Resonance 2.7 eV above the ^{64}Ni(p,n_1)^{64}Cu* threshold†

H. W. Lefevre and E. W. Ross
University of Oregon, Eugene, Oregon 97403
(Received 17 November 1975)

Time of flight spectra of near threshold neutrons from the ^{64}Ni(p,n_1)^{64}Cu* reaction clearly show the presence of a $\frac{5}{2}^+$ resonance which is located 2.7 eV above the 2.67-MeV threshold. Its total width is 5 eV and its peak cross section is 14 mb. Through this study one deduces the basic limitation on the technique of high resolution spectroscopy very near reaction thresholds. Very near neutron thresholds, because a number of kinematic factors conspire in a favorable way, one can achieve the equivalent of slow-neutron resolution even though the neutrons are not slow. We know of no other technique which would allow individual study of such resonances.

[NUCLEAR REACTIONS ^{64}Ni(p,n_1)^{64}Cu*, near threshold; measured neutron spectra. Deduced resonance parameters of the first resonance above threshold. Deduced basic limitations on the near threshold technique.]

Resonances in compound nuclei which are excited by charged particle capture have nearly always been studied by means of excitation functions obtained with thin targets. Earlier work at this laboratory has shown: (1) that in reactions where neutrons are produced, high resolution excitation functions may be obtained directly from the thick target neutron spectrum[1,2]; (2) The Doppler resolution limit depends on the laboratory energy of outgoing neutrons rather than on the incident charged particle energy,[3] and that near reaction thresholds the Doppler limit in the exit channel is often in the electron volt region; and (3) that one can directly measure electron volt widths of states that are excited by charged particles whose energy is several MeV.[4] Those earlier studies, however, left several questions unanswered. First, while it was clear that the resolution of the technique should markedly improve as one discovered resonances nearer reaction thresholds, it was not clear how the Doppler width and the kinematic magnification were related. Second, since cross sections for negative Q reactions approach zero as one approaches threshold because the available phase space volume does, one could well wonder whether resonances could be detected very near reaction thresholds.

In the course of continuing these studies of neutrons from (p, n) reactions on intermediate weight nuclei, a strong resonance was found, which is only a few electron volts above the 2.67 MeV ^{64}Ni(p, n_1)^{64}Cu* reaction threshold.[5] This resonance is a factor of 50 nearer threshold than any other that we have found. A study of that resonance leads directly to an understanding of the basic limitations on the technique of high resolution spectroscopy very near reaction thresholds.

Figure 1 shows a neutron time of flight spectrum from the ^{64}Ni(p, n_1)^{64}Cu* reaction. It was obtained by bombarding a 1-mg/cm^2 ^{64}Ni target with a 2.67-MeV nanosecond pulsed and bunched proton beam from the University of Oregon Van de Graaff accelerator. Neutrons were detected with a 2-mm-thick by 12.5-mm-diam NE 908 ^{6}Li loaded glass scintillator coupled to an Amperex XP1010 phototube. The γ-ray sensitivity of the scintillator was reduced by setting a pulse height window to accept ^{6}Li(n, α)^{3}H events; the thermal neutron sensitivity was reduced with cadmium shielding. The flight path to the detector was 20.2 cm, and it was accurately positioned at 0° by re-

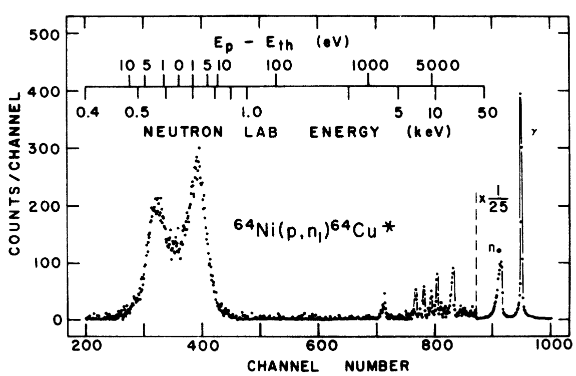

FIG. 1. Neutron time of flight spectrum from a 1 mg/cm^2 ^{64}Ni target bombarded by protons of energy ~2670 keV as obtained with a 12.5 mm diam ^{6}Li loaded glass scintillator at a flight path of 20.2 cm and a channel width of 0.976 ns. A flat background of 18 counts per channel has been subtracted. The 2.7 eV resonance neutrons produced the broad double peak near channel 360.

flecting a laser beam from a microscope cover glass mounted as a mirror near the target. The spectrum of Fig. 1 was accumulated in eight hours with an average beam current of 3 μA.

Figure 1 contains a γ-ray peak which was used to establish the time origin of the spectrum, a peak caused by arrival of ~160-keV ground state neutrons at the detector, several small narrow peaks which indicate neutron decay of several ^{65}Cu resonances to ^{64}Cu*, and a large double peak at ~640-eV neutron energy. The latter is from neutron decay of a single resonance in ^{65}Cu which delivers neutrons into a forward cone of half angle ~4°.

The shape of the peak at ~640-eV neutron energy may be understood in terms of Fig. 2. It shows a velocity diagram which has been converted into a spatial diagram by multiplying by a flight time t. For a narrow resonance near threshold, neutrons lie near the surface of an isochronous sphere which is constrained to expand within a cone as its center moves to the right with center of mass velocity. For a detector which is smaller than the sphere, one first sees c.m. forward neutrons arrive, and later, the c.m. backward neutrons. In order to fit an experimental spectrum, one lays a Breit-Wigner velocity distribution upon the sphere as a radial density function, and integrates numerically out to the laboratory detector angle to calculate the neutron arrival time distribution upon the flat scintillator

One should note particularly that the diagram in Fig. 2 converts phase space volume into a real volume which one samples with a real detector. For a resonance very near threshold, the cone angle is small, the phase space volume is small, and it may be sampled with a small detector. Thus, even if the yield becomes small as a resonance is moved toward threshold (because the available phase space volume does) the background also becomes smaller at the same rate if one matches the detector to the sphere. The signal to background ratio does not become poorer as one moves nearer threshold. This kinematic phase space concentration makes measurements possible near threshold. It was partly for this reason that such a small neutron detector was used for these measurements.

Figure 3 shows a fit to the ~640-eV peak from Fig. 1 obtained as outlined above. The parameters of the fit were $\Gamma_{\text{total}} = 5$ eV; $\sigma_{\text{peak}} = 14$ mb; and $Q_1 - Q$ (the resonance energy) $= 2.7$ eV. The variation of neutron penetrability with c.m. neutron energy was included in the Breit-Wigner density function to obtain the fit shown in Fig. 3. One deduces the spin and parity by noting that these are s-wave neutrons to the 2^+ first excited state of ^{64}Cu; the

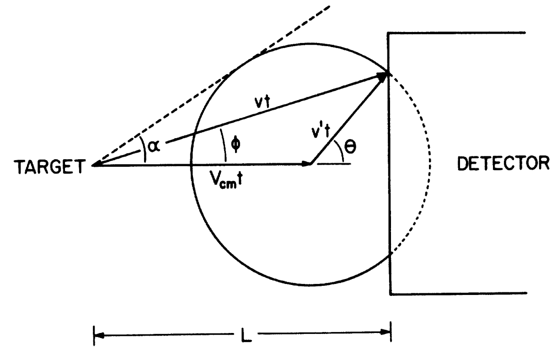

FIG. 2. Geometrical relationship between the spatial distribution of resonance neutrons at time t and the neutron detector. The cone half angle, α, for the resonance discussed in the text is about 4°. Imagine a Breit-Wigner velocity distribution as a radial density function on the sphere.

state is thus $\frac{3}{2}^+$ or $\frac{5}{2}^+$. A $\frac{5}{2}^+$ state can decay to the 1^+ ground state of ^{64}Cu by emission of 160-keV d-wave neutrons while a $\frac{3}{2}^+$ state could decay by emitting 160-keV s-wave neutrons. By comparing penetrabilities, one finds that 3-eV s-wave neutrons can compete with 160-keV d-wave neutrons, but that they could not compete with 160-keV s-wave neutrons. This state is thus $\frac{5}{2}^+$ and its three main decay channels are d-wave ground state (g.s.) neutrons, d-wave g.s. protons, and s-wave first excited state neutrons in order of decreasing penetrability.

The neutron energy resolution at 640 eV in Fig. 3, determined predominantly by the flight time of neutrons of that energy through the 2-mm-thick scintillator, was 13 eV. The Doppler resolution limit for 640-eV neutrons from this target is 1.7

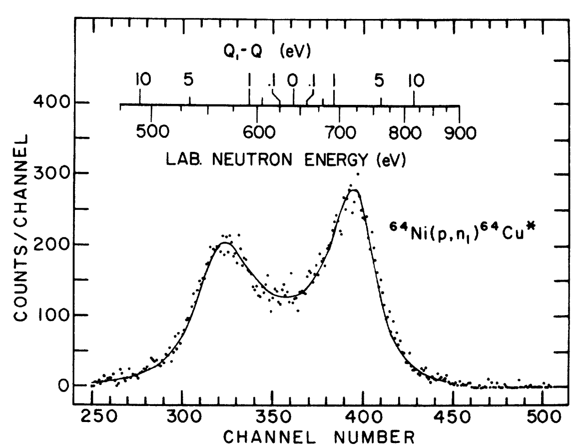

FIG. 3. The solid curve is a fit to the data of Fig. 1 obtained with c.m. parameters $\Gamma = 5$ eV, $\sigma_p = 14$ mb, and $\Delta Q = 2.7$ eV. Variation of neutron penetrability with c.m. neutron energy was included in the Breit-Wigner density function.

eV. These resolution factors, however, must be converted to the center of mass system to obtain the center of mass resolutions. We perform that conversion for the Doppler width below in order to deduce the basic limitation on the technique.

From the energy scales in Fig. 3, one notes that the excess Q scale becomes greatly magnified as one approaches threshold. This kinematic magnification may be understood as follows: From Fig. 2 and kinematics one may derive for the excess Q in terms of laboratory velocities

$$\Delta Q = \frac{m_3 + m_4}{m_4} \tfrac{1}{2} m_3 (v_{nL} - v_{\mathrm{c.m.}})^2$$

$$\cong \frac{m_3 + m_4}{m_4} (E_{nL}{}^{1/2} - E_{nT}{}^{1/2})^2 \ . \qquad (1)$$

The replacement of $(m_3/2)^{1/2} v_{\mathrm{c.m.}}$ by $E_{nT}{}^{1/2}$, the laboratory energy a neutron would have at threshold, is valid to high accuracy near threshold since $v_{\mathrm{c.m.}}$ changes only slowly with ΔQ. Figure 4 is a plot of Eq. (1) for this reaction for $\Delta Q \leq 0.1$ eV.

Upon differentiating (1) one obtains

$$d(\Delta Q) = \left(\frac{m_3 + m_4}{m_4} \frac{\Delta Q}{E_{nL}} \right)^{1/2} dE_{nL} \ . \qquad (2)$$

The Doppler resolution limit (full width at half maximum) on neutron energy for free target atoms is given by[3]

$$dE_{nL} = 4(\ln 2)^{1/2} \left(kTE_{nL} \frac{m_3}{m_3 + m_4} \right)^{1/2} \ . \qquad (3)$$

Upon substituting (3) into (2) one obtains

$$d(\Delta Q) = 4(\ln 2)^{1/2} \left(kT\Delta Q \frac{m_3}{m_4} \right)^{1/2} \ . \qquad (4)$$

The neutron energy variation has canceled, and the result is exactly the Doppler resolution limit for the inverse reaction. One can thus achieve the equivalent of slow neutron resolution even though the neutrons are not slow. We summarize this result in the form of a theorem:

The Doppler broadening in the exit channel of a reaction is equal to the Doppler broadening in the entrance channel of the inverse reaction.

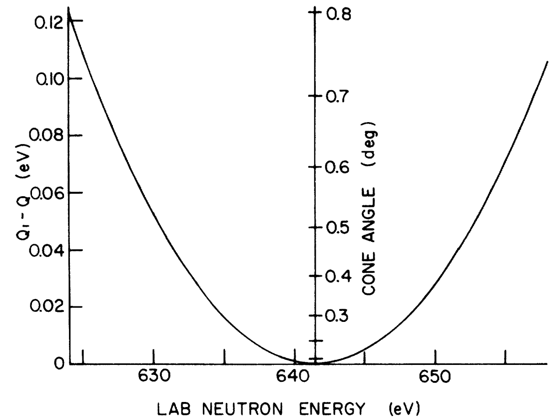

FIG. 4. A plot of excess Q vs laboratory neutron energy very near threshold for the $^{64}Ni(p, n_1)^{64}Cu^*$ reaction. The excess Q is nearly (to 2%) the laboratory proton energy above threshold. This simply shows that near threshold, the lab neutron energy changes very fast with proton energy.

The inverse of $^{64}Ni(p, n_1)^{64}Cu^*$ is slow neutrons upon ^{64}Cu nuclei in their first exited state which is an experiment that cannot be done. It is true in general that the compound system resonances which are accessible by this near threshold technique cannot be studied with reactor neutrons because the necessary targets are all unstable.

The crystal blocking technique for measurement of short nuclear decay times is directly applicable for study of resonances whose width is comparable to that of the state reported here.[6] That technique, however, can at best give only an average of the cross-section-width products over all of the resonances located within the Doppler width of the entrance channel. It is applicable, of course, in energy regions which are devoid of neutron thresholds, and in that sense the threshold technique and the blocking technique are complementary.

†Work supported in part by the National Science Foundation.

[1]W. R. Wylie, R. M. Bahnsen, and H. W. Lefevre, Nucl. Instrum. Methods 79, 2 (1970).

[2]D. W. Kneff, H. W. Lefevre, and G. U. Din, Phys. Rev. Lett. 25, 1210 (1970).

[3]D. W. Kneff, R. G. Clarkson, and H. W. Lefevre, Phys. Rev. C 7, 1645 (1973).

[4]H. W. Lefevre and D. W. Kneff, Phys. Rev. C 11, 524 (1975).

[5]H. W. Lefevre, E. W. Ross, and J. F. Fazio, Bull. Am. Phys. Soc. 20, 1165 (1975).

[6]W. M. Gibson and M. Maruyama, in *Channeling in Solids*, edited by D. V. Morgan (Wiley, New York, 1973), p. 349.