Decay of a Resonance in ^{18}Ne by the Simultaneous Emission of Two Protons

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Radioactive ion beams of ^{17}F were used to study several resonance states in ^{18}Ne. Clear evidence for simultaneous two-proton emission from the 6.15 MeV state ($J^{\pi} = 1^{-}$) in ^{18}Ne has been observed with the reaction ^{17}F + ‘H. Because of limited angular coverage, the data did not differentiate between the two possible mechanisms of simultaneous decay, di-proton (^{2}He) emission or direct three-body decay. The two-proton partial width was found to be 21 ± 3 eV assuming ^{2}He emission and 57 ± 6 eV assuming three-body decay. The total width of the 1‘ state was measured to be 50 ± 5 keV. Several additional resonances that decay by single proton emission were also studied.

I. Introduction

With the increased availability of radioactive ion beams, a wider variety of nuclei near the proton drip line can be produced. This provides an opportunity to study exotic decay modes, which can be a powerful probe of the nuclear structure of very weakly bound systems. One of the most exotic and elusive of these decay modes is the simultaneous emission of a pair of protons. Simultaneous two-proton emission can occur either by a sequential process involving a strongly correlated proton pair ^{2}He nucleus or di-proton) [I], which subsequently breaks up into two protons, or as a direct three-body process, sometimes called democratic decay [2]. If appropriate intermediate states are available, the same final state can be populated by two sequential single proton emissions. Extensive searches for di-proton emission have been carried out. Evidence for democratic decay in the ^{6}Be $\rightarrow \alpha$ pp system has been reported [2]. The two-proton decay of the isobaric analog state in ^{31}Ar has also been analyzed in terms of the democratic decay mechanism [3], but these data are not conclusive. In every other case studied [4–6] to date, the data are consistent with sequential one-proton emission through a well-defined intermediate state.

II. Experimental Procedure

As can be seen from the energy level diagram of the ^{17}F + ^{1}H system shown in Figure 1, excited states of ^{18}Ne below an excitation energy of ~ 6.5 MeV are a good place to look for simultaneous two-proton decay, since there are no intermediate states in ^{17}F available through which sequential one-proton decay can occur. This statement is true to the extent that sequential decay occurring through intermediate states formed by the tails of higher lying broad states in ^{17}F can be discounted. (It will be shown later on that it is possible to rule out contribution from sequential emission by a detail analysis of the correlation of the kinetic energies of the two protons).

The experiment to search for the two-proton emission from ^{18}Ne was performed at the Holifield Radioactive Ion Beam Facility (HRIBF), using the thick target technique described in References [7, 8] and references therein. Measurements were done in inverse kinematics with ^{17}F beams of 44 MeV and 33 MeV. A post-acceleration stripper was used to produce a ^{17}F 9’ beam with an intensity of aboui.1.2 x 10^{5} ions/s with no contamination from the ^{17}O isobar [8]. A 40-μm (CH_2) n target stopped the fluorine ions, but allowed the recoil protons to escape. A 256 pixel solid-state E-AE telescope

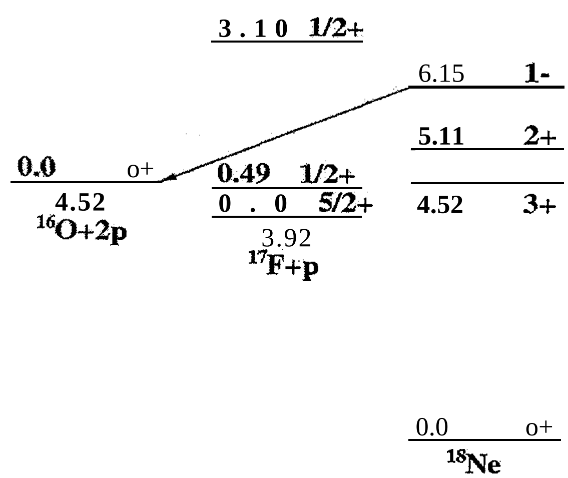

Figure 1. Decay species of ^{18}Ne. Spins and parities taken from Reference [13,14].

was placed behind the target. The AE detector consisted of a 300-μm double-sided strip detector (DSSD) providing an angular resolution of 1.9” and subtending an angle of ± 15^0. The E detector consisted of a 100-μm 900-mm^2 surface barrier detector (SBD) subtending an angle of ± 10^0. The telescope was calibrated with elastic scattering of 8 and 10 MeV proton beams from thin C and CH_2 targets to provide information necessary to interpret events with laboratory energies larger than the 7.5 MeV, which is the maximum energy of protons stopped by the telescope. An event time reference for each beam particle was provided by passing the beam through a thin carbon foil viewed by a microchannel plate detector prior to incidence on the target. This beam time reference enabled us to suppress the significant positron background resulting from the decay of ^{17}F beam particles stopped in the thick target or scattered to the chamber walls. For each event, energy, time, and position information from the DSSD along with energy and time information from the SBD were recorded. A study of cross-talk effects between DSSD strips with a 5.5-MeV alpha source showed that a small fraction of single hits gave signals in neighbor strips and could be mistakenly interpreted as two independent hits. In the final analysis, timing gates and rejection of nearest neighbor events assured clean two-particle hit identification. No evidence for cross talk from next nearest neighbor strips was observed,

III. Results

Although for the present case, the maximum excitation energy in ^{18}Ne is 6.3 MeV (3 MeV in ^{17}F) and no discrete states exists in ^{17}F for which sequential emission can proceed (see Figure 1) still is possible that highly excited states in ^{17}F whose widths are large enough could produce some sequential emission. In particular, the excited state in ^{17}F at 5.1 MeV (8.4 MeV in ^{18}Ne) has a width of 1.5 MeV and could produce small amounts of sequential emission of the two protons through the tail of the 5.1 MeV state, however the E_1 E_2 correlation (E, is the lab kinetic energy of one proton and E_2 that of the coincident proton) will be to asymmetric since the first proton decaying from ^{18}Ne to ^{17}F will have a very small energy. In Figure 2 we show the E, vs. E_2 two-dimensional plot for an angular opening of 10° for all the 2p events that are stopped in the first stage of the telescope. This requirement eliminates most of the protons coming from fusion evaporation reactions with the ^{12}C of the target since they will punch through the first stage and will therefore be vetoed by the E detector. The gate drawn in the figure corresponds to the kinematic Monte Carlo simulation of decay of a ^2He by two protons and, as can be seen, no low-energy protons [i.e., below ~ 2.0 MeV) are observed. Thus we concluded that all the 2p events seen in Figure 2 are attributed to simultaneous emission.

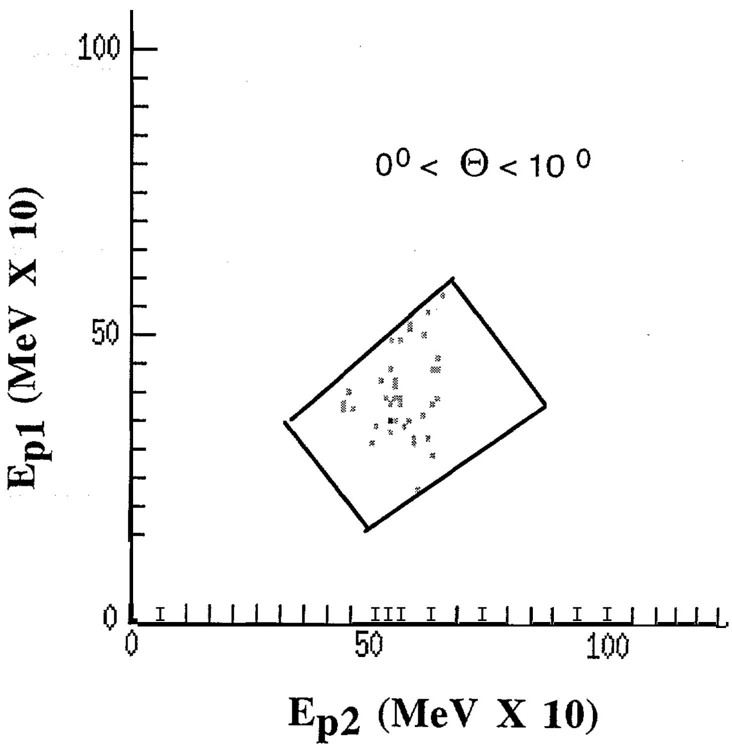

Fig. 2. Energy correlation between two coincident protons (p_1, p_2) for the ^{17}F + ^1H system.

The ^{17}F + ^1H excitation function reconstructed from single proton (lp) events is shown in Figure 3. It is split into two segments with a small energy gap between them resulting from dead layers between the two sensitive detector layers (AE and E). For the lower energy segment 0.4 to 1.6 MeV (top panel, Figure 3), the detected proton was stopped in the telescope, while for the higher energy region (bottom panel, Figure 3), the proton escaped from the E detector. With the careful energy calibration described earlier, we were able to reconstruct the excitation function in the higher energy region up to -2.45 MeV with only slightly worse resolution than in the stopped p region. The method used to construct the excitation function from the thick-target data is discussed in References [7] and [8]. An important source of potential background for the two-proton (2p) events is the reaction of ^{17}F with the C atoms of the CH_2, which at 44 MeV produce both 1p and 2p events. Evidence of protons from the ^{17}F + ^{12}C reaction was found in the lp events by the observation of protons with energies greater than the 9.2 MeV, the kinematic limit for $^{17}F + ^{1}H$ recoils. The 2p events (e.g., energies E,,, E,,) resulting from $^{17}F + ^{12}C$ could be clearly identified in the two-dimensional spectra of E_{p1} vs. E_{p2} and E vs. AE. The separation of 2p events in the two-proton sum energy spectra are shown in Figure 4 for events identified as arising from $^{17}F + ^{12}C$ (open circles) and those arising from $^{17}F + ^{1}H$ (filled circles).

Heavy-ion fusion in the mass and energy range relevant to the $^{17}F + ^{12}C$ data is well studied [9,10]. We used the code LILITA [1 1] to simulate the resulting compound nucleus decays. The dashed line on Figure 4 is the resulting simulated sum energy spectrum from $^{17}F + ^{12}C$ reactions producing 2p events. The normalization is not arbitrary; it is obtained by fitting the LILITA simulation of lp events to the lp experimental data. The good agreement of the simulation with the data confirms our identification and separation of the $^{17}F + ^{12}C$ 2p events.

The ^{17}F + 'H excitation functions shown in Figure 3 were analyzed using the R-matrix code MULTI [12], using the known spectrum of states in ^{18}Ne from References [13] and [14]. The resulting fit is shown as a solid line in Figure 3, with the spins and parities of the states employed indicated on the plot. The astrophysically important 3' state at E_{cm} = 0 .6 ± .05 MeV, Γ = 18 ± 2 keV, has recently been identified [14] after many unsuccessful searches. Our data confirm this result. A 3^- state reported [13] at E_{cm} = 2.37 MeV was not needed to fit our data.

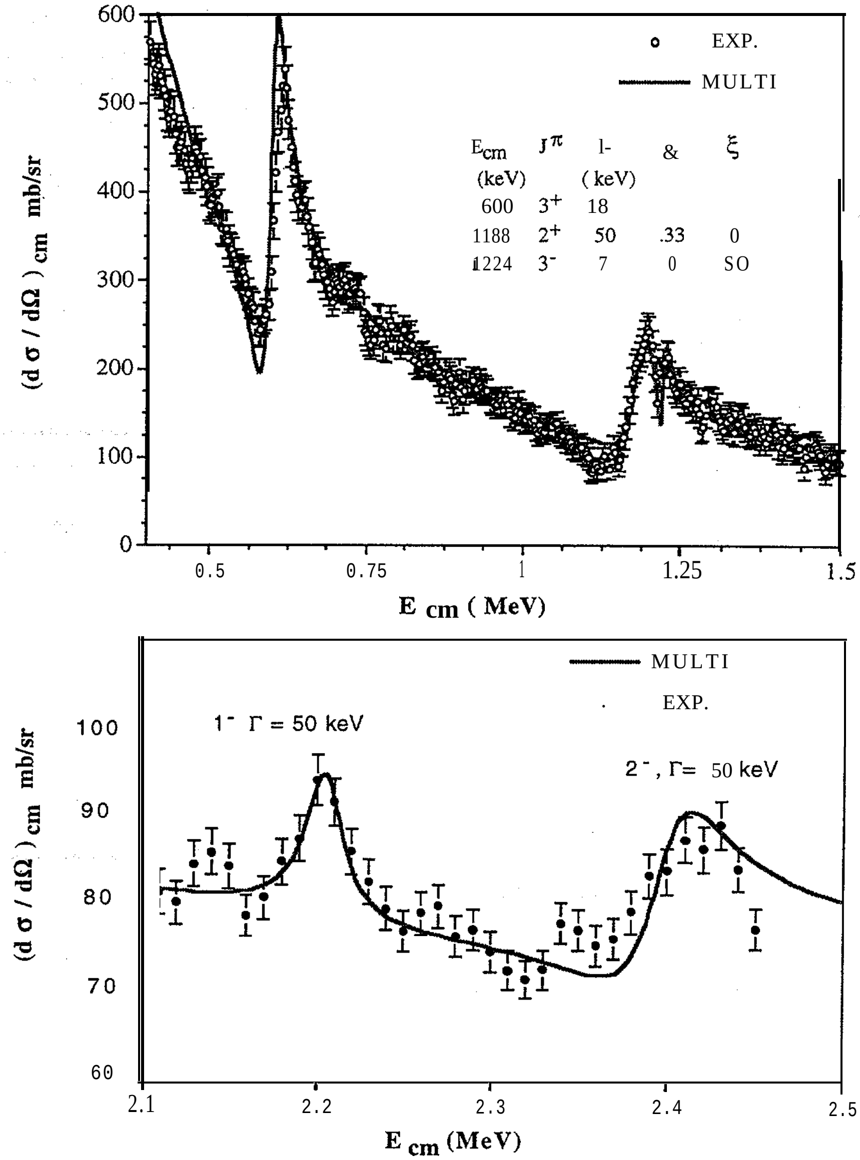

Figure 3. Experimental excitation function obtained from the recoil proton spectra for the reaction $^{1}H(^{17}F,p)$ at $E(^{17}F)$ = 44 MeV. The solid curve is the R-matrix fit using the code MULTI [12]. The top panel shows the excitation energy region of 0.4 to 1.8 MeV and the bottom panel of 2.1 to 2.5 MeV.

We now consider the two-proton (2p) data. The excitation energy region in which 2p decay can occur without a contribution from sequential 1p decay through ^{17}F corresponds to the center-of-mass energy range from' the 2p emission threshold at 600 keV to -3 MeV 4 (see Figure 3). The states identified in this range include 2^+, E_{cm} = 1.118 MeV, Γ = 45 ± 2' keV; 1 E_{cm} = 2.22 ± .01 MeV, Γ = 50 ± 5 keV, and 2^-, E_{cm} = 2.42 ± .01 MeV, Γ~50 keV. The very small phase space available for ^{2}He emission from the 2' state, and the fact that ^{2}He emission from the 2^- state is forbidden by parity considerations, leads us to expect the 1^- state at an excitation energy of 6.15 MeV (E, = 2.22 MeV) to be the best candidate. To illustrate this more clearly, we make simple partial-width estimates for ^{2}He cluster emissions from these states using the R-matrix expression of Ref. [15]. We find Γ He (1^-) = 59 eV, while Γ He (2^+) = 1.8 x 10^5 eV. Consequently, we assume initially that the 2p events result from the decay of the 1^- 6.15 MeV state in ^{18}Ne.

IV. Discussion

The two possible mechanisms for simultaneous two-proton emission lead to dramatically different energy and angular correlations between the two protons, provided the correlations are studied over a large enough angular range. However, in the present experiment, the angular coverage, which was originally designed for the 1p excitation functions, is not large enough for the differences to be significant compared to the uncertainty in our data. In the top panel of Figure 5, we show the laboratory separation angle Θ_{12} between the two protons, compared to Monte Carlo simulations assuming ^{2}He emission (solid line) and three-body decay neglecting final state interaction (dashed line). In the lower panel, a similar comparison is shown for the relative energy of the two protons. We have made plausible arguments that the most likely ^{18}Ne state responsible for the 2p decay we observe is the 6.15 MeV l-state (E_{cm} =2.22). Because of the thick target method employed in the experiment, we cannot directly determine the energy of the state responsible for the 2p decay with high accuracy, like in the case of 1p events (see Figure 3). However, we can determine the 2p excitation function by making a kinematic reconstruction based on the measured energies and angles of the emitted protons alone. This is done in an iterative way by assuming an initial resonance energy (E_{oi}) to generate the 2p excitation function such as the one shown in Figure 6 (solid dots, top panel) and determining its centroid E of $=E_{oi}$ + AE. This procedure is repeated setting E_{oi} for the (n +1) th iteration to the value of E of the n th, until AE AO. For the excitation function given in Figure 6, we found that AE =0 5 ± 100 keV for E_{oi} = 2.22 MeV. The solid curve drawn in the top panel of Figure 6 is a Monte Carlo simulation using the geometry and detector constraints. The significant broadening of the resonance (the horizontal axis E/E,,,) is mostly due to the angular resolution of the experiment. In fact, using a narrower angular coverage of the detector (0" to 10°) the 2p excitation function obtained (shown in the bottom panel of Figure 6) has a width nearly a factor of two narrower than for the full angular coverage (top panel, Figure 6).

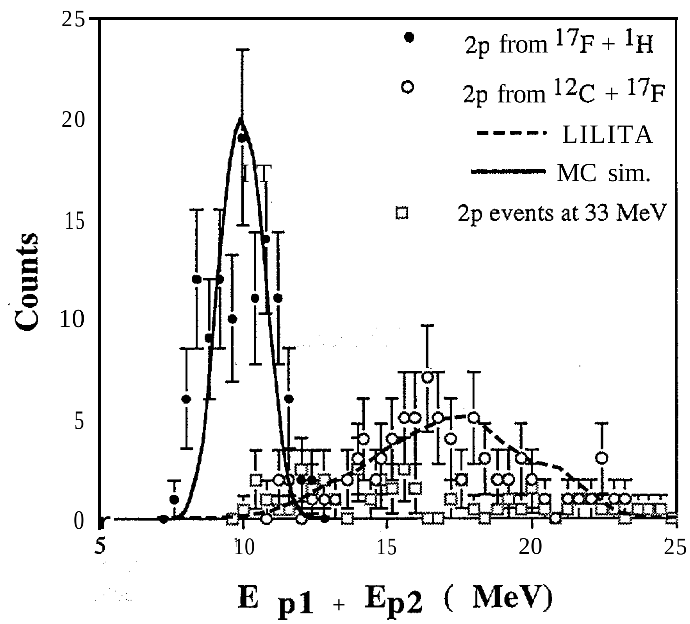

Fig. 4. Experimental sum energy spectra (filled and open circles) of 2p coincident events produced in the 44 MeV ^{17}F reactions on CH_2. The solid and dashed curves are Monte Carlo simulations described in the legend and in the text.

The solid squares plotted in the top panel of Figure 6 correspond to the generated excitation function for the 2p events measured at 33 MeV bombarding energy assuming E_{oi} = 2.22 MeV. As can be seen from the figure, the cross section for the 2p events at 33 MeV is nearly a factor of ten smaller than at 44 MeV, with no resonance visible. This fact provides additional experimental evidence in support of the identification of the 1^- resonance at E_{cm} = 2.22 MeV, since it demonstrates the absence of yield from any state at E_{cm} < 1.9 MeV. Because the pp angular correlations are different for the two 2p decay mechanisms considered here, and because our angular coverage is limited, the total 2p cross-sections and hence the partial width for 2p decay deduced from the data depends on the mechanism assumed. We find a 2p decay branching ratio of 4.2×10^{-4} for the ^{2}He emission mode and 1.1×10^{-3} assuming a three-body (democratic) decay. If all of the 2p decays originate from the 1^- state at 6.15 MeV, the corresponding partial widths are Γ_{2p} = 21 ± 3 eV for ^{2} He emission or Γ_{2p} = 57 ± 6 eV for democratic decay. As discussed earlier, simple R-matrix estimates [3] of the widths for ℓ = 1 ^{2}He emission from the 6.15 MeV state gives

Γ_{2p} = 60 eV. -This calculation includes integration over the density of states in the So pp system, calculated using final state interaction theory [16]. Thus, we estimate a spectroscopic factor of Γ_{exp} 2p/Γ_{Calc} 2p ~ 0 .35 which is somewhat larger than bne would expect since the 1^- state is probably quite complex, involving a substantial core excitation component. If we consider the three-body decay mechanism, estimating the widths as suggested in Ref. [16] we get Γ_{Calc} 2p = 0.25 eV for proton angular momenta $\ell 1$, $\ell 2$ = 1,2 and Γ_{Calc} 2p = 55 eV for $\ell 1$, $\ell 2$ = 0,1.

The width deduced from experimental data on the basis of the three-body decay assumption is actually larger than both calculated estimates and would lead to Γ_{exp} 2p/Γ_{Calc} 2p 230 and 1.03, respectively. These results clearly rule out the three-body decay hypothesis with Cl, $\ell 2$ = 1, 2 emission, and might be regarded as providing at least circumstantial support for the ^{2}He emission mechanism.

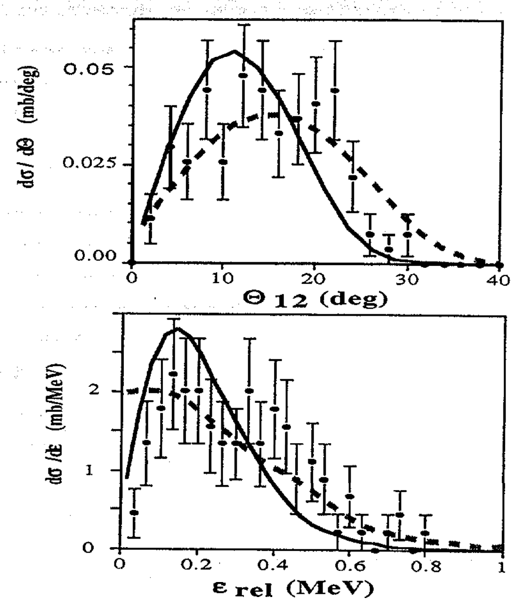

Figure 5. The top panel shows the experimental angular correlation (filled circles) compared to a Monte Carlo simulation assuming a ^{2}He emission (solid line) and a “democratic” decay (dashed curve). The bottom panel refers to the relative kinetic energy distribution.

In conclusion, we have observed simultaneous two-proton decay of a resonance in ^{18}Ne. Our energy and angular distribution data do not distinguish between the two extreme decay mechanisms, ^{2}He cluster emission and direct three-body decay with no final state interactions. It should de noted, however, that we have performed extensive simulations that indicate that data acquired with larger lab angle coverage could easily distinguish between the two. Both the kinematic reconstruction analysis and the 2p branching ratio (or partial width) strongly favor the association of the observed 2p events with the 6.15 MeV l-state in ^{18}Ne. The observed 2p decay width also provides at least circumstantial evidence in favor of the ^{2}He cluster emission.

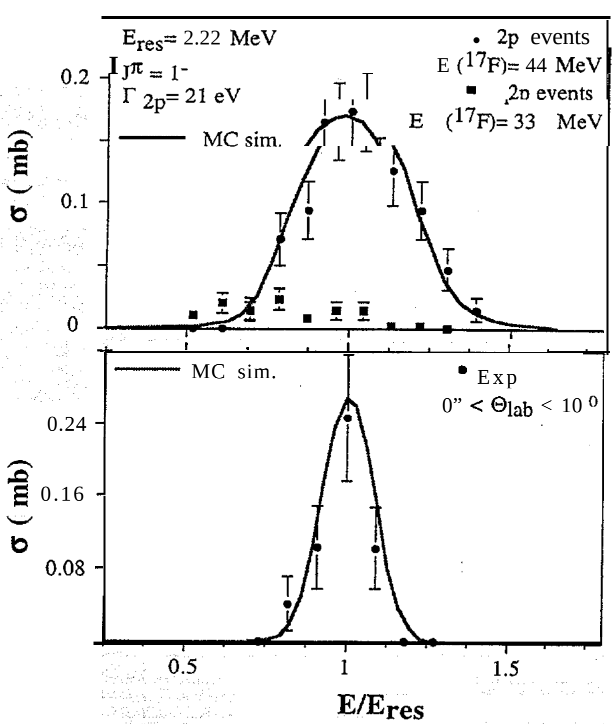

Figure 6. Experimental 2p for the full angular coverage of the detector (top panel) and for the angular range 0^0 to 10^0 (bottom panel) excitation functions extracted from the recoil protbns for the reaction of 44 MeV ^{17}F on ^{1}H. The solid curves are the MULTI calculation coupled to a Monte Carlo simulation.

V. ACKNOWLEDGEMENTS

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