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An Update on Measurements of Helium-Production Reactions with a Spallation Neutron Source

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ABSTRACT

This report gives the status, updated since the last Research Coordination Meeting, of alpha-particle production cross sections, emission spectra and angular distributions which we are measuring at the spallation source of fast neutrons at the Los Alamos Meson Physics Facility (LAMPF). Detectors at angles of 30, 60, 90 and 135^{o} are used to identify alpha particles, measure their energy spectra, and indicate the time-of-flight, and hence the energy, of the neutrons inducing the reaction. The useful neutron energy ranges from less than 1 MeV to approximately 50 MeV for the present experimental setup. Targets under study at present include C, N, O, ^{27}Al, Si, ^{51}V, ^{56}Fe, ^{59}Co, ^{58,60}Ni, ^{89}Y and ^{93}Nb. Data for ^{59}Co have been re-analyzed. The results illustrate the capabilities of the approach, agreement with literature values, and comparisons with nuclear reaction model calculations.

I. Introduction

Neutron-induced reactions that result in alpha particles, so-called (n,xalpha) reactions, are of importance in terms of the energy transferred to charged particles, the highly ionizing character (high linear energy transfer or LET) of the emitted alpha particles, and the production of helium. Radiation effects of high LET particles are attracting increased interest for biomedical applications and in studies of the response of computer components to neutrons produced by cosmic rays. In fission and fusion reactors, structural materials can be weakened by helium accumulation from nuclear reactions, and it is therefore important to know the helium production cross section to assess these radiation damage effects. To address questions in basic nuclear physics, such as nuclear reaction mechanisms, preformation probabilities of alpha particles in the nucleus, nuclear level densities, optical model parameters and isospin effects, nuclear data over a wide range of energy are essential.

The present program of investigating alpha-particle production by fast neutrons has been described previously.[1-6] The status of our work on (n,α) reactions is updated in this report. The specific example of our experiments on $^{59}Co(n,x\alpha)$ is used to illustrate the approach. Because a detailed paper on the cobalt studies[7] will soon be available, the present report will focus on the results rather than the technique.

II. Experimental Procedure

A brief description of the experimental approach is given here. Neutrons over the energy range from below 1 MeV to over 50 MeV are produced by the WNR spallation neutron source facility at the Los Alamos Meson Physics Facility (LAMPF). The source is created when the 800 MeV proton beam from LAMPF interacts with a tungsten target to produce neutrons. The 90-degree neutron production angle is chosen for these measurements because the neutron spectrum below 30 MeV is the most intense at this angle and the component above 50 MeV is small compared with that at other production angles.[6] A collimator system limits the beam dimensions at the sample position to 50 mm x 50 mm. The flight path from the source to the sample to be investigated is 9.123 m. Neutron flux is monitored with a fission chamber containing both ^{235}U and ^{238}U placed at 10.10 m from the source.[8] All cross sections are normalized to the fission cross sections of these isotopes.[9-11] Samples are placed in the center of a conventional scattering chamber. The samples are usually foils, nominally 10 cm in diameter, held by a ring that leaves a clear area 8.9 cm in diameter.

Detector telescopes with ΔE and E counters are placed at angles of 30, 60, 90 and 135^{o} with respect to the incident neutron beam direction. The ΔE counters are thin-window low pressure gas proportional counters. The E-counters are silicon surface barrier detectors, 450 mm^2 by 500 μm thick and therefore stopping to alpha particle of 33 MeV or less. Alpha particles of somewhat higher energy can be identified and separated from lower energy alpha particles to furnish data on the production cross section at neutron energies approaching 50 MeV. At energies where the maximum alpha particle energy exceeds 33 MeV, the spectral data are "folded over", with alpha-particle energies of greater than 33 MeV being registered with energies lower than 33 MeV. Spectral information at these higher neutron energies is therefore complicated and non-unique.

Angle-integrated cross sections and emission spectra are obtained by weighting the data at the detector angles by sin θ and summing. For most of the data, this procedure gives results similar to fitting by Legendre polynomials.

III. Results

We present here results of a re-analysis of the data on ^{59}Co to indicate the quality of the experimental data as well as to provide cross section information on this material which is an important constituent of alloys used in structural materials. Helium-producing reactions on this isotope have been studied near E_n = 14 MeV by detecting the alpha-particle reaction products[12,13] and by helium accumulation measurements.[14] Furthermore, there is a large body of activation data for the $^{59}Co(n,\alpha)^{56}Mn$ reaction,[15,16] and cross sections for this reaction must equal those for alpha-particle production at incident neutron energies below about 12 MeV where other alpha-particle producing channels are negligible. Thus there are several checks on the accuracy of the present results, and the present results extend the data base for helium production well above the energy range reported in the literature.

Angle-integrated energy spectra of alpha-particles are given in Figure 1 for four incident neutron energies. The data extend to approximately 22.5 MeV alpha-particle emission energy at which point the electronics saturated. Alpha particles of higher energy were detected, however and they are all lumped in the highest energy bin. At the time this experiment was carried out, we believed that the neutron flux would fall off with energy so that there would be very few alpha particles above 22 MeV. Because of the observation of alpha particles with higher energy and the demonstration that neutron energies of up to 50 MeV were useful, subsequent experiments have higher alpha-particle-energy cutoffs.

To facilitate comparisons with nuclear model codes and with previously reported data at E_n = 14 MeV,[12] alpha-particle emission spectra are reported here as functions of channel energy. The agreement of the present results with those of Ref.12 is seen to be excellent in this figure.

The total alpha-production cross section is obtained by integrating the spectra over the channel energy. Results are given in Figures 2-4 for the excitation function of $^{59}Co(n,x\alpha)$ from threshold to 50 MeV. It is seen that the production cross section increases monotonically over this energy range. Statistical errors are plotted on the figure, and they are small, ranging from ± 7% at 6 MeV where the cross section is small and the neutron energy bin is 0.5 MeV wide, to 3% above 15 MeV where the cross section is larger and the neutron energy bin is 1 MeV. Even at 40 MeV, where the cross section is relatively large but the neutron flux is lower, in a 2 MeV wide energy bin, the statistical uncertainty is less than 3%.

Angular distributions of the emitted alpha particles are given in Figure 5. Alpha particles near the evaporation peak (7-10 MeV) are seen to be emitted nearly isotropically whereas forward-peaking becomes much more noticeable at the higher emission energies.

Systematic uncertainties in these data include those that influence the overall normalization as well as those that could change the shape of the excitation function. The largest uncertainty comes from integrating the data from the detectors at four angles to obtain the angle-integrated cross section. The next most important contribution to the uncertainties is the non-uniformity of the fission deposit in the fission chamber. That distribution was mapped by thermal neutrons at the Los Alamos Omega West Reactor.

IV. Discussion

The present results for the $^{59}Co(n,\alpha)$ reaction in good agreement with the large body of activation data[15-19] where the two can be compared, namely in the region below threshold for (n,n'α) and (n,pα) reactions. The present results extend the data base for neutron-induced alpha-particle production to much higher energies than previously reported.

The present cross sections can be understood well through calculations with nuclear reaction models such as in the GNASH code. The angular distributions of emitted alpha particles are described well by Kalbach systematics.[20]

The cross section for the $^{59}Co(n,\alpha)$ reaction is seen to increase monotonically in the region from threshold to 50 MeV. The reaction mechanism throughout this energy range appears to be statistical evaporation from a compound nucleus as evidenced by the shape of the alpha-particle emission spectra and the near isotropy of the majority of the alpha particles. For the most energetic part of the alpha-particle emission spectrum at the higher incident neutron energies, there is evidence of precompound alpha-particle emission: the spectra have an excess of particles at the high energy end of the spectra and the angular distributions for this part of the spectra are forward-peaked.

This method, using a spallation neutron source, has been shown to yield reliable data with very low background. The results are in good agreement with other measurements over the energy range where comparisons are possible. The spallation source fills in regions where monoenergetic sources encounter difficulty, for example between 9 and 14 MeV and above 15 MeV. The present results show that the range from threshold to 50 MeV can be covered well with the present techniques.

V. Acknowledgments

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Figure Captions:

1. Angle-integrated alpha-particle emission spectra at four incident neutron energies. The spectra at the higher neutron energies saturated electronically, and all events greater than 22.5 MeV channel energy are lumped into the channel at 22.5 MeV.

2. Excitation function for neutron-induced alpha-particle production from cobalt from threshold to 50 MeV neutron energy. The present results are denoted as WNR. The GNASH curve is calculated by the Hauser-Feshbach plus pre-equilibrium code.

3. Same as Figure 2, but in the "ENDF region" from threshold to 20 MeV. The ENDF-curve below about 12 MeV represents a large body of activation data. Recent activation values of Mannhart et al. (Ref. 16) are also shown. Near 14 MeV, alpha-particle emission data from Fischer et al. (Ref. 12) and from Dolya et al. (Ref. 13) are given as well as helium accumulation data from Kneff et al. (Ref 14). The ENDF curve is noted to have an unphysical shape in the region above 15 MeV.

4. Threshold region of the 59Co(n,xa) cross section showing the present results in comparison with activation data from Refs. 15-19 together with the ENDF evaluation and the GNASH calculation.

5. Angular distributions of alpha-particles emitted from cobalt grouped in regions of alpha-particle energy (channel energy) and incident neutron energy. The curves are from systematics as given by Kalbach (Ref. 20).

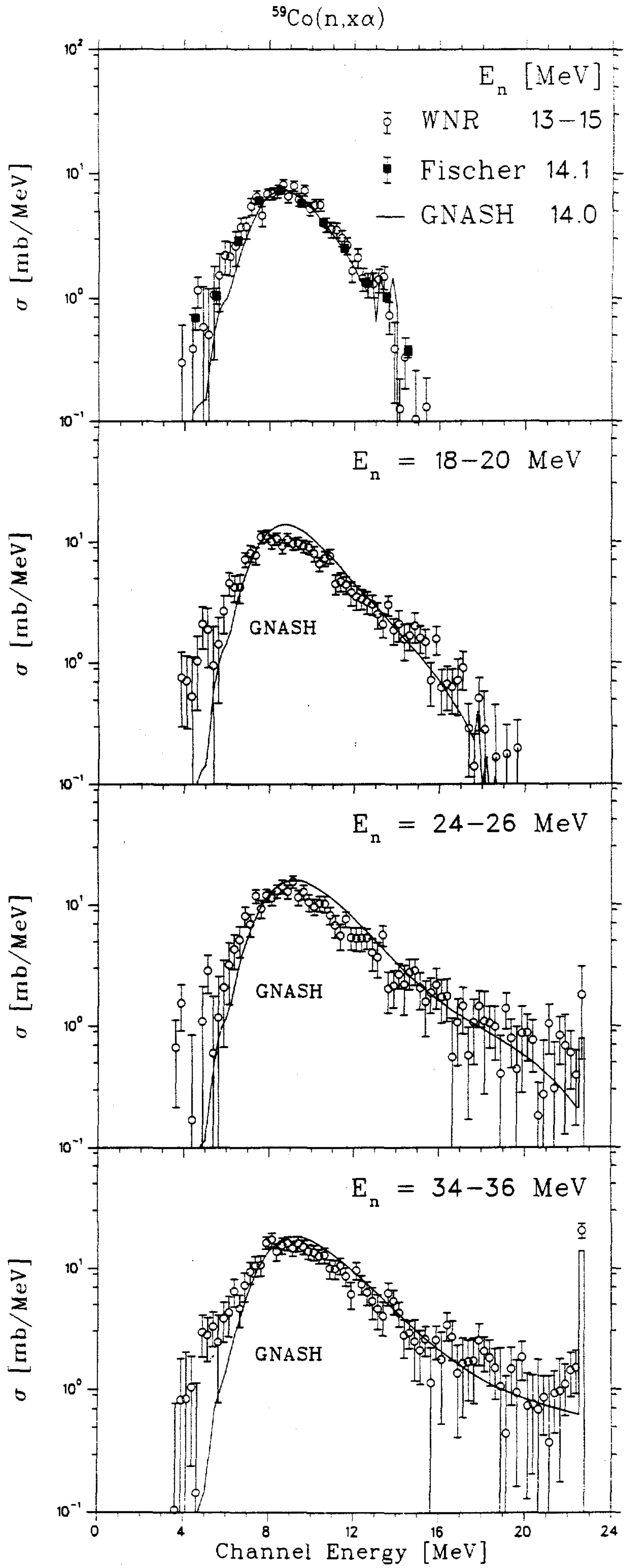
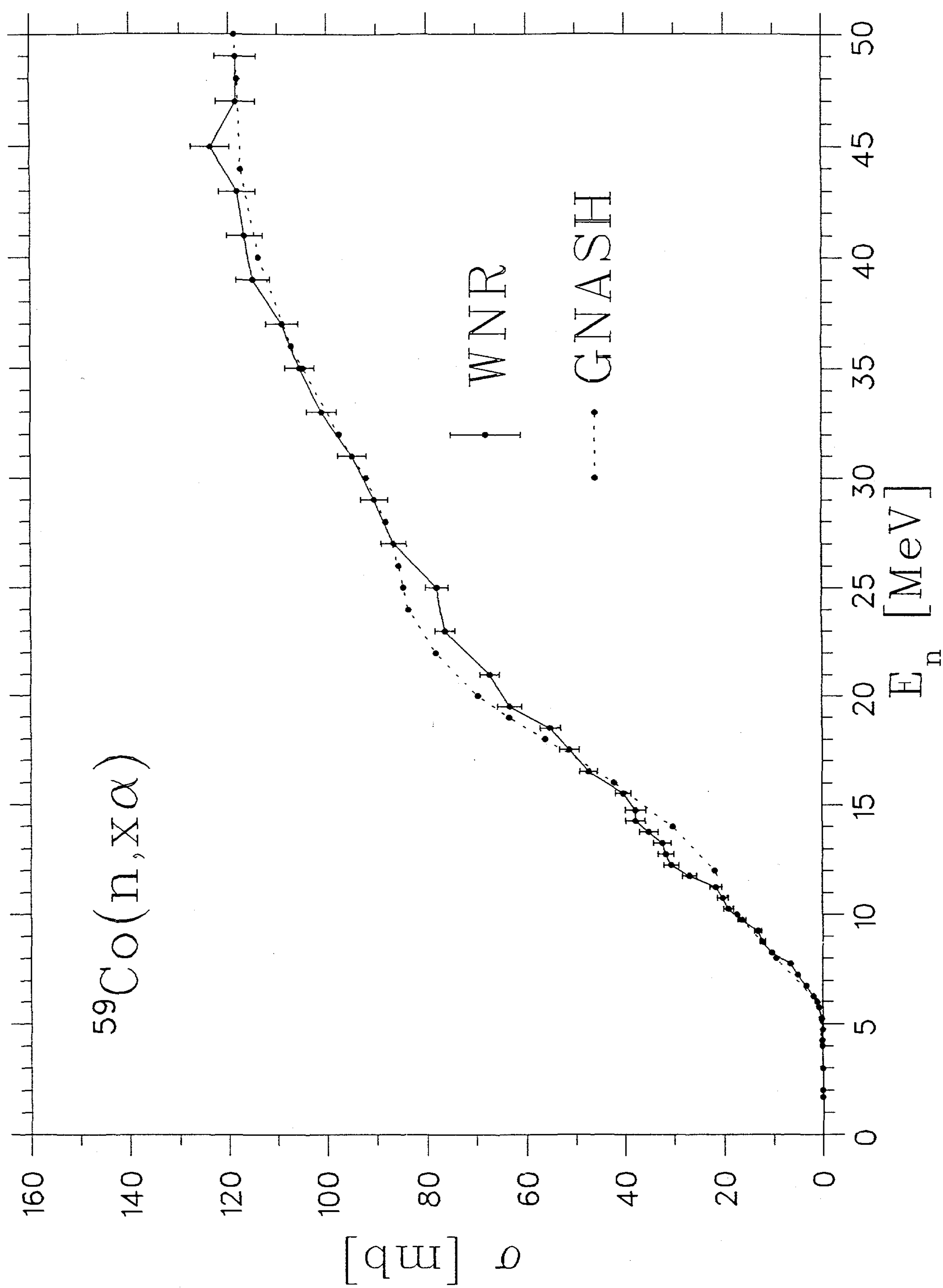
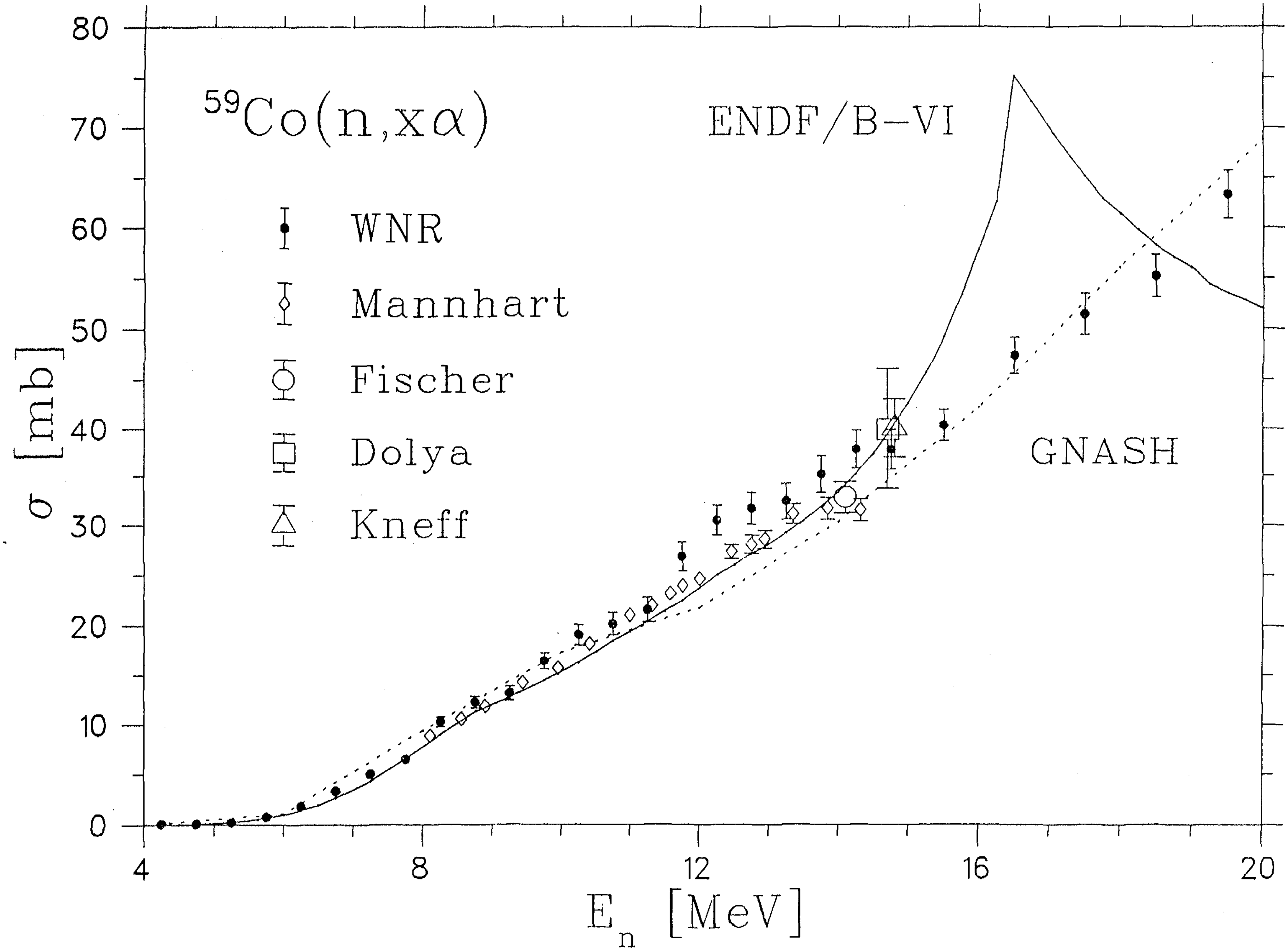

^{59}Co(n,xα)
E_n [MeV]
WNR 13–15
Fischer 14.1
GNASH 14.0
E_n = 18–20 MeV
GNASH
E_n = 24–26 MeV
GNASH
E_n = 34–36 MeV
GNASH
σ [mb/MeV]
Channel Energy [MeV]

Figure 1



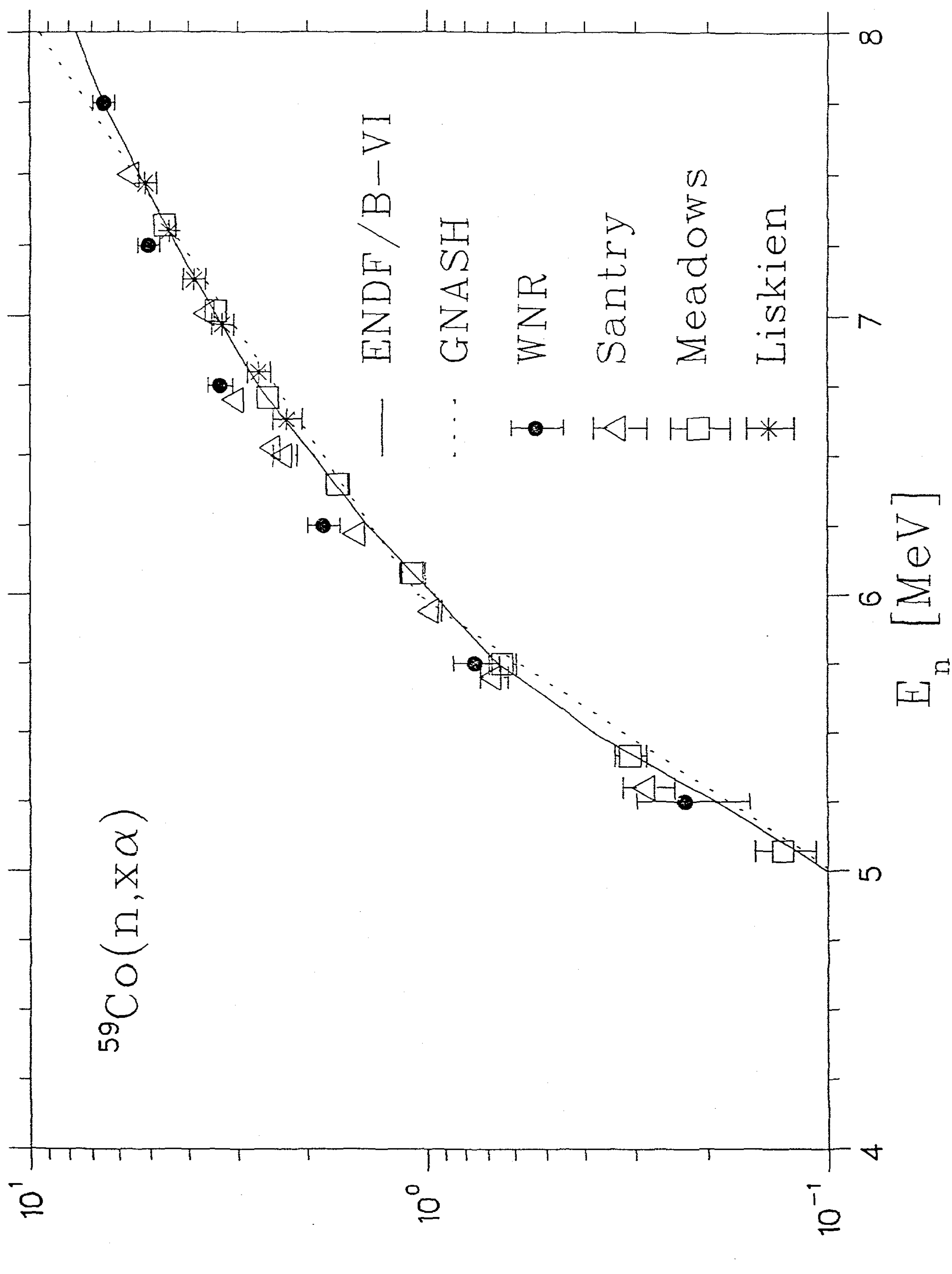
^{59}Co(n,xα)
WNR
GNASH
σ [mb]
E$_n$ [MeV]
0
20
40
60
80
100
120
140
160
0
5
10
15
20
25
30
35
40
45
50

Figure 2



^{59}Co(n,xα)
ENDF/B-VI
WNR
Mannhart
Fischer
Dolya
Kneff
GNASH
σ [mb]
E_n [MeV]
0
10
20
30
40
50
60
70
80
4
8
12
16
20

Figure 3



^{59}Co(n,xα)
ENDF/B-VI
GNASH
WNR
Santry
Meadows
Liskien
E_n [MeV]
σ [mb]
4
5
6
7
8
10^{1}
10^{0}
10^{-1}

Figure 4

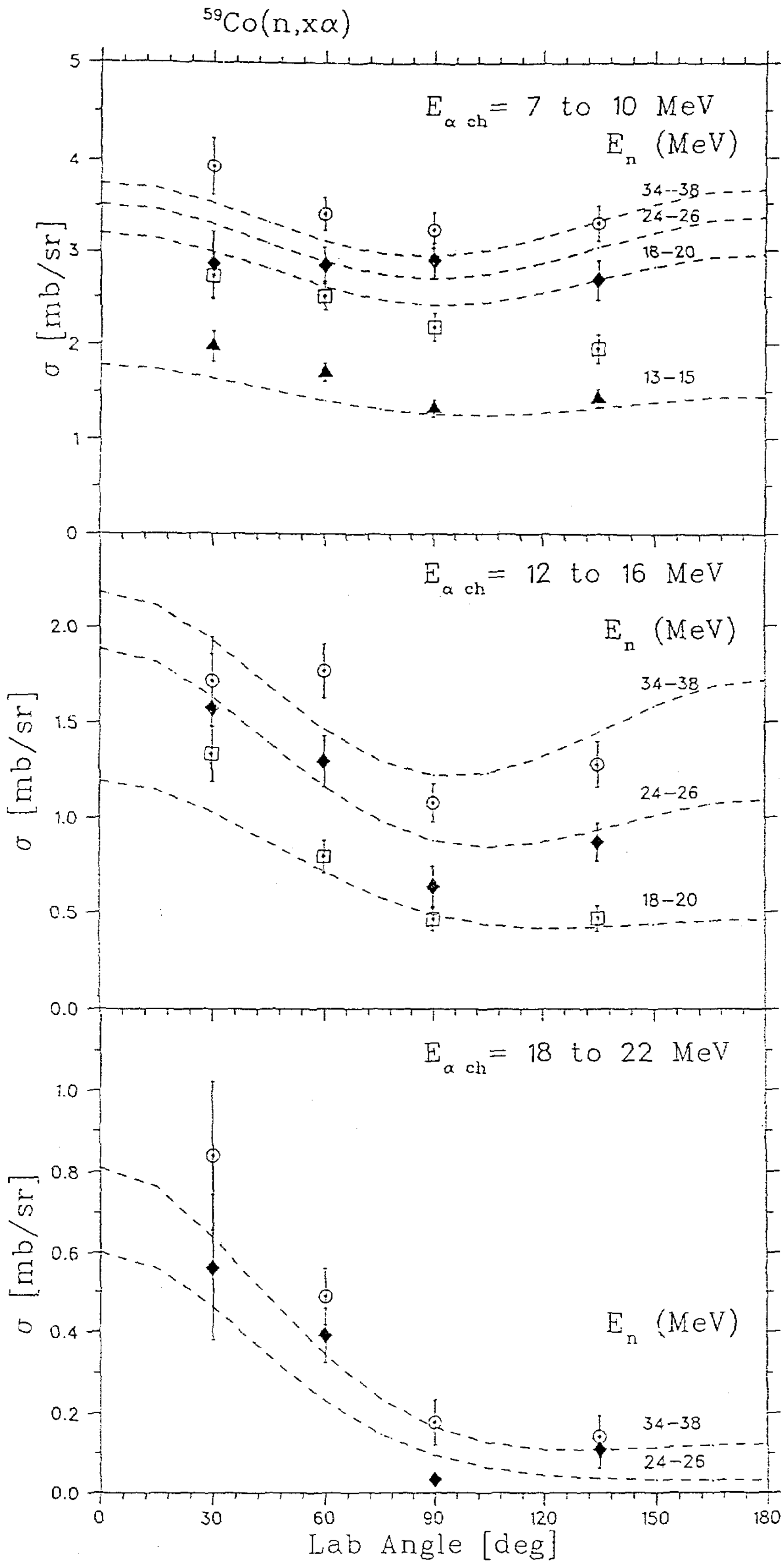

$^{59}Co(n,x\alpha)$
$E_{\alpha\ ch}$= 7 to 10 MeV
E_n (MeV)
34--38
24-26
18-20
13-15
σ [mb/sr]
0
1
2
3
4
5
$E_{\alpha\ ch}$= 12 to 16 MeV
E_n (MeV)
34-38
24-26
18-20
σ [mb/sr]
0.0
0.5
1.0
1.5
2.0
$E_{\alpha\ ch}$= 18 to 22 MeV
E_n (MeV)
34-38
24-26
σ [mb/sr]
0.0
0.2
0.4
0.6
0.8
1.0
0
30
60
90
120
150
180
Lab Angle [deg]

Figure 5