First-excited 0^+ state in ^{144}Nd

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Gamma-ray angular correlation measurements have led to a definite identification of the 2084.5-keV level as the first-excited 0^+ state in ^{144}Nd. This level is in good accord with the predictions of both the unified model and the interacting boson approximation model.

RADIOACTIVITY ^{144}Pr (β^-); measured $\gamma\gamma(\theta)$. ^{144}Nd deduced levels, J. NaI(Tl)-Ge(Li) combination.
NUCLEAR REACTIONS ^{144}Nd; calculated levels, J, π, electromagnetic properties. Interacting boson approximation model.

I. INTRODUCTION

As part of the first reported Ge(Li) study of γ rays from ^{144}Pr decay, Raman[1] proposed that a new level existed in ^{144}Nd at 2084 keV. Measuring the angular correlation of the 1388-696 cascade (see Fig. 1), he obtained $A_{22}=0.45\pm0.15$ and $A_{44}=+1.3\pm0.4$ and suggested a 0^+ assignment for the 2084-keV level in view of the theoretical values of $A_{22}=+0.357$ and $A_{44}=+1.143$ for a $0\rightarrow2\rightarrow0$ cascade. The positive parity was based largely on level systematics. At about the same time, Heyde and Brussaard[2] reported on their unified model calculations for several nuclides, and predicted that the first excited 0^+ state in ^{144}Nd would occur near 2063 keV. The agreement between the experiment and the calculation was striking, especially since each was performed independently of the other.

In a subsequent and more detailed angular correlation study of ^{144}Nd cascades populated in both ^{144}Pr and ^{144}Pm decays, Behar, Grabowski, and Raman[3] remeasured the same correlation and obtained

$$A_{22}=+0.310\pm0.035$$

and

$$A_{44}=+0.303\pm0.067 .$$

These smaller and more precise values were no longer consistent with the $J=0$ assignment for the 2084.5±0.2 keV level; instead they led to a unique $J=2$ assignment. Positive parity was suggested by the 23% dipole + 77% quadrupole nature found for the 1388-keV γ ray. Meanwhile, a ^{143}Nd thermal (n,γ) study[4] indicated that, in addition to the 2084.5-keV level, there were three other levels in the 2070- to 2110-keV region at 2072.7, 2092.9, and 2109.6 keV. Moreover, studies[5,6] using the (p,t) reaction, which is known to offer a generally reliable tool for identifying 0^+ states, revealed the presence of a 0^+ state in ^{144}Nd at 2080±18 keV. This result,

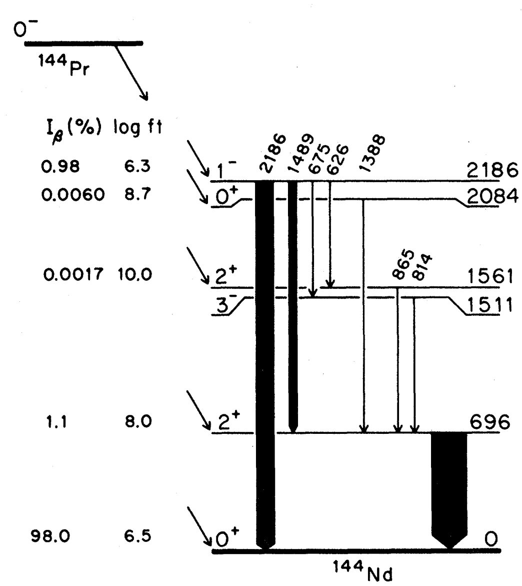

FIG. 1. Decay scheme of ^{144}Pr. The relative intensities of the 2186, 1489, 675, and 626 keV γ rays are 72, 28, 0.28, and 0.12, respectively. With this information, the absolute intensities of all γ rays shown can be deduced from the I_β values and intensity balance.

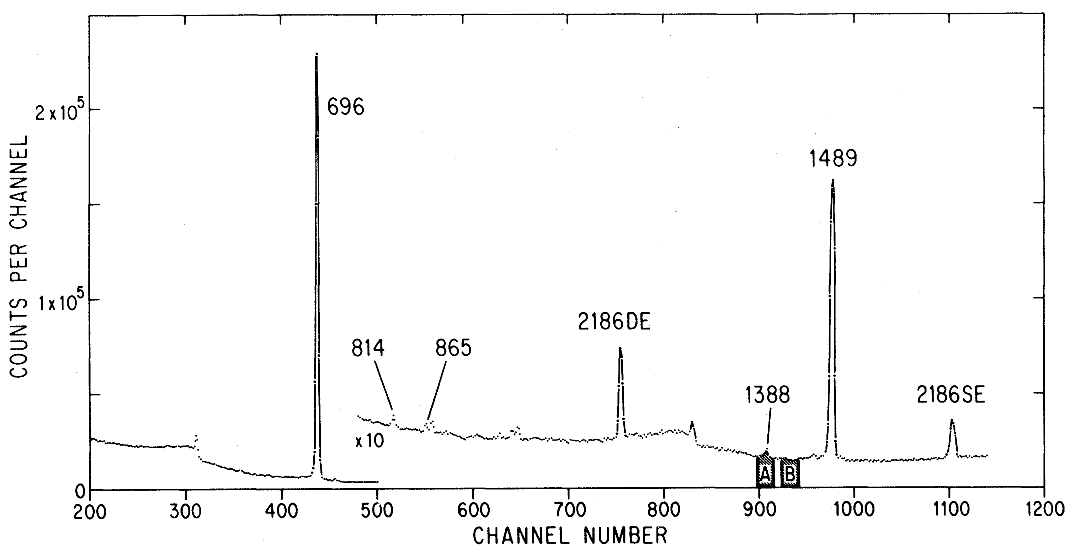

FIG. 2. Gamma-ray spectrum from ^{144}Ce. All energies are in keV. The small unlabeled peaks are from contaminant ^{154}Eu activity. Regions A and B denote windows employed in the present experiment.

however, was clearly inadequate to establish a definite correspondence with one of the four levels in the 2070- to 2110-keV region, or, for that matter, to rule out the possibility of an additional level.

Meanwhile, the 2^+ assignment proposed[3] for the 2084.5-keV level began to cause severe problems. The ^{143}Nd thermal (n,γ) measurements[4] revealed that this level was not fed directly by a primary γ ray and that the total intensity feeding this level was <0.3 photons per 100 n captures. Since the spin and parity of the capturing state was known to be predominantly 3^-, this abnormally small value for the total feeding intensity was inexplicable even if the near absence of a primary γ ray to this level could be attributed to the Porter-Thomas fluctuations. Next, in resonance (n,γ) measurements,[7,8] a primary γ ray to the 2084.5-keV level was absent from any of the five 3^- resonances studied. Finally, and most seriously, this primary γ ray was again absent in "2-keV" resonance-averaged (n,γ) measurements.[9] From a fluctuation analysis, as outlined by Chrien,[10] it can be shown that if the 2084.5-keV level is indeed a 2^+ level, the possibility of such an occurrence is $<2\%$.

Such inconclusive results and problems concerning the 2084.5-keV level led to a remeasurement of the 1388-696 angular correlation, the results of which are reported in this paper. The present data lead unambiguously to $J=0$ for this level and suggest that the previous $J=2$ assignment might have been due to an incorrect correction applied to the observed correlation to account for the background contribution.

II. EXPERIMENTAL PROCEDURE

The limitations imposed by the short half-life of ^{144}Pr (17.3 min) were avoided by utilizing a source of ^{144}Pr in equilibrium with its long-lived (285 d) ^{144}Ce parent. A liquid source of fission product ^{144}Ce in HCl was prepared with a strength of approximately 100 μCi. A sample γ-ray spectrum is shown in Fig. 2. The 1388-keV transition of interest is weak and sits on a substantial Compton background which could influence the angular correlation significantly. The 696-keV transition is intense and reasonably free from interference. It was, therefore, appropriate to offset the expected weak 1388-696 coincidence rate by choosing a NaI(Tl) detector for the 696-keV transition. The angular correlations were performed with a NaI(Tl)-Ge(Li) system described in previous publications.[11,12] Both detectors were well shielded against the intense low-energy γ rays from ^{144}Ce decay and against the 3 MeV β rays (and their associated bremsstrahlung) from ^{144}Pr decay. With the time resolution of ≈ 50 ns, the true/chance ratio was 5/1, and the 1388-696 coincidence rate was ≈ 0.5 per min. The angular correlations were measured at nine positions between 90° and 270° over a span of six months.

Two single channel analyzer (SCA) windows were set on the Ge(Li) spectrum: Window A included the

1388-keV peak plus its accompanying background, and window B included a region of background of approximately the same width. The two windows were interchanged several times during the course of the experiment, and the discriminator settings were varied by a few channels, all of which produced no significant effect on the observed correlations. The coincidence counts were routed to appropriate scalers; the spectra themselves were not recorded (however, see Sec. III for a discussion of a subsequent remeasurement). The coincidence data were fitted to the usual angular correlation function

$$W(\theta)=1+A_{22}Q_{22}P_2(\cos\theta)+A_{44}Q_{44}P_4(\cos\theta) ,$$

where A_{22},A_{44} are the angular correlation coefficients, and Q_{22},Q_{44} are corrections for the finite detector solid angles ($Q_{22}=0.90$ and $Q_{44}=0.70$ for the present system).

III. RESULTS

The system was first checked by measuring the 696-1489 correlation. The result was

$$A_{22}=-0.248\pm0.004 ,$$

$$A_{44}=+0.001\pm0.009 .$$

These values have been corrected for finite solid angles but not for Compton background coincidences, which were negligible for this particular cascade. These results are in good agreement with those obtained earlier by Behar, Grabowski, and Raman[3]

$$(A_{22}=-0.249\pm0.003,\ \ A_{44}=-0.002\pm0.010)$$

and with those expected ($A_{22}=-0.250$, $A_{44}=0$) for a $1\rightarrow2\rightarrow0$ correlation.

The measured angular correlation coefficients, corrected for finite solid angles, for the 696-keV γ ray in coincidence with the 1388-keV peak plus Compton background (window A of Fig. 2) were

$$A_{22}=-0.111\pm0.008 ,$$

$$A_{44}=+0.262\pm0.014 ,$$

while those for the Compton background (window B in Fig. 2) were

$$A_{22}=-0.234\pm0.014 ,$$

$$A_{44}=+0.033\pm0.022 .$$

The measured background correlation suggests that the background is primarily associated with the 1489-keV γ ray.

It is, in principle, possible for the ^{144}Pr β decay to populate a level at 2949 or 2899 keV, which level could then deexcite to the level at 1561 or 1511 keV, respectively, by emitting a 1388-keV γ ray. This possibility was excluded by recording a 1388-keV Ge(Li)-Ge(Li) coincidence spectrum, with the gating window set on region A of Fig. 2. The 696-keV peak appeared prominently, as expected (about 40% of its intensity coming from background events in the window and from chance coincidences), but no evidence was seen for either the 814- or 856-keV peak to within an upper limit of 0.5% of the true 696-keV coincidence intensity. Since no other correlations interfere with the 1388-696 correlation, it remained only to correct the observed coefficients for the background included in window A. As shown below, these correlations profoundly alter the observed A_{22} and A_{44} values.

Figure 2 shows that the background level accepted by window B extends virtually undiminished well above the 1489-keV peak. This background is associated with the 2186-keV transition (see Fig. 1), which is not in coincidence with the 696-keV transition. Therefore, this portion of the background does not affect the angular correlation. It is necessary to determine the fraction of the B-window intensity that is associated with the 1489-keV transition, and whether the background is sufficiently flat to be extrapolated to the A-window region. Figure 3 shows a portion of the Ge(Li) spectrum in coincidence with the 696-keV window of the NaI detector. The *coincident* background drops sharply beyond the 1489-keV peak, where it is indistinguishable from chance coincidences. It was therefore assumed that the B-window true coincidences are characteristic of the 1489-keV transition and contribute to the angular correlation with $A_{22}=-0.250$, $A_{44}=0$. The observed B-window correlation coefficents are consistent with this assumption.

Figure 3 also shows that the B-window background is not representative of that in window A; the 1388-keV peak rests on a substantially greater background than that in window B. Fitting a linear function to the sloping background in the vicinity of the 1388-keV peak gives 1.95 as the correction factor by which the B-window *true* coincidence intensity must be scaled before correcting the A-window correlation. (It is necessary to emphasize that the correction is to be applied to the true coincidences, since the true-to-chance ratio varied by about 30% owing to source decay over the course of these measurements.)

After reasonable estimates for the uncertainties introduced by the background extrapolation were included, the final corrected 1388-696 correlation coefficients were

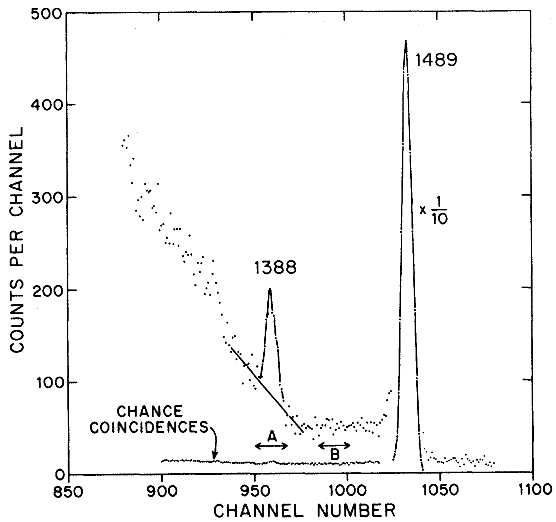

FIG. 3. Portion of the Ge(Li) spectrum in coincidence with the 696-keV NaI(Tl) window. The A and B regions correspond to those of Fig. 2. The short line segment shows the result of a straight-line fit to the sloping background above and below the 1388-keV peak.

$$A_{22}=0.282\pm0.041 ,$$

$$A_{44}=1.064\pm0.067 .$$

These coefficients, especially the large A_{44}, are in sufficiently good agreement with those expected for a $0\to2\to0$ correlation ($A_{22}=0.357$, $A_{44}=1.143$) that we are confident in assigning the 2084-keV level as 0^+, the positive parity being consistent with level systematics and the logft value. The 2080 ± 18 keV state populated in the (p,t) reaction via an $L=0$ transfer[5,6] is most probably identifiable with the 2084-keV level populated in ^{144}Pr decay.

The effects of the background coincidences were so dramatic that the results were rechecked with a system in which the complete spectrum in coincidence with the γ ray was explicitly recorded in a multichannel analyzer (MCA). These measurements were made by moving the Ge(Li) detector sequentially to four positions, and recording the data in each of the four quadrants of the MCA. In this way the background contributions could be subtracted reliably at each angle and the correlation coefficients could be determined unambiguously from the resulting peak areas. The results for the 1388-696 correlation were

$$A_{22}=0.432\pm0.050 ,$$

$$A_{44}=1.122\pm0.084 ,$$

again in excellent agreement with those expected for a $0\to2\to0$ correlation.

An added benefit of the MCA-based approach was the measurement of the 814-(696 + 675) and the 865-696 correlations (see Fig. 1) which were not measured with the SCA-based approach. The NaI(Tl) gates were such that the influence of the 865-626 correlation in the 865-696 correlation was negligible ($<10\%$). The results were

$$A_{22}=-0.122\pm0.040 ,$$

$$A_{44}=-0.038\pm0.042$$

for the 814-(696 + 675) correlation. If the 814-keV transition is assumed to be pure $E1$, the expected combined correlation is $A_{22}=-0.117$, $A_{44}=0$. Conversely, the observed correlation yields

$$\delta(M2/E1)=-0.01\pm0.08$$

for the 814-keV transition. The results for the 865-696 correlation were

$$A_{22}=0.490\pm0.085 ,$$

$$A_{44}=0.140\pm0.140 ,$$

which implies

$$\delta(E2/M1)=-(0.75\pm0.30)$$

for the 865-keV transition. This mixing ratio is slightly lower than the δ value of $-(1.6\pm0.5)$ obtained earlier by Behar, Grabowski, and Raman[3] and that of $-(1.2\pm0.2)$ obtained recently by Snelling and Hamilton.[13]

IV. DISCUSSION

The special interest in the first-excited 0^+ (denoted as 0_2^+) state in $^{144}_{60}\mathrm{Nd}_{84}$ arises partly as follows. Heyde and Brussaard[2] have treated some $N=84$ nuclei in a unified model calculation. They coupled the motion of two extra neutrons, restricted in the $2f_{7/2}$ single particle orbit, to the vibrational motion of the $N=82$ core. For ^{144}Nd, the unknown parameters in their Hamiltonian were obtained from a least squares fitting procedure of the eigenvalues of the energy matrices to the experimental level energies of the 2_1^+, 2_2^+, 4_1^+, and 6_1^+ states (see Fig. 4). At the time these calculations were made, little additional usable information was available on ^{144}Nd. The calculations of Heyde and Brussaard[2] led to a concrete and testable prediction that the 0_2^+ state should be near 2063 keV. It was impossible, in fact, to push this state below or very near the 1314-keV 4_1^+ and the 1561-keV 2_2^+ states, which are the other two members of the "two-phonon triplet." The re-

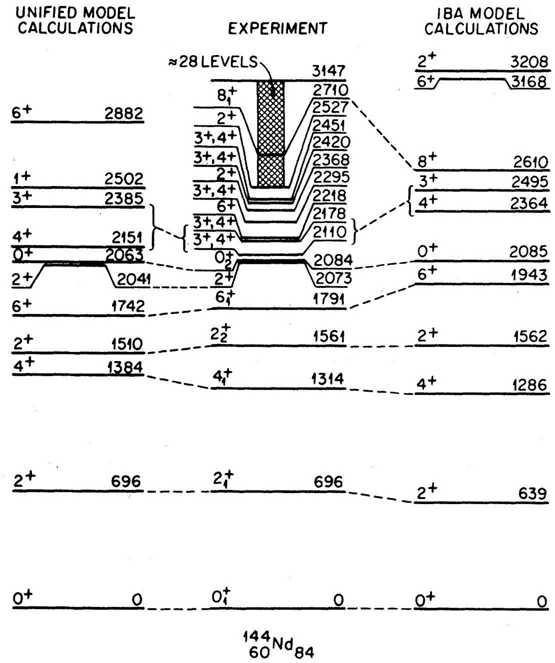

FIG. 4. Comparison between calculated and experimentally known positive parity levels in ^{144}Nd. All energies are in keV. The unified model results are from Ref. 2. The interacting boson approximation (IBA) model results are from the present work. In the experiment column, the 6^+ and 8^+ levels are from Y. Y. Berzin *et al.*, Izv. Akad. Nauk SSSR, Ser. Fiz. 40, 1193, (1976) and from L.-E. de Geer *et al.*, Nucl. Phys. A259, 399 (1976). The remaining levels are from Refs. 4 and 9.

sults of the calculations are shown in Fig. 4.

In the more extensive calculations reported by Vanden Berghe,[14] the two extra neutrons in ^{144}Nd were allowed to occupy the $3p_{1/2}$, $3p_{3/2}$, $2f_{7/2}$, $1h_{9/2}$, and $1i_{13/2}$ orbits. By removing the serious restrictions imposed by Heyde and Brussaard[2] on the available single-particle orbits, Vanden Berghe[14] was able to greatly improve the agreement between theory and experiment and to also extend such comparisons to the (d,p) spectroscopic factors, negative parity states, and electromagnetic properties. He also predicted the occurrence of the 0_2^+ state at $\approx$2120 keV.

In recent years, the interacting boson approximation (IBA) model[15] has been quite successful in describing the properties of low-lying collective states in even-A nuclei of medium and heavy mass.

TABLE I. Electromagnetic properties of levels in ^{144}Nd.

Property	Experiment	IBA model calculation
$B(E2;0_1^+\rightarrow 2_1^+)e^2b^2$	$0.51^a\pm 0.016$	0.51^b
$Q(2_1^+)e$ b	$-0.39^a\pm 0.21$	-0.25
$B(E2;4_1^+\rightarrow 2_1^+)e^2b^2$	$0.08^c\pm 0.010$	0.16
$\frac{B(E2;2_2^+\rightarrow 0_1^+)}{B(E2;2_2^+\rightarrow 2_1^+)}$	$0.007^{d}{}^{+0.003}_{-0.001}$	0.005

[a]Reference 17.
[b]Assumed value to fix $E2SD$ and $E2DD$. These parameters in the general $E2$ operator of the model play the role of an effective boson charge.
[c]Reference 22.
[d]Reference 3.

Therefore, it was instructive to enquire whether this model worked well also for ^{144}Nd. This was done with the aid of the computer program[16] PHINT. The aim was not as much to attempt to predict the position of the 0_2^+ state as to see whether this model would also readily accommodate a widely split two-phonon triplet. To do the former in a unique and credible fashion would require more levels in ^{144}Nd with definite spin and parity assignments than are available at present. The parameters in the IBA model were fixed with the aid of the experimentally known positions of the 0_2^+, 2_1^+, 2_2^+, 4_1^+, 6_1^+, and 8_1^+ levels (see Fig. 4) and the $B(E2,0_1^+\rightarrow 2_1^+)$ value of $0.51\pm 0.016\ e^2b^2$ (Ref. 17). The PHINT parameters employed were $HBAR=635$ keV, $C_0=812$ keV, $C_2=248$ keV, $C_4=6.0$ keV, $F=68.3$ keV, $G=-50$ keV, and $E2SD=-E2DD=0.1185\ e$b. Taking $E2SD=-E2DD$ is consistent with the IBA model description[18–21] of extensive sets of $E2$ transition probabilities in ^{110}Pd, $^{152-160}$Gd, $^{160-164}$Dy, and $^{166-170}$Er. The results of the IBA model calculations for ^{144}Nd are compared with the experimental results in Fig. 4 and Table I. The IBA model overestimates the preliminary experimental $B(E2,4_1^+\rightarrow 2_1^+)$ value[22] by a factor of 2. Otherwise, this model is reasonably successful in describing the gross features of ^{144}Nd.

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[1]S. Raman, Nucl. Phys. A107, 402 (1968).
[2]K. Heyde and P. J. Brussaard, Nucl. Phys. A104, 81 (1967); and private communication.
[3]W. Behar, Z. W. Grabowski, and S. Raman, Nucl. Phys. A219, 516 (1974).
[4]S. Raman, G. G. Slaughter, J. A. Harvey, E. T. Jurney, D. A. McClure, J. C. Wells, Jr., and J. Lin, in *Proceedings of the Second International Symposium on Neutron Capture Gamma Ray Spectroscopy and Related Topics,* edited by K. Abrahams, F. Stecher-Rasmussen, and P. van Assche (Reactor Centrum Nederland, Petten, 1975), p. 562.
[5]J. B. Ball, R. L. Auble, J. Rapaport, and C. B. Fulmer, Phys. Lett. 30B, 533 (1969).
[6]S. Raman, R. L. Auble, J. B. Ball, E. Newman, J. C. Wells, Jr., and J. Lin, Phys. Rev. C 14, 1381 (1976).
[7]H. Weigmann, G. Rohr, and M. Heske, Nucl. Phys. A185, 229 (1972).
[8]S. Raman and G. G. Slaughter, quoted by C. M. McCullagh, Ph. D. thesis, State University of New York at Stony Brook, 1979, available through University Microfilms, Inc., Ann Arbor, Michigan.
[9]S. Raman, O. Shahal, D. A. McClure, and M. J. Kenny, in *Neutron Capture Gamma Ray Spectroscopy and Related Topics, 1981,* edited by T. von Egidy, F. Gönnenwein, and B. Maier (Institute of Physics, Bristol, 1981), p. 435.
[10]R. E. Chrien, in Ref. 9, p. 342; and private communication.
[11]K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).
[12]K. S. Krane, Phys. Rev. C 17, 213 (1978); Nucl. Phys. A349, 68 (1980).
[13]D. M. Snelling and W. D. Hamilton, private communication.
[14]G. Vanden Berghe, Z. Phys. A 272, 245 (1975).
[15]A. Arima and F. Iachello, Ann. Phys. (N.Y.) 99, 253 (1976); 111, 201 (1978); O. Scholten, F. Iachello, and A. Arima, *ibid.* 115, 325 (1978).
[16]O. Scholten, Ph.D. thesis, Rijksuniversiteit te Groningen, 1980 (unpublished); and private communication.
[17]P. A. Crowley, J. R. Kerns, and J. X. Saladin, Phys. Rev. C 3, 2049 (1971).
[18]I. Y. Lee, N. R. Johnson, F. K. McGowan, R. L. Robinson, M. W. Guidry, L. L. Riedinger, and S. W. Yates, Phys. Rev. C 25, 1865 (1982).
[19]N. R. Johnson, I. Y. Lee, F. K. McGowan, T. T. Sugihara, S. W. Yates, and M. W. Guidry, Phys. Rev. C 26, 1004 (1982).
[20]F. K. McGowan and W. T. Milner, Phys. Rev. C 23, 1926 (1981).
[21]F. K. McGowan, Phys. Rev. C 24, 1803 (1981).
[22]J. P. Collins, C. T. Wunker, R. L. Place, and D. R. Ober, Bull. Am. Phys. Soc. 21, 149 (1976).