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

J. Gómez del Campo,[1] A. Galindo-Uribarri,[1] J. R. Beene,[1] C. J. Gross,[1,2] J. F. Liang,[1] M. L. Halbert,[1] D. W. Stracener,[1] D. Shapira,[1] R. L. Varner,[1] E. Chavez-Lomeli,[3] and M. E. Ortiz[3]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*
[2]*Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee 37831*
[3]*Instituto de Física, Universidad Nacional Autónoma de México, México 01000 D.F., México*
(Received 10 July 2000)

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 + $^1$H. Because of limited angular coverage, the data did not differentiate between the two possible mechanisms of simultaneous decay, diproton ($^2$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.

DOI: 10.1103/PhysRevLett.86.43 PACS numbers: 25.60.–t, 23.50.+z, 24.30.–v, 25.40.Ny

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 (a $^2$He nucleus or diproton) [1], 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 diproton emission have been carried out. Evidence for democratic decay in the $^6$Be $\rightarrow \alpha p p$ 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.

As can be seen from the energy level diagram of the $^{17}$F + $^1$H system shown in Fig. 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. This is also the case in the decay of $^6$Be [2]. There may, in fact, not be a meaningful distinction between the democratic decay mechanism and sequential decay through the tails of a very broad state. However, in the case of $^{18}$Ne (states below ~6.5 MeV), the sequential decay will cover a region of excitation energy in $^{17}$F that is far removed from the centroid of the relevant high-lying states compared to the width of the states, thus producing distinctive proton energy distributions that can be easily distinguished from three-body or diproton decays.

The experiment to search for the two-proton emission from $^{18}$Ne was performed at the Holifield Radioactive Ion Beam Facility, using the thick target technique described in Refs. [7,8] and references therein. Measurements were done in inverse kinematics with $^{17}$F beams of 33 and 44 MeV. A postacceleration stripper was used to produce a $^{17}$F$^{9+}$ beam with an intensity of about $1.2 \times 10^5$ ions/s with no contamination from the $^{17}$O isobar [8]. A 40-$\mu$m $(CH_2)_n$ target stopped the fluorine ions, but allowed the recoil protons to escape. A 256 pixel solid state $E$-$\Delta E$ telescope was placed behind the target. The $\Delta E$ detector consisted of a 300 $\mu$m double-sided strip detector (DSSD) providing an angular resolution of 1.9° and subtending an angle of ±15°. The $E$ detector consisted of a 100-$\mu$m 900 mm$^2$ surface barrier detector (SBD) subtending an angle of ±10°. 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,

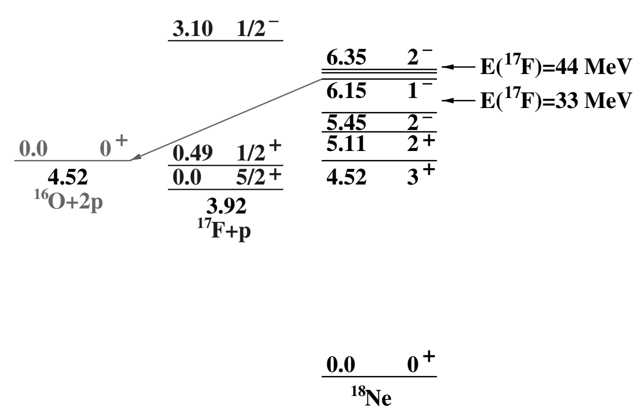


FIG. 1. Decay scheme of $^{18}$Ne. Spins and parities taken from Refs. [13,14].

  

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.

The $^{17}$F + $^{1}$H excitation function reconstructed from single proton ($1p$) events is shown in Fig. 2. It is split into two segments with a small energy gap between them resulting from dead layers between the two sensitive detector layers ($\Delta E$ and $E$). For the lower energy segment 0.4 to 1.6 MeV (top panel, Fig. 2), the detected proton was stopped in the telescope, while for the higher energy region (bottom panel, Fig. 2), the proton escaped from the $E$ detector. With the careful energy calibration described earlier, we were able to construct 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 Refs. [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 $1p$ 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 $Ep_1$, $Ep_2$) resulting from $^{17}$F + $^{12}$C could be clearly identified in the two-dimensional spectra of $Ep_1$ vs $Ep_2$ and $E$ vs $\Delta E$. The separations of $2p$ events in the two-proton sum energy spectra are shown in Fig. 3 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 [11] to simulate the resulting compound nucleus decays. The dashed line in Fig. 3 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 $1p$ events to the $1p$ experimental data. The good agreement of the simulation with the data confirms our identification and separation of the $^{17}$F + $^{12}$C $2p$ events. Plotted also in Fig. 3 are the data points (closed squares) measured at 33 MeV, where the peak at about 10 MeV is absent.

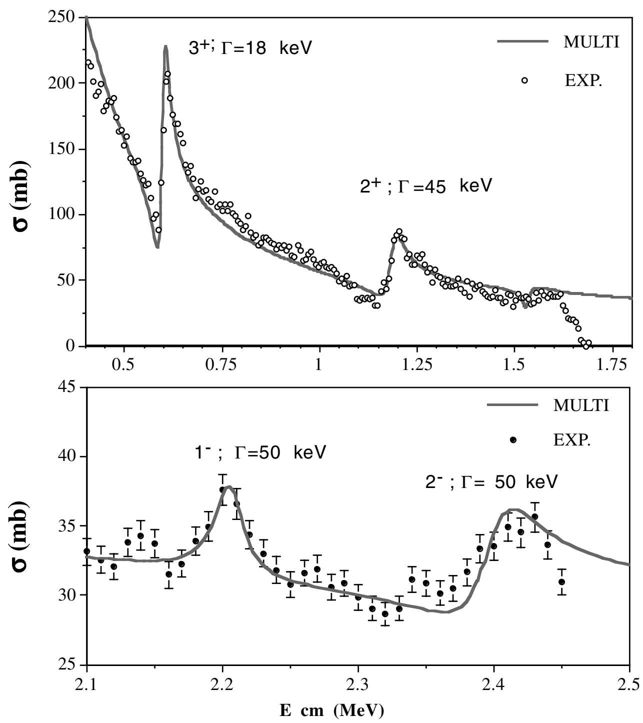


FIG. 2. Experimental excitation function obtained from the recoil proton spectra for the reaction $^{1}$H($^{17}$F, $p$) at $E$($^{17}$F) = 44 MeV. The solid curve is the $R$-matrix fit using the code MULTI [12]. The top panel shows the excitation energy region of 0.4 to 1.8 MeV and the bottom panel of 2.1 to 2.5 MeV. The vertical scale corresponds to the angle integrated cross sections for center of mass angles from 162° to 178°.

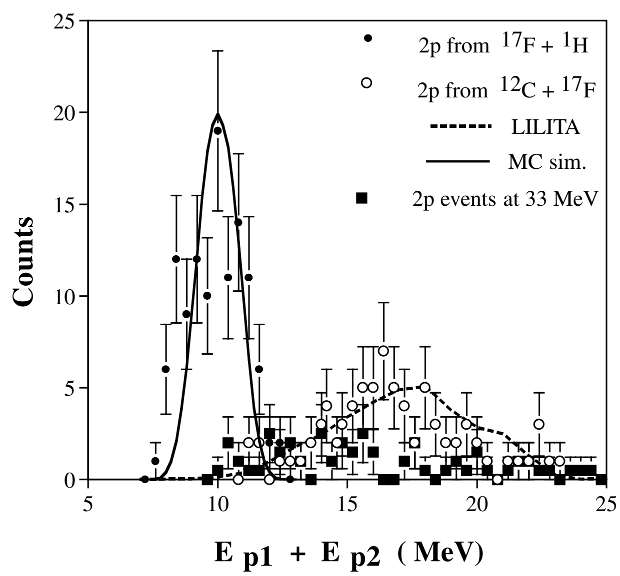


FIG. 3. Experimental sum energy spectra (filled and open circles) of $2p$ coincident events produced in the 44 MeV $^{17}$F reactions on $CH_2$. The solid and dashed curves are Monte Carlo simulations described in the legend and in the text. The closed squares correspond to the data at 33 MeV normalized to the same total exposure as at 44 MeV.

The $^{17}$F + $^{1}$H excitation functions shown in Fig. 2 were analyzed using the $R$-matrix code MULTI [12], using the known spectrum of states in $^{18}$Ne from Refs. [13] and [14]. The resulting fit is shown as a solid line in Fig. 2, with the spins and parities of the states employed indicated on the plot. The astrophysically important $3^+$ state at $E_{\mathrm{cm}} = 0.6 \pm 0.05$ MeV, $\Gamma = 18 \pm 2$ keV, has recently been identified [14] after many unsuccessful searches. Our data confirm this result. A $3^-$ state reported [13] at $E_{\mathrm{cm}} = 2.37$ MeV was not needed to fit our data.

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 $\sim$3 MeV (see Fig. 2). The states identified in this range include $2^+$, $E_{\mathrm{cm}} = 1.118$ MeV, $\Gamma = 45 \pm 2$ keV; $1^-$, $E_{\mathrm{cm}} = 2.22 \pm 0.01$ MeV, $\Gamma = 50 \pm 5$ keV; and $2^-$, $E_{\mathrm{cm}} = 2.42 \pm 0.01$ MeV, $\Gamma \sim 50$ 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 for parity considerations, leads us to expect the $1^-$ state at an excitation energy of 6.15 MeV ($E_{\mathrm{cm}} = 2.22$ 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 $\Gamma_{\mathrm{He}}(1^-) = 59$ eV, while $\Gamma_{\mathrm{He}}(2^+) = 1.8 \times 10^{-5}$ eV. Consequently, we assume initially that the $2p$ events result from the decay of the $1^-$ 6.15 MeV state in $^{18}$Ne.

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 Fig. 4 we show the laboratory separation angle $\theta_{12}$ 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 $1^-$ state ($E_{\mathrm{cm}} = 2.22$). 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, as in the case of $1p$ events (see Fig. 2). 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 Fig. 5 (solid dots, top panel) and determining its centroid

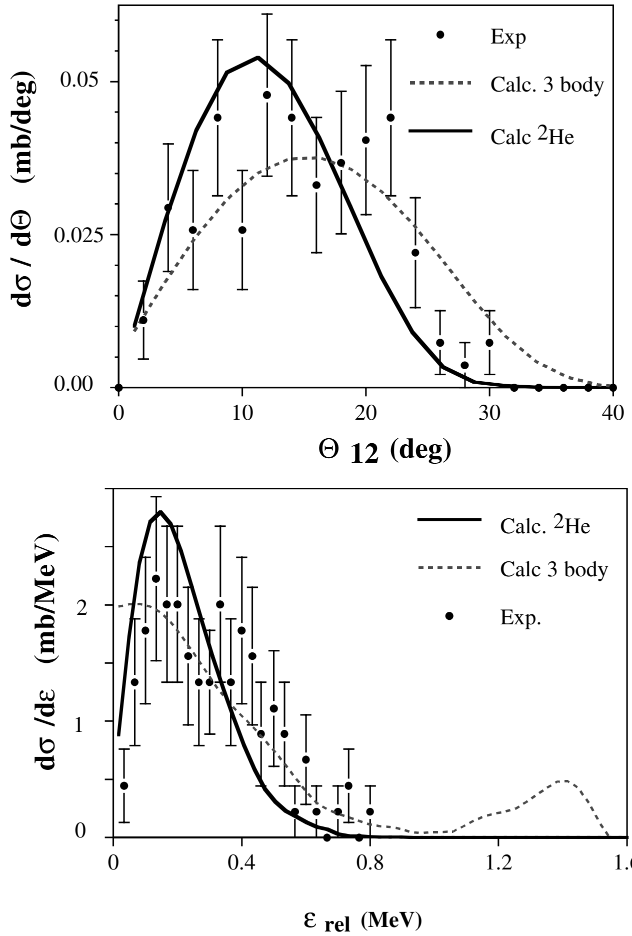


FIG. 4. The top panel shows the experimental angular correlation (filled circles) compared to a Monte Carlo simulation assuming a $^2$He emission (solid line) and a "democratic" decay (dashed curve). The bottom panel refers to the relative kinetic energy distribution.

$E_{of} = E_{oi} + \Delta E$. This procedure is repeated setting $E_{oi}$ for the $(n + 1)$th iteration to the value of $E_{of}$ of the $n$th, until $\Delta E \sim 0$. For the excitation function given in Fig. 5, we found that $\Delta E = 0 \pm 100$ keV for $E_{oi} = 2.22$ MeV. The solid curve drawn in the top panel of Fig. 5 is a Monte Carlo simulation using the geometry and detector constraints. The significant broadening of the resonance (the horizontal axis $E/E_{\mathrm{res}}$) 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 Fig. 5) has a width nearly a factor of 2 narrower than for the full angular coverage (top panel, Fig. 5).

The solid squares plotted in the top panel of Fig. 5 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 10 smaller than at 44 MeV, with no resonance visible. This fact provides additional experimental evidence in support of the identification of the $1^-$ resonance

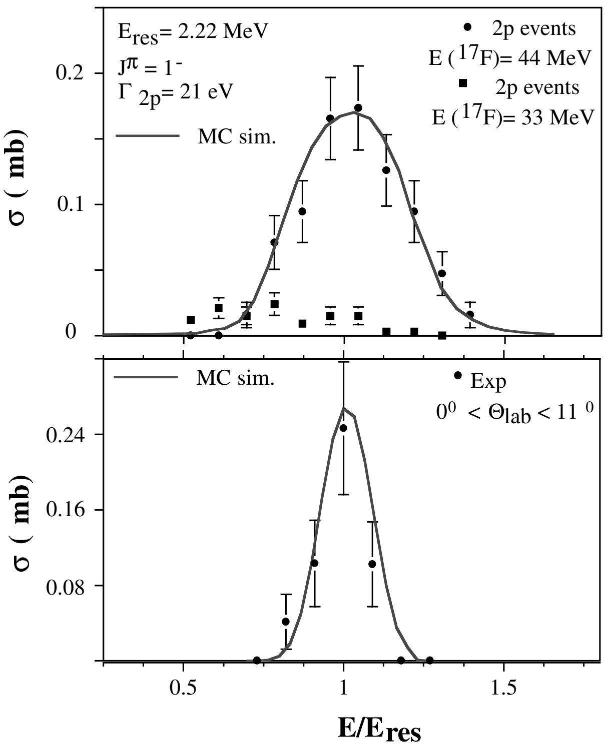


FIG. 5. Experimental $2p$ excitation functions for the full angular coverage of the detector (top panel) and for the angular range 0° to 10° (bottom panel), extracted from the recoil protons for the reaction of 44 MeV $^{17}$F on $^{1}$H. The solid curves are the MULTI calculation coupled to a Monte Carlo simulation.

at $E_{\rm cm} = 2.22$ MeV, since it demonstrates the absence of yield from any state at $E_{\rm cm} < 1.9$ 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 $4.2 \times 10^{-4}$ for the $^2$He emission mode and $1.1 \times 10^{-3}$ assuming a three-body (democratic) decay [16]. If all of the $2p$ decays originate from the $1^-$ state at 6.15 MeV, the corresponding partial widths are $\Gamma_{2p} = 21 \pm 3$ eV for $^2$He emission or $\Gamma_{2p} = 57 \pm 6$ eV for democratic decay. As discussed earlier, simple $R$-matrix estimates [3] of the widths for $\ell = 1$ $^2$He emission from the 6.15 MeV state gives $\Gamma_{2p} = 60$ eV. This calculation includes integration over the density of states in the $^1S_0$ $pp$ system, calculated using final state interaction theory [15]. Thus, we estimate a "spectroscopic factor" of $\Gamma_{2p}^{\rm exp}/\Gamma_{2p}^{\rm calc} \approx 0.35$ which is somewhat larger than one 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. [17] we get $\Gamma_{2p}^{\rm calc} = 0.25$ eV for proton angular momenta $\ell_1$, $\ell_2 = 1$, 2 and $\Gamma_{2p}^{\rm calc} = 55$ 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 $\Gamma_{2P}^{\rm exp}/\Gamma_{2p}^{\rm calc} \sim 230$ and 1.03, respectively. These results clearly rule out the three-body decay hypothesis with $\ell_1$, $\ell_2 = 1$, 2 emission.

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 be noted, however, that we have performed extensive simulations that indicate that data acquired with a 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 $1^-$ state in $^{18}$Ne.

Research at the Oak Ridge National Laboratory is supported by the U.S. Department of Energy under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC, and under Contract No. DE-AC05-76OR000333 between the U.S. Department of Energy and Oak Ridge Associated Universities. This research was supported in part by the Oak Ridge National Laboratory Postdoctoral Research Associates Program administered jointly by the Oak Ridge National Laboratory and the Oak Ridge Institute for Science and Education.

[1] V. I. Goldansky, Nucl. Phys. **19**, 482 (1960).
[2] O. V. Bochkarev *et al.,* Sov. J. Nucl. Phys. **55**, 955 (1992).
[3] I. Mukha *et al.,* Nucl. Phys. **A630**, 394c (1998).
[4] R. A. Kryger *et al.,* Phys. Rev. Lett. **74**, 860 (1995).
[5] D. F. Geesaman *et al.,* Phys. Rev. C **15**, 1835 (1977).
[6] C. R. Bain *et al.,* Phys. Lett. B **373**, 35 (1996).
[7] A. Huerta-Hernandez *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. B **143**, 569 (1998).
[8] A. Galindo-Uribarri *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. B **172**, 647 (2000).
[9] U. Mosel, in *Treatise on Heavy-Ion Science,* edited by D. A. Bromley (Plenum Press, New York, 1981), Vols. 2 and 3.
[10] J. Gomez del Campo *et al.,* Phys. Rev. C **19**, 2170 (1979).
[11] J. Gomez del Campo and R. G. Stokstad, Report No. ORNL TM-7295, 1981.
[12] R. O. Nelson, E. G. Bilpuch, and G. E. Mitchell, Nucl. Instrum. Methods Phys. Res., Sect. A **236**, 128 (1985).
[13] K. I. Hahn *et al.,* Phys. Rev. C **54**, 1999 (1996).
[14] D. Bardayan *et al.,* Phys. Rev. Lett. **83**, 45 (1999).
[15] R. J. N. Phillips, Nucl. Phys. **53**, 650 (1964).
[16] The cross sections over the angular range from 90° to 180° were determined by extrapolating the angular distribution outside the measured range using the code MULTI [12] in conjunction with a Monte Carlo simulation. The cross section value for the $1p$ resonance (6.15 MeV, $1^-$, see Fig. 2) is 3660 mb and the one for the $2p$ resonance (see Fig. 5, top panel) assuming $^2$He emission is 1.54 mb. Thus the ratio of widths is $4.2 \times 10^{-4}$.
[17] L. V. Grigorenko *et al.,* Phys. Rev. Lett. **85**, 22 (2000).