The $^{93}$Nb($n, xp$) Reaction at $E_n = 14.6$ MeV

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Abstract — The energy spectra and angular distributions of the proton emission from the $^{93}$Nb($n, xp$) reaction are measured by means of the multitelescope system at the University of Science and Technology of China. The total proton production cross sections are in fair agreement with the results obtained by other groups. The energy spectrum is explained well by the sum of the spectra calculated on the basis of the pre-equilibrium and Hauser-Feshbach theories. There are deviations from a previous measurement of the high-energy end of the angle-integrated proton spectrum. The angular distribution, which shows a strongly energy-dependent forward-backward asymmetry, is in fair agreement with the Kalbach-Mann phenomenological model.

1. INTRODUCTION

The nuclear data of neutron-induced charged-particle reactions on structural materials are important in the design of fission and fusion energy reactors. The reactor materials chosen must minimize the production of unwanted radioactivity and maintain their structural rigidity under intense neutron bombardment. These requirements depend on the minimization of proton- and alpha-particle-emitting reactions because these reactions can ultimately result in bubbles of hydrogen and helium that weaken the reactor materials.

Measurements of the energy spectra and angular distributions of particles emitted from fast neutron ($n, \alpha$) reactions are scarce, even around 14 MeV, because of the small cross-section values and high background. The neutron-induced event rate due to ($n, n'\gamma$), ($n, p$), and ($n, \alpha$) reactions in the materials and surroundings of a detector is much higher than the actual rate (a factor of $10^3$ to $10^5$ for an unshielded detector).

Niobium is a possible component of structural materials for fusion reactors. During the last 10 yr, measurements of the energy spectra and angular distributions of protons emitted from $^{93}$Nb($n, xp$) reactions have been reported by Koori, Ohsawa, and Kumabe; Traxler et al.; Fischer et al.; and Grimes, Haight, and Anderson. The measurements reported in this paper were performed with 14.6-MeV neutrons on the University of Science and Technology of China (USTC) multitelescope system. A target that was thick compared with the range of the most energetic protons was used, and the double-differential proton emission cross sections were subsequently derived by unfolding the thick-target spectra.

II. THE DETECTOR SYSTEM AND ELECTRONICS

II.A. The Multitelescope System

In 1981, a Vienna research group built a small multiwire proportional chamber that was suitable for the study of ($n, \alpha$) reactions. This system was upgraded in 1983 (Ref. 7), and it has been successfully used to study the ($n, p$) reaction. The USTC system
is based on the Vienna system, with improvements, as shown in Fig. 1. All the associated electronics were designed and built at USTC.

The USTC system consists of two-layer ring-shaped energy loss ($\Delta E$) detectors and a central CsI(Tl) energy detector. The outer detector ($\Delta E_1$) consists of 32 separate proportional counters, which are used to obtain the energy signals of charged particles. The inner detector ($\Delta E_2$) consists of 16 separate proportional counters, and its signals serve as one of the triple-coincidence signals. The target is laid in a semicircle in the target holder. Each of the proportional counters, in conjunction with the central scintillator, acts as a normal counter telescope that allows measurement of particle energy and particle identification. The different telescopes correspond to different reaction angles and allow simultaneous measurement of charged-particle spectra at 16 reaction angles (33 to 159 deg). The half of the chamber that is not covered by the target is used for simultaneous measurement of the background.

A 25-mm-diam $\times$ 1-mm-thick CsI(Tl) crystal serves as the central energy detector because cesium and iodide have very low $(n,p)$ and $(n,\alpha)$ cross sections and because CsI(Tl) has a pulse-shape property that allows discrimination of gamma rays, protons, and alpha particles. The 1-mm thickness stops protons with an energy up to 18 MeV emitted from the target foil. The CsI(Tl) detector is shielded from the neutron source by 20 cm of iron.

A mixture of 95% argon and 5% CO$_2$ gas is used in this system. The system operates at a low gas pressure (100 mbar) and in the gas flow mode. A graphite ring is used as the target holder; there is practically no proton production in the graphite because of the large negative $Q$ value for the $^{12}$C$(n,p)$ reaction.

II.B. Electronics System

The electronics system consists of two parts: the electronic signal readout circuits and the CAMAC data collection system. A block diagram of the associated electronics is shown in Fig. 2. For each $(n,xp)$ reaction, five parameters are recorded sequentially on disk in an on-line computer. The parameters are as follows: the energy loss signal ($\Delta E$) of the charged particle measured by the outer proportional counter; the wire address signal from which the reaction angle is obtained; the signal for the time difference between the proportional counter and the energy detector (TIME); the energy signal ($E$), and the pulse-shape discrimination (PSD) signal produced by the CsI(Tl) crystal.

Charged particles produced by neutron-induced reactions at the target foil must traverse the outer proportional counters and produce both an analog and a digital signal (address readout). The digital signals are fed to an address logic that transforms them into five-bit addresses that characterize the different counting wires. The analog pulses are amplified and then combined in summing amplifiers that separately total the outputs of the four preamplifiers. These signals are fed into the eight-channel linear gates, which open when the inner wire signals correspond to the energy detector signals. At last, all the proportional counter signals are combined in a final summing amplifier.

The CsI scintillator is used to produce both an energy signal and PSD signal. The PSD signal is fed into a slow coincidence (SC) circuit and produces an SC signal that acts as a strobing signal to open all the analog-to-digital (ADC) gates.

A new intelligent CAMAC crate controller was designed to control the ADC circuits and communicate with the on-line computer. Data are recorded in the buffer region of the CAMAC crate controller. When the buffer region is full or the collection of data is complete, the data are read out and stored on disk by the host computer.

III. EXPERIMENT AND DATA HANDLING

III.A. Experimental Arrangement

The $^{93}$Nb target was 0.8 mm thick. The 99.99% pure niobium metal was placed in one-half of the reaction chamber (with 16 telescopes), and the graphite ring was placed in the other half of the chamber for simultaneous measurement of the background.

The $^{93}$Nb$(n,xp)$ reactions were studied by means of a multitelescope system irradiated by 14.6-MeV neutrons produced by a 150-kV Cockcroft-Walton accelerator. The stability of the entire measuring system was
checked continually by monitoring all the important single counter rates. One background telescope was equipped with a weak $^{241}$Am alpha source, and another was equipped with polyethylene foil. These telescopes were used to monitor the energy calibration of the CsI crystal during the entire experiment.

The system was irradiated for ~40 h at an average neutron flux of ~1.8 x 10⁸ n/s. The target foil was rotated 180 deg at the midpoint of the experiment to reduce the asymmetry effects due to the two different halves of the reaction chamber.

### III.B. Data Handling

For each reaction event, five parameters were acquired by the CAMAC system and recorded on a magnetic disk in an IBM-PC computer. The recorded data were analyzed in the following way.

The particles were identified, and chance coincidence counts from each telescope were eliminated on the basis of PSD and $E\cdot\Delta E$ spectra. The PSD spectrum, shown in Fig. 3, indicated that the alpha-particle/proton/gamma-ray identification was accurate. The alpha particles and gamma rays were eliminated so that the appropriate channel ranges could be selected. The remaining alpha particles were eliminated by the selection of appropriate ranges in the $E\cdot\Delta E$ spectra. Few chance coincidence counts remained in the final data. Those counts could be eliminated through the time spectra.

The true background due to the working gas and other materials near the target was eliminated by subtraction of the background energy spectra from the corresponding foreground energy spectra, channel by channel. Two examples of the foreground and background energy spectra are shown in Fig. 4 for the protons measured. The No. 11 and No. 15 wires correspond to reaction angles of 64 and 35 deg, respectively.

In this way, thick-target proton energy spectra were obtained for 16 reaction angles from 33 to 159 deg. To obtain the proton emission spectra, the thick-target

![Fig. 2. Block diagram of the electronics system.](image)

![Fig. 3. Pulse-shape spectra of protons, alpha particles, and gamma particles.](image)
Fig. 4. Proton energy spectra from the $^{99}$Nb(n,xp) reaction at 64 and 36 deg. The solid lines show the foreground spectra, the dotted lines show the background spectra, and the dash-dotted lines show the net energy spectra of the $^{99}$Nb(n,xp) reaction obtained by subtracting the background spectra.

Fig. 5. Typical data from the $^{99}$Nb(n,xp) reaction in a thick target: (a) proton spectrum for a niobium target at 44 deg; (b) proton spectrum for a niobium target at 44 deg multiplied by $dE_p/dX(E_p)$ (Ref. 10); and (c) equivalent thin-target spectrum obtained by numerical differentiation of the spectrum given in (b).

IV. EXPERIMENTAL RESULTS
AND DISCUSSION

IVA. Experimental Results

The double-differential proton emission spectra were obtained for reaction angles from 33 to 159 deg (Ref. 11). Because of the limited counts for the individual angular and energy spectra, however, the statistical errors are rather large in these spectra. The statistical error and all identified systematic errors are combined to obtain the total error. The uncertainties are as follows: 3.3% in neutron flux, 1% in target thickness, 3% in solid angle of the central detector, 2% in the $dE/dX$ values, and 2% due to the data reduction procedure. The total systematic error is 5.4%. The statistical error, corresponding to one standard deviation, is calculated according to the counts in individual energy bins.
To compare these results with those of other authors, it is useful to integrate the results over either angle or energy. The angle-integrated proton emission cross sections for 1-MeV energy bins were obtained by Legendre fits to the double-differential cross sections; the results are shown in Table I. The total proton emission cross section is 47.7 ± 3.0 mb for energies of 4 to 14 MeV.

IV.B. Total Cross Sections

Four experimental results for the $^{93}$Nb$(n, xp)$ reaction cross section are shown in Table II. The energies of the incident neutrons are 14.1 MeV for Koori, Ohsawa, and Kumabe; 15.0 MeV for Grimes, Haight, and Anderson; and 14.6 MeV for this work. The calculated total cross sections obtained by Koori, Ohsawa, and Kumabe; Wilmore and Hodgson; and Gruppelar are shown in Table III.

The $^{93}$Nb$(n, xp)$ reaction cross section increases with incident neutron energy. The Weisskopf-Ewing, Hauser-Feshbach, and Feshbach-Kerman-Koonin theories have been used for the compound and statistical multistep compound contributions to the proton emission cross section. Figure 6 shows the data from Refs. 2 and 4 and the present work. The calculated total proton emission cross section is in good agreement with the measured results.

IV.C. Angular Distributions

Kalbach and Mann developed a simple phenomenological approach to calculating the angular distributions in pre-equilibrium reactions. The shapes of the angular distributions can be described in terms of Legendre polynomials. The polynomial coefficients are given by simple phenomenological relations involving the energy of the outgoing particle. This procedure utilizes the reduced Legendre coefficients $b_1$, defined by

$$b_1 = a_1/a_0,$$

Continuum angular distributions tend to be smoothly varying with angle, and the amount of forward peaking for a given reaction increases regularly with the energy.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>Angle-Integrated Proton Emission Cross Sections for the $^{93}$Nb$(n, xp)$ Reaction at 14.6 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_n$ (MeV)</td>
<td>$d\sigma/dE$ (mb/MeV)</td>
</tr>
<tr>
<td>4 to 5</td>
<td>2.49 ± 1.45</td>
</tr>
<tr>
<td>5 to 6</td>
<td>5.82 ± 1.43</td>
</tr>
<tr>
<td>6 to 7</td>
<td>8.00 ± 0.83</td>
</tr>
<tr>
<td>7 to 8</td>
<td>8.49 ± 1.01</td>
</tr>
<tr>
<td>8 to 9</td>
<td>6.68 ± 1.01</td>
</tr>
<tr>
<td>9 to 10</td>
<td>6.42 ± 0.62</td>
</tr>
<tr>
<td>10 to 11</td>
<td>4.14 ± 0.79</td>
</tr>
<tr>
<td>11 to 12</td>
<td>3.12 ± 0.77</td>
</tr>
<tr>
<td>12 to 13</td>
<td>2.12 ± 0.55</td>
</tr>
<tr>
<td>13 to 14</td>
<td>0.41 ± 0.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>Experimental Total Proton Emission Cross Sections (mb) of the $^{93}$Nb$(n, xp)$ Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_n$ (MeV)</td>
<td>Ref. 1 ($E_n = 14.1$ MeV)</td>
</tr>
<tr>
<td>4.3 to 9.0</td>
<td>34.3 ± 3.1</td>
</tr>
<tr>
<td>9.0 to 14.1</td>
<td>8.0 ± 2.6</td>
</tr>
<tr>
<td>4.3 to 14.1</td>
<td>42.3 ± 3.9</td>
</tr>
<tr>
<td>4.0 to 14.0</td>
<td>1.5 to 14.0</td>
</tr>
</tbody>
</table>
of the outgoing particle. In this case, the concepts of multistep direct (MSD) and multistep compound (MSC) reactions were adapted. In terms of the energy differential cross sections \( \sigma_{t_0}(\epsilon_b) \) and \( \sigma_{t_0}(\epsilon_b) \), the cross section given in Eq. (1) becomes

\[
\frac{d^2 \sigma}{d\epsilon_b d\Omega} = \sigma_0(\text{MSD})(\epsilon_b) \sum_{l=0}^{\text{max}} b_l \cos \theta_b + \sigma_0(\text{MSC})(\epsilon_b) \sum_{l=2}^{\text{max}} b_l \cos \theta_b .
\]

The various \( \sigma_0 \) values are obviously related as follows:

\[
\sigma_0(\text{tot}) = \sigma_0(\text{MSD}) + \sigma_0(\text{MSC}).
\]

It is clear that the odd-order polynomials are contributed only by the MSD part. The reduced Legendre coefficients \( b_l \) are given by the following equations:

\[
b_l(\epsilon_b) = \begin{cases} 
  c_l(\epsilon_b), & l = \text{even} \\
  \frac{a_0(\text{MSD})(\epsilon_b)}{[a_0(\text{MSD})(\epsilon_b) + a_0(\text{MSC})(\epsilon_b)]} c_l(\epsilon_b), & l = \text{odd}
\end{cases}
\]

The dependence of the functions \( c_l(\epsilon_b) \) on the energy \( \epsilon_b \) in the exit channel and on order \( l \) can be represented by the following relation:

\[
c_l(\epsilon_b) = (2l + 1)(1 + \exp[A_l(B_l - \epsilon_b))]^{-1} .
\]

The values of \( A_l \) and \( B_l \) were chosen to fit a variety of data and are given as follows:

\[
A_1 = 0.036 \text{ MeV}^{-1} + 0.0039 \text{ MeV}^{-1}(l + 1)
\]

and

\[
B_1 = 92 \text{ MeV} - 90 \text{ MeV} [l(l + 1)]^{-1/2} .
\]

Kalbach and Mann determined the ratio of the MSD cross section to the MSC cross section for different energies of the outgoing particle from the PRECOD code. Figure 7 shows the comparison between double-differential cross sections based on Eqs. (1) through (5) for three proton energy groups and the experimental \((\nu, p)\) data of the present work. The angular distributions of the protons are forward peaked for all but the very low energy levels; the amount of forward-backward asymmetry increases strongly with proton energy.

For all energies, the angular distributions can be described well by a series of Legendre polynomials up to \( l = 2 \). Thus, the information on the angular distributions can be summarized in the form of the reduced Legendre coefficients, \( a_0 / a_0(\epsilon_b) \) and \( a_2 / a_0(\epsilon_b) \), derived from least-squares fitting of Eq. (1). Figure 8 compares the reduced Legendre coefficient \( b_1 \) and \( b_2 \) for the \( ^{93}\text{Nb}(n, p) \) reaction and the predictions on the basis of the Kalbach-Mann system. The agreement is satisfactory for \( b_1 \), but the experimental \( b_2 \) values deviate from the calculated values.

\[\text{Fig. 7. Comparison of double-differential cross sections for the } ^{93}\text{Nb}(n, p) \text{ reaction for three proton energy groups and calculations based on the Kalbach-Mann system.}\]

IV.D. Angle-Integrated Cross Sections

Figure 9 compares the results of this work with the results obtained by Ko ori, Ohsawa, and Kumabe, Traxler et al., Fischer et al., and Grimes, Haight, and Anderson. It is apparent that the proton production in the present results is not as strong as that in the work by Grimes, Haight, and Anderson at both the low- and high-energy ends of the spectra. Good agreement is found with the proton emission spectra data of Ko ori, Ohsawa, and Kumabe, except at the high-energy end of the spectra.

A comparison between the results of Fischer et al. and the present work is especially interesting because the measurements were taken with similar systems and with thick targets. At the middle and at the high-energy end, the present result is higher than that of Fischer.
et al., and the opposite is true for the low-energy end. The present results are less accurate than those of Fischer et al.

A possible cause for the difference at the high-energy ends of the proton emission spectra is the increase in the spectra at the high-energy end with an increase in the incident neutron energy (14.1 MeV for Koori, Ohsawa, and Kumabe and for Traxler et al.; 14.6 MeV for this work; and 15.0 MeV for Grimes, Haight, and Anderson). That is, the pre-equilibrium proton emission increases with the incident neutron energy. On the other hand, the difference at the low-energy end shows that the equilibrium proton emission (the main contribution is in the low-energy end) is not as strong as Fischer et al.’s result.

Strohmaier calculated the angle-integrated $^{93}$Nb($n,xp$) reaction cross sections for $E_n = 14.1$ and 15.0 MeV by means of a combination of the pre-equilibrium and Hauser-Feshbach models. The excitation model was used to account for pre-equilibrium decay. The excitation model uses a particle-hole state density formula with energy shifts to account for pairing. The particle transmission coefficients were generated from the single-channel optical model; however, at an incident energy of ~8 MeV, the absorption cross section, and hence all neutron-induced cross sections, were reduced by ~6% to account for the loss due to direct inelastic scattering. Figure 10 compares the results of Strohmaier’s calculations with the experimental results of the present work. There is good agreement between the two sets of data.

Figure 11 compares the present results with those obtained by Koori, Ohsawa, and Kumabe, who used the formula given by Braga-Mareazan et al. The parameters selected are described in detail in Ref. 1. As Fig. 11 shows, the experimental energy spectrum is well reproduced by the sum of the spectra predicted by the pre-equilibrium and statistical evaporation models. In the pre-equilibrium model calculation, the proton emission from the three-exiton (n = 3) state is predominant in the total pre-equilibrium proton emission (~78% of the total). The contribution from statistical evaporation is small in the energy region above 9 MeV. The results of the calculation are smaller in the peak range (6 to 8 MeV) than those of the present work.
Feshbach, Kerman, and Koonin\textsuperscript{18} developed a fully quantum-mechanical theory of pre-equilibrium emission. Kalita, Seiliger, and Zhivopisnev\textsuperscript{19} completed the calculation by using this theory. Figure 12 compares the calculated differential cross sections with the experimental data. The theory agrees with the proton emission spectra for \(^{99}\text{Nb}\), but the result is not very satisfactory.

V. SUMMARY

The multitelescope system described in this paper was used to measure double-differential proton and alpha-particle production cross sections in neutron-induced reactions. This system allows the simultaneous measurement of 16 reaction angles from 33 to 159 deg and of the foreground and background spectra. The energy of the charged particles measured ranged from 3 to 20 MeV for protons and from 4 to 30 MeV for alpha particles. Triple coincidence was used to reduce chance coincidence. Particle identification based on the PSD spectrum was excellent. The event rate in the thick target is high, \(-0.4\%\).

The energy spectra and angular distributions have been measured for protons emitted from the \(^{99}\text{Nb}(n,\alpha p)\) reaction at 14.6 MeV. The total cross section is 47.7 \pm 3.0 mb for protons with energies above 4.0 MeV, which is consistent with the experimental results of others and with theoretical calculations. The angular distribution is well reproduced by the Kalbach-Mann formula. The forward peaking increases strongly with proton emission energy. The energy spectra were compared with calculations and were in fairly good agreement.

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