactions have been investigated for many years, experimental data of high quality are not abundant. The reason is that the experiments are difficult due to low neutron source strengths (even for present-day sources), the short range of the charged particles in matter, and the difficulty of shielding the charged-particle detector from the source neutrons and other background radiation. To obtain data of acceptable quality, most experiments have been optimized so that only one type of charged particle is detected and only a portion of the charged-particle energy spectrum (usually the high end) is measured. Thus even where reasonably good data exist, they are usually incomplete in the energy range of the charged particles and in the particle type.

The present report is not intended to be a comprehensive review of (n,charged particle) reactions. Instead it is a commentary on some facets that are of current interest. Selected experimental methods are listed to point the reader to certain approaches considered successful by the author. The types of physics issues that are crucial to an understanding of the data are discussed.

II. EXPERIMENTAL METHODS

The methods of investigating (n,charged particle) reactions may be grouped into two classes: those that employ the detector material itself as the target and the more general techniques where the target and detector are separate entities. This distinction is useful to indicate which approaches are especially suited to low intensity neutron sources (the former) and which require higher neutron fluxes (the latter).

A. Target = Detector

Because of the short range in matter of charged particles with energies of interest here (about 1 to 20 MeV), a significant increase in the counting rate can be made if the target is not required to be a thin foil from which the charged particles escape but rather a much thicker sample where the particles can be detected internally. Photographic emulsions, scintillators, cloud chambers, and semiconductor detectors have been used as these thicker samples. Of course the materials that can be investigated are those that are major constituents of the detectors or those that can be heavily loaded into them.

Photographic emulsions have many advantages when used as a target-detector combination. They have no dead-time, they allow investigations of many-body decays in kinematically complete experiments, they can be used with broad-spectrum neutron sources in selected experiments, and they are simple yet well characterized, having been used for decades. Of particular note are the experiments on the $^{12}C(n,n')3$ alpha reaction, both old[1] and new.[2] The difficulties of using emulsions include the problems of measuring short tracks (particles of low energy), of kinematically confusing events where two particles have nearly identical directions, and of reactions on other elements in the emulsion. Proton recoils from n-p elastic scattering, for example, are an unavoidable background. If the element to be studied is not a major component of the emulsion, then it may be difficult to load the emulsion with enough of the element to obtain a good signal-to-background ratio.

Scintillators have been used in the study of (n,charged particle) reactions on $^{6,7}Li$, Na, CsI and other materials. Innovative experiments by Bartle[3-5] showed that not only is it possible to measure the energy spectra of the out-going charged particles, but one can in favorable cases also deduce the angular distribution.

Cloud chambers were used many years ago in the study of (n,alpha) reactions on oxygen, nitrogen, and argon.[6] To the author's knowledge no further work is being done with this technique. The time required to analyze the data from many photographs has deterred further experiments of this type.

Semiconductor detectors have been used to measure (n,alpha) and (n,p) reactions on silicon for example.[7] Because of the good resolution available in such detectors, it is possible to resolve individual states populated in the residual nucleus. The recoiling nucleus does carry away some energy and the resolution is consequently worsened. Certain tricks, such as the use of two detectors in coincidence, help overcome this problem.

For all of these approaches where the pulse-time can be recorded (e.g. all except the emulsions and cloud chambers), a coincidence may be made with a pulsed beam or with an associated particle from the neutron source reaction. These coincidences help reduce the background from scattered neutrons, and they can be used to indicate the neutron energy.

B. Target ≠ Detector

To investigate other target nuclides, one must use an approach where the target and the detector are different entities. Many of the types of detectors mentioned above can be used, but in this case they must be shielded from the neutron source lest the (n,charged particle) reaction take place in them rather than in the target. In addition the target must be thin, for example, a thin foil so that the charged particles can escape and pass to the detector.

Data of high quality have been obtained using photographic emulsions as detectors (e.g. Ref. 8) and individual counter telescopes (e.g. Refs. 9). A recent innovative approach to measuring the complete angular distribution of the emitted charged particles has recently been reported.[10]

To improve the signal-to-background ratio in these experiments, three laboratories have developed charged-particle transport schemes to conduct the charged-particle reaction products from the target foil to detectors far away that can be shielded well from the background radiation.[11-14] Most of these schemes use magnetic quadrupole lenses to focus the charged particles, but not the background neutrons and gamma rays, onto energy-sensitive detectors (Fig. 1). Electrostatic transport is also possible.[12] These transport approaches reduce the background typically by two orders of magnitude and thereby allow the detection, reliably, of charged particles with energies as low as 1 MeV.

III. PHYSICS ISSUES

A rich variety of physical effects have been inferred from (n,charged particle) data at 14 MeV neutron energy. To interpret future data the relative strengths of each of these contributions must be quantified.

For targets of very light nuclei, the reaction mechanism in many cases is not obvious from the charged particle emission data. For example, the alpha-particle emission spectrum from the $^{12}C(n,n')$ 3 alpha reaction has been used to infer a 3-body breakup, 4-body breakup, or sequential two-body break-up. In addition, final state interactions may be important in the multi-body breakup channels. Finally, resonances in the incident channel may confuse the interpretation of the energy dependence of the data, unless data points at many energies are obtained.

For heavier nuclei, say in the range of $20 < A < 70$, the charge-particle emission is dominated by compound nuclear, statistical evaporation. The competition between neutron and charged-particle emission is crucial here, and thus one needs reliable level densities and transmission coefficients derived from the optical model. The energies and spins of low-lying levels can also be important when only a few channels are open for charged-particle emission. In cases where the neutron emission is energetically impossible, one may also require information on the competing gamma-ray decay widths. In many cases, a Hauser-Feshbach calculation that uses state-of-the-art parameters can reproduce the compound-statistical emission (e.g. Ref. 15, see Fig. 2).

Precompound emission of charged particles is evident in some cases near mass 60 and becomes more obvious for heavier nuclides where the compound-statistical contribution is less. With the hybrid formulation of Blann,[16] some of the pre-compound emission data are well described[15] (see Fig. 2) whereas in the molybdenum isotopes significant discrepancies remain between experiment and calculation (Fig. 3).[17] Because the cross sections for (n,charged particle) reactions generally decrease with increasing target mass, measurement of targets heavier than molybdenum is difficult and only a few groups have attempted such work. Yet with these heavier targets, the ratio of precompound to compound charged-particle emission increases and thus such studies are of great importance in understanding the precompound mechanism.

Direct (n,charged particle) reactions have been studied at 14 MeV in relatively light nuclides (e.g. in the 2s-1d shell and 1-p shell). Charged-particle-induced reaction studies have for many years indicated that the reaction mechanism is complicated at these energies by the contributions of compound mechanisms, multi-step processes, and severe distortion by coulomb effects and the nuclear optical potential. Thus one may prefer to go to higher energies to enhance the direct effects. In any case, for targets of medium and heavy nuclides, the level density in the residual nuclide is often so high that very few states can be separated with the available experimental resolution (150 keV would be considered very good). Thus it is unlikely that much more work will be carried out soon in this area of reaction studies with 14 MeV neutrons. Certain questions, for example of M1 strength, can be in principle be tackled best by (n,p) investigations, but again the higher incident energy is preferred.

IV. SUMMARY

Recent developments in experimental techniques are being used to obtain data of much improved quality for (n,charged particle) reactions at 14 MeV. The new data put nuclear reaction models to more stringent tests. In particular our understanding of the compound-statistical model and of precompound particle emission is increasing as a result of these new comparisons between theory and experiment. This increased understanding leads to increased confidence in the data, provided by a combination of experiment and theory, for applications such as in fusion reactor development and medicine.

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FIGURE CAPTIONS

1. Two methods of studying (n,charged particle) reactions: (a) Traditional method; (b) Newly developed method employing a magnetic quadrupoles for transporting the charged particles from their point of production (the target foil) to detectors located in a region of low background.

2. Alpha-particle emission spectra compared with Hauser-Feshbach calculations.

3. Upper end of the proton emission spectra for mass $\cong$ 60 targets compared with Hauser-Feshbach calculations (dashed curves) and preequilibrium calculations according to the hybrid model (dot-dashed curves). The sums of the model calculations are given by the solid curves.

4. Proton emission spectra for mass $\cong$ 90 targets compared with multi-step Hauser-Feshbach (dashed curves) and hybrid-model (dot-dashed curves) calculations. The sums of the calculations are given by the solid curves.

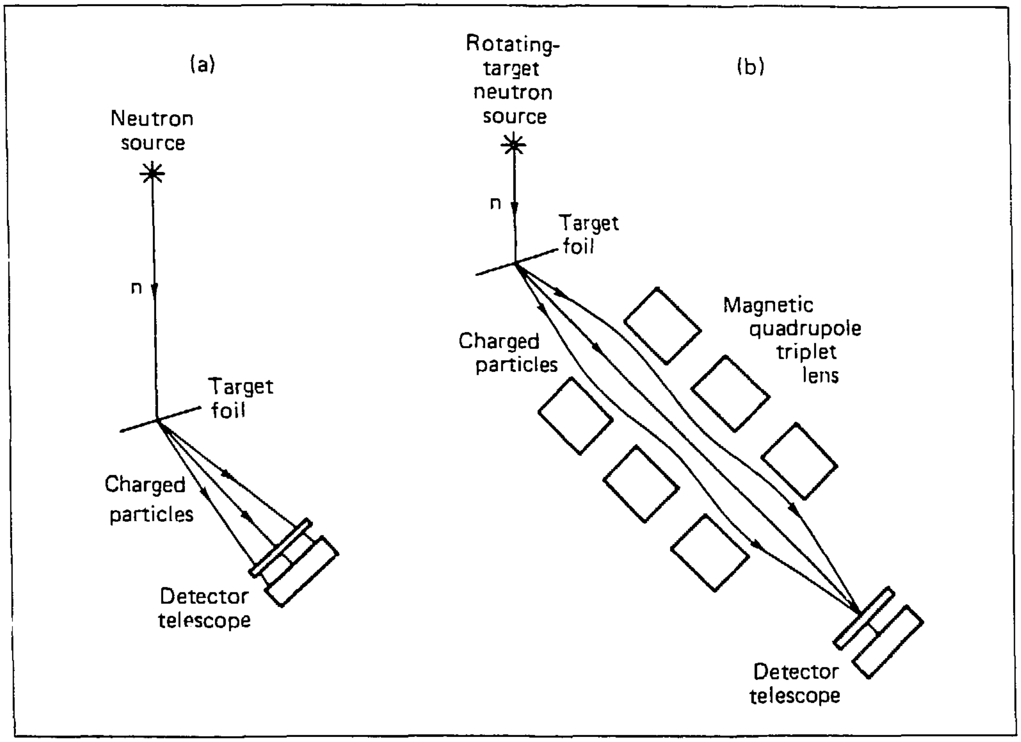
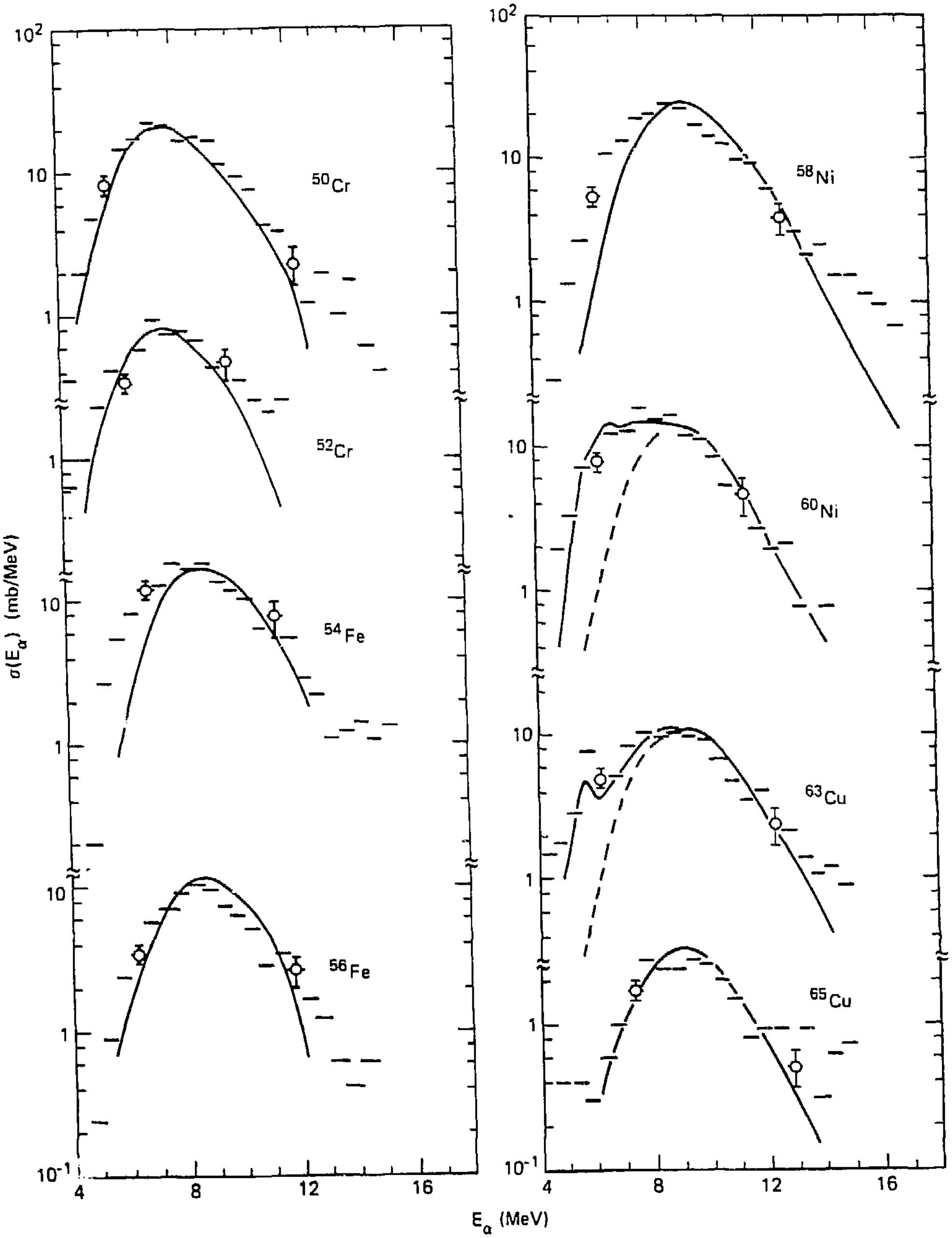
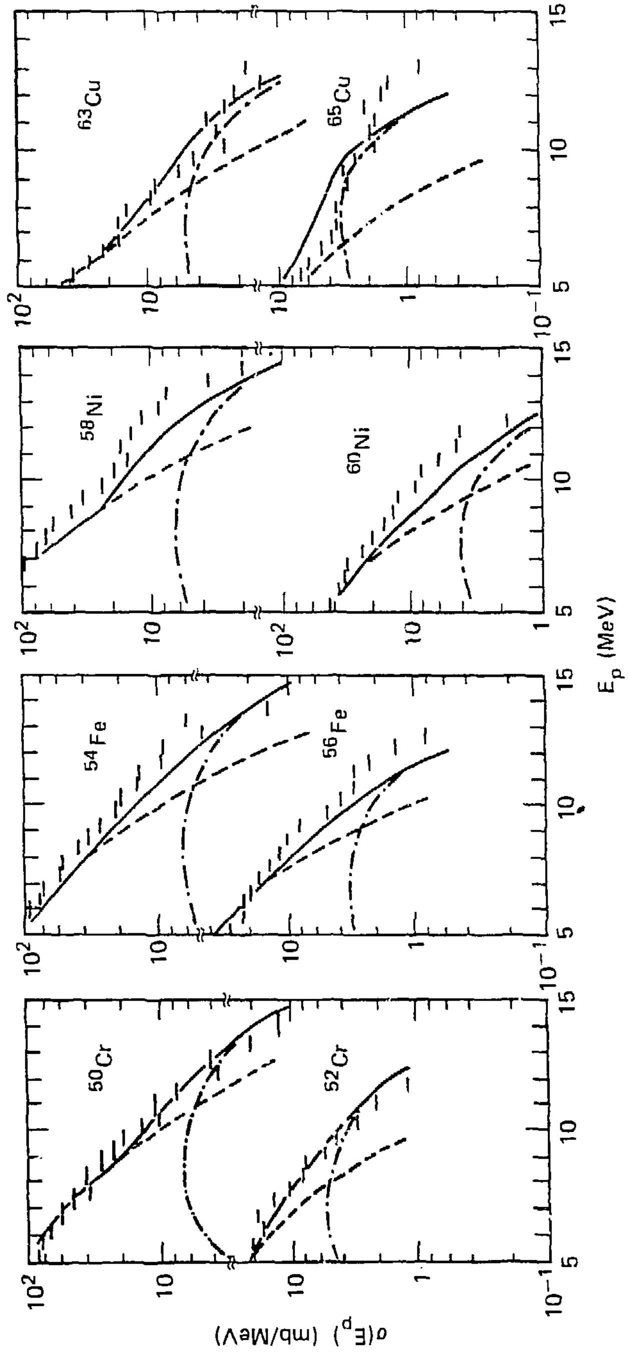

(a)
Neutron
source
n
Target
foil
Charged
particles
Detector
telescope
Rotating-
target
neutron
source
(b)
n
Target
foil
Magnetic
quadrupole
triplet
lens
Charged
particles
Detector
telescope

Figure 1



10^2
10
1
1
10
1
10
1
10^{-1}
^{50}Cr
^{52}Cr
^{54}Fe
^{56}Fe
10^2
10
1
10
1
10
1
1
10^{-1}
^{58}Ni
^{60}Ni
^{63}Cu
^{65}Cu
$\sigma(E_\alpha)$ (mb/MeV)
4
8
12
16
4
8
12
16
E_α (MeV)

Figure 2



^{50}Cr
^{52}Cr
^{54}Fe
^{56}Fe
^{58}Ni
^{60}Ni
^{63}Cu
^{65}Cu
10^2
10
10
1
10^{-1}
10^2
1
5
10
15
E_p (MeV)
σ(E_p) (mb/MeV)

Figure 3

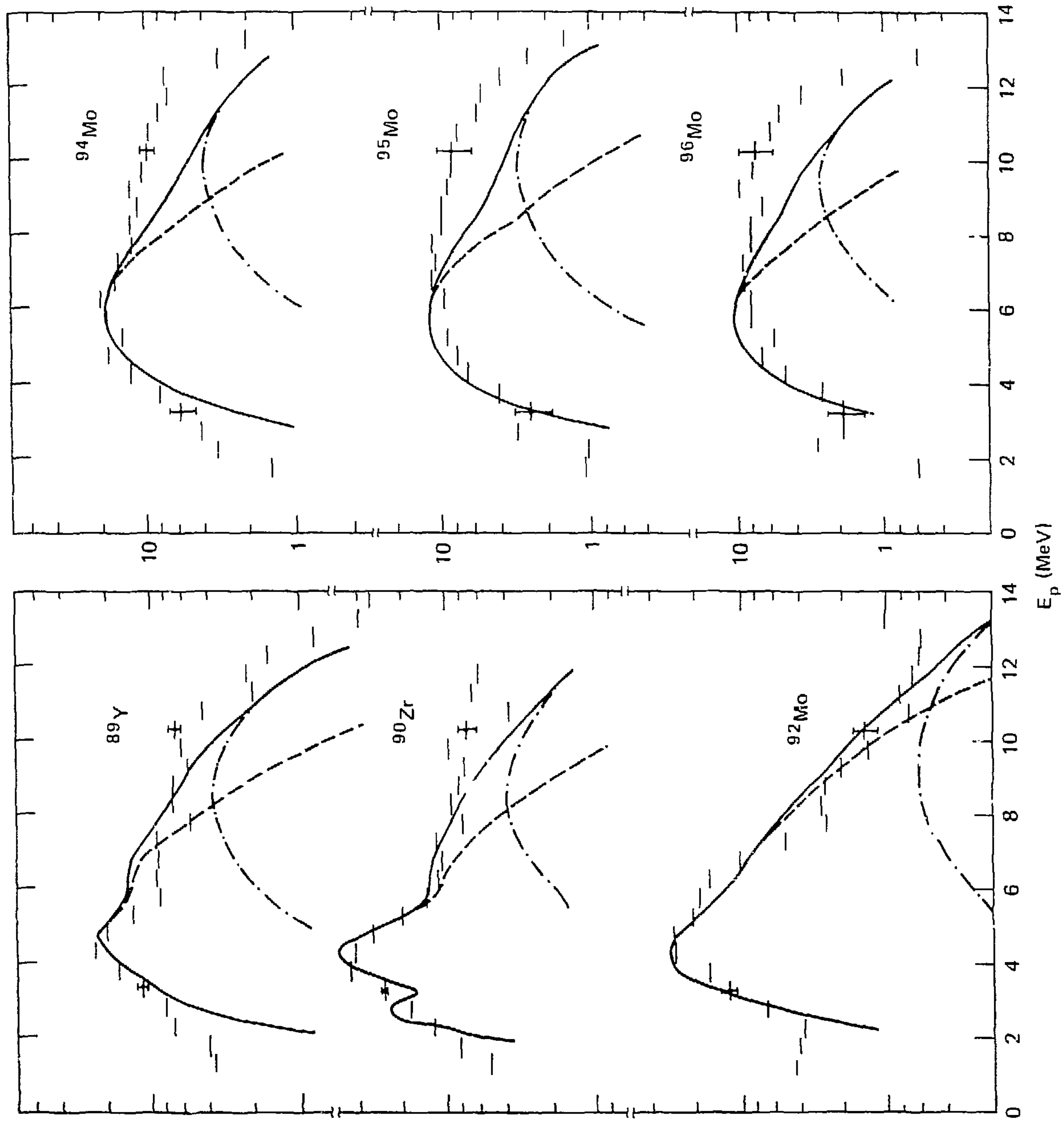

89Y
90Zr
92Mo
94Mo
95Mo
96Mo
σ (n, p)(mb · MeV⁻¹)
10
1
10
1
100
10
5
10
1
10
1
10
1
0
2
4
6
8
10
12
14
E_p (MeV)

Figure 4