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(n–γ) Directional Correlation in the Reaction ^{20}Ne(d,$n\gamma$)^{21}Na ($E^* = 330$ keV)

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Abstract. Time-of-flight measurements of neutron–gamma directional correlation have been performed in two different geometric arrangements for the first excited 330 keV state of ^{21}Na. From the deduced multipole mixing parameter δ and the known life-time τ the characteristics of the low energy level can be determined and discussed. The assignment $5/2^+$ is established on the basis of the γ transition probability amounting to ~40 Weisskopf units. These results favour the nuclear model of collective rotational bands with Coriolis coupling for the low-lying levels of the 21 nucleon system.

1. Introduction

From the point of view of the nuclear spherical shell-model, the system of 11 protons and 10 neutrons should be considered as a triplet-configuration $(1d_{5/2})^3_{3/2}$ of the 3 protons in the $1d_{5/2}$ sub-shell, holding for the ground state spin 3/2. The first excited state would then have the single-particle configuration $(1d_{5/2})^2_0 + 1d_{5/2}$, giving the spin 5/2 and rejecting the alternative value 3/2 for that state; this also fits the transferred angular momentum $l_p = 2$, when the reaction is assumed to go through a stripping mechanism [1, 2].

More recent investigations suggest the interpretation of low-lying nuclear states in the mass-region $A \approx 20$ by collective motions of a deformed rigid core. The attempt to explain ground state and first excited state in $^{21}_{11}$Na by collective rotational behaviour leads to the Coriolis coupling model used by Malik and Scholz [3]. The six $1d$-$2s$ rotational bands, $1d_{5/2}$ ($K = 3/2$), $2s_{1/2}$ ($K = 1/2$), $1d_{5/2}$ ($K = 1/2$ hole, 5/2), $1d_{3/2}$ ($K = 1/2$, 3/2), given here with increasing band head energy, are mixed under fixed parametrization.

The ground and first excited state in ^{21}Na can then be interpreted as levels of the ground state rotational band with unambiguous spin assignment of 3/2 and 5/2 respectively (Fig. 1). If the Coriolis coupling model holds for the ground and first excited state, the probability $T(E2)$ for electric quadrupole transition, which is nearly completely determined by collective behaviour only, in contrast to $T(M1)$, should be much larger than one Weisskopf unit.

With this in mind, the discussion of nuclear structure and spin assignment of the

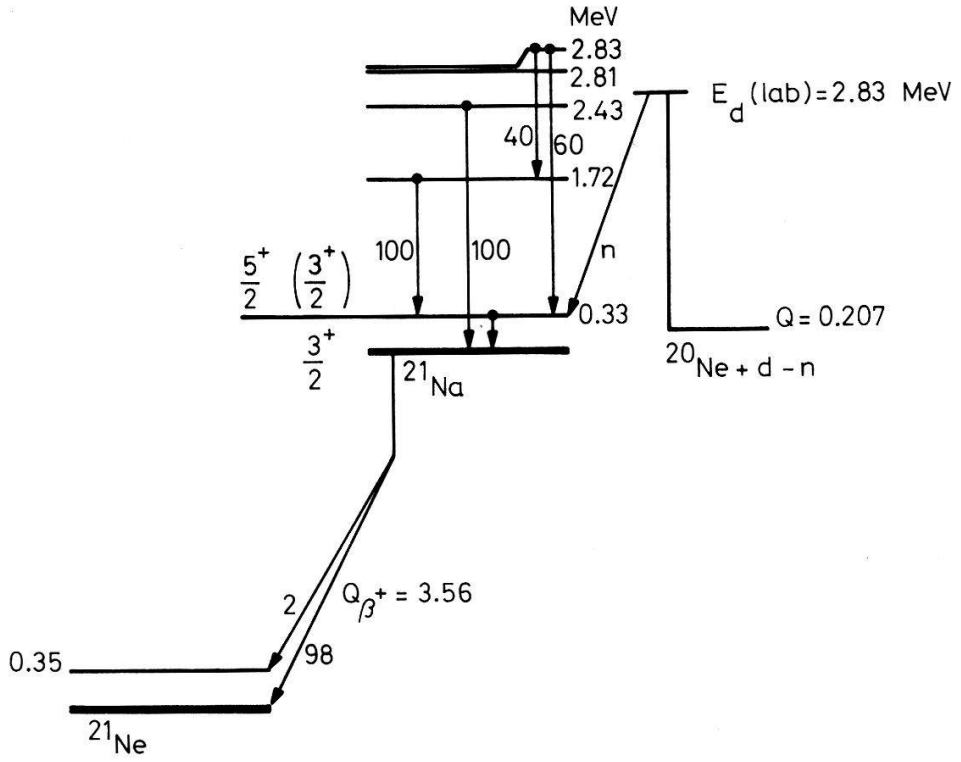

Figure 1
Level scheme of the low-lying levels in ^{21}Na. The energy available for the outgoing neutron and the residual nucleus is $E(\text{C.M.}) = 2.78$ MeV.

first excited state in ^{21}Na can be done by considering the multipole mixing parameter δ, obtained here from $(n-\gamma)$ directional correlation analysis, and the life-time τ, measured by Bamberger et al. [5].

2. Neutron–γ-Ray Directional Correlation Measurements

The directional correlation of the 330 keV γ-ray in coincidence with the neutron group, leading to the first excited state in the final nucleus, was measured in two geometries:

— 'colinear', with the particle counter at $\theta_n = 0°$ (θ_γ = variable) and fitting with the 'method II' of Litherland and Ferguson [6];
— 'off-axis' geometry, with the particle counter at the maximum of the reaction cross-section: $\theta_n = \pi/4$ ($\theta_\gamma = \pi/2$, ϕ_γ = variable).

The 'off-axis' geometry has finally been used only for confirmation of the weakness of the electric quadrupole component.

The neutron groups have been detected in a 1.5″ ⌀ × 1.5″ plastic counter, which was connected in a time-of-flight, fast–slow, coincidence circuit to the 2″ ⌀ × 2″ NaI(Tl) gamma detector. The distances of the two detectors from the target were large enough (30 cm and 50 cm, respectively) to keep the effects from finite solid angle very small.

Special attention was paid to the response-stability of the 56 AVP photomultipliers and the electronics. For this purpose an automatic differential spectrum stabilizer was placed in the slow γ-channel, readjusting periodically the γ-ray spectrum stored

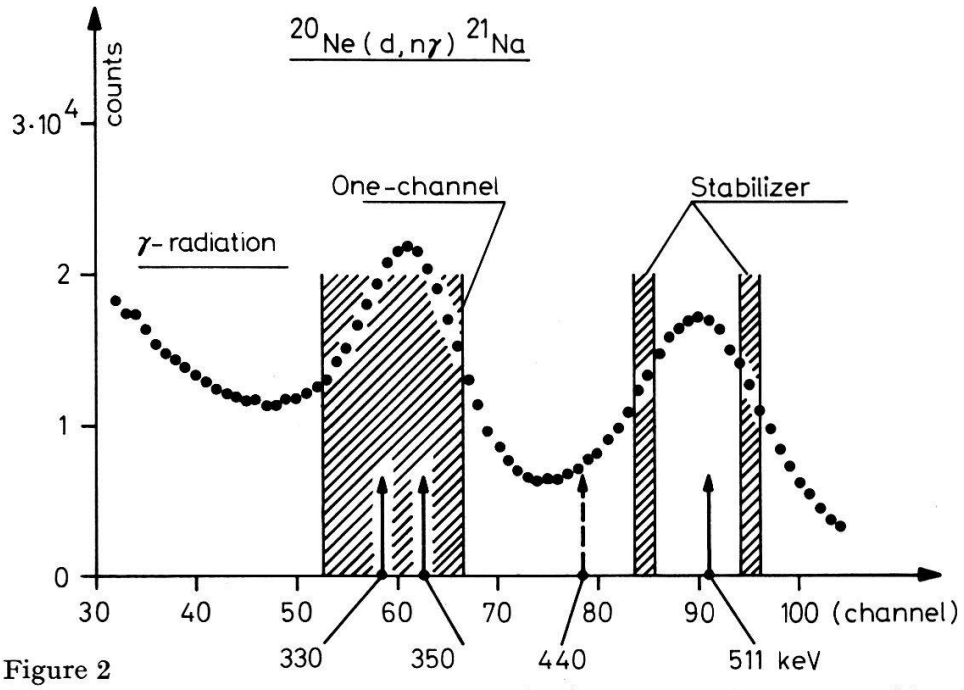

Figure 2
Associated gamma-ray spectrum. The arrows indicate γ-rays from competitive reactions:
^{21}Ne $\rightarrow E_1^* = 350$ keV.
^{23}Na $\rightarrow E_1^* = 440$ keV.
^{21}Na, β^+ decay of the ground state $\rightarrow E$(annihil.) = 511 keV.

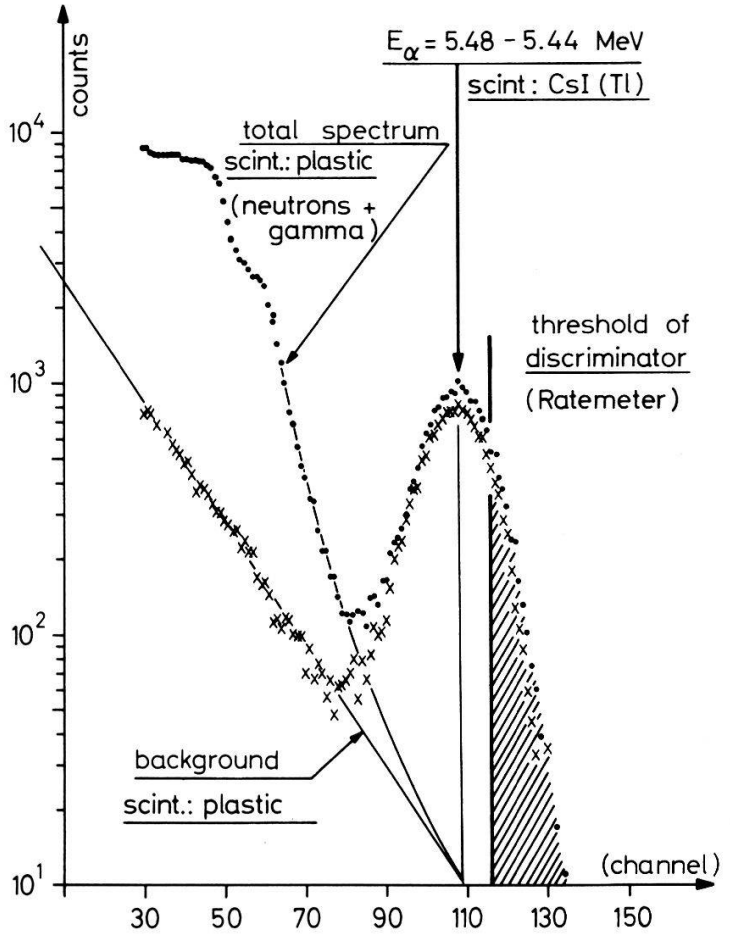

Figure 3
Spectrum of the integrated pulses in the neutron channel.
× empty target.
● filled target, 200 mmHg nat. neon.
$I_d = 0.2$ μA, E_d(Lab) = 2.83 MeV.

in the first group of 128 channels. The stability control of the neutron counter was carried out by counting the 5.4 MeV α-particles from an $^{241}_{95}Am$ source after integration of the light pulses produced by a $4 \times 4 \times 1$ mm CsI(Tl) scintillator. This small crystal was mounted directly on the neutron counter PM. Figure 2 shows a typical γ-ray spectrum and Figure 3 the spectrum of the integrated pulses in the neutron counter. It must be noted that the dashed part of the α-particle reference peak was not affected by the tail of the 'outside' spectrum; on the other hand, the zero-cross threshold did not accept for fast correlation analysis the non-integrated pulses from the α-particles.

The cylindrical gas-target was filled at 200 mmHg with spectroscopic pure neon of natural isotopic abundance (92% neon-20, 8% neon-22). The 3 MeV deuteron beam from the van de Graaff accelerator entered the gas cell through a 1.25 μ nickel foil and had then a mean energy of $E_d = (2.83 \pm 0.06)$ MeV. The current was held constant at 0.2 μA.

The peak area of the neutron time-of-flight spectrum, stored in the second group of 128 channels, has been used for the measurement of the directional correlation function (Fig. 4). Competitive reactions, leading either to higher excited states in ^{21}Na,

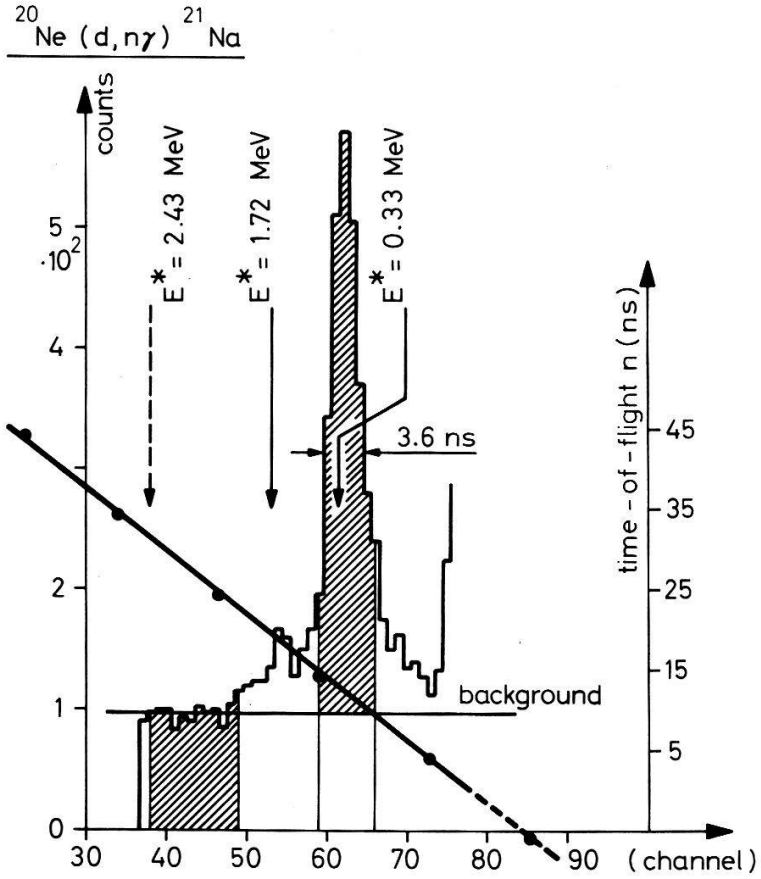

Figure 4
Neutron time-of-flight spectrum. 'Off-axis' geometry: $\theta_n = \pi/4$, $\theta_\gamma = \pi/2$, $\phi_\gamma = 120°$. $I_d = 0.2$ μA, E_d(Lab) = 2.83 MeV. $Q_d = 2500$ μCb. The arrows indicate competitive levels.

or to other final nuclei, were excluded either by γ-ray energy selection, or by time-of-flight separation:

$^{20,22}Ne(d, n\gamma)^{21,23}Na$,

$^{20,22}Ne(d, p\gamma)^{21,23}Ne$,

$^{12}C(d, n\gamma)^{13}N$.

More detailed information on the apparatus and on the experimental corrections are given in reference [7].

3. Particle–γ-Ray Directional Correlation Analysis

The correlation function for the emission of γ-rays in the direction $(\theta_\gamma, \phi_\gamma)$, when the emitting state, with angular momentum and magnetic quantum number (a, α), decays to the final state (b, β), is derived in detail in reference [7] and has the general form

$$W(\theta_\gamma \phi_\gamma) \sim \sum_{LL'k\kappa} (-)^{L-L'} F_k(LL'ba)\, \rho_{k\kappa}(aa) \hat{k}^{-1} Q_k \times Y_k^\kappa(\theta_\gamma \phi_\gamma) \langle b|L\|a\rangle \langle b|L'\|a\rangle^*, \quad \hat{k} = \sqrt{2k+1}.$$

In this expression $\rho_{k\kappa}(aa)$ is the statistical tensor describing the polarization of the emitting state, F_k the well-known γ-emission coefficient [8], L, L' the γ-multipolarity and $\langle b|L\|a\rangle$ the reduced matrix element of the electromagnetic interaction Hamiltonian in the notation of Ferguson [9]. k takes only even values limited by the selection rule

$$k \leqslant \text{minimum } (L + L', 2a),$$

and Q_k is the correction factor for finite counter solid angle [9, 10].

In the 'colinear' set-up of the neutron counter the density matrix is diagonal and symmetric within the diagonal:

$$\langle a\alpha|\rho|a\alpha'\rangle = \langle a - \alpha|\rho|a - \alpha'\rangle\, \delta_{\alpha\alpha'}.$$

The spins involved in the present reaction are such that in principle only γ-rays from $|\alpha| = \frac{1}{2}, \frac{3}{2}$ magnetic substates are selected. Under these conditions the introduction of the multipole mixing parameter δ and of the relative population parameter

$$P = \frac{\langle a\tfrac{3}{2}|\rho|a\tfrac{3}{2}\rangle}{\langle a\tfrac{1}{2}|\rho|a\tfrac{1}{2}\rangle}$$

leads to a simple form for the 'colinear' correlation function:

$$W = 1 + \sum_{k=2,4} A_k P_k(\cos\theta_\gamma).$$

The A_k coefficients can be written either in terms of $a = \frac{3}{2}$, or $a = \frac{5}{2}$:

$$A_2(a = \tfrac{3}{2}) = \frac{1}{1+\delta^2}\left[F_2(11\tfrac{3}{2}\tfrac{3}{2}) - 2\delta F_2(12\tfrac{3}{2}\tfrac{3}{2}) + \delta^2 F_2(22\tfrac{3}{2}\tfrac{3}{2})\right] Q_2 \frac{\langle \frac{3}{2}\frac{1}{2}, \frac{3}{2} - \frac{1}{2}|20\rangle}{\langle \frac{3}{2}\frac{1}{2}, \frac{3}{2} - \frac{1}{2}|00\rangle} \frac{1 - \dfrac{\langle \frac{3}{2}\frac{3}{2}, \frac{3}{2} - \frac{3}{2}|20\rangle}{\langle \frac{3}{2}\frac{1}{2}, \frac{3}{2} - \frac{1}{2}|20\rangle} P}{1 - \dfrac{\langle \frac{3}{2}\frac{3}{2}, \frac{3}{2} - \frac{3}{2}|00\rangle}{\langle \frac{3}{2}\frac{1}{2}, \frac{3}{2} - \frac{1}{2}|00\rangle} P}$$

$$A_4(a = \tfrac{3}{2}) \equiv 0$$

$$A_2(a=\tfrac{5}{2}) = \frac{1}{1+\delta^2}[F_2(11\tfrac{3}{2}\tfrac{5}{2}) - 2\delta F_2(12\tfrac{3}{2}\tfrac{5}{2}) + \delta^2 F_2(22\tfrac{3}{2}\tfrac{5}{2})]\, Q_2 \frac{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|20\rangle}{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|00\rangle} \frac{1-\frac{\langle \frac{5}{2}\frac{3}{2},\frac{5}{2}-\frac{3}{2}|20\rangle}{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|20\rangle}P}{1-\frac{\langle \frac{5}{2}\frac{3}{2},\frac{5}{2}-\frac{3}{2}|00\rangle}{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|00\rangle}P}$$

$$A_4(a=\tfrac{5}{2}) = \frac{\delta^2}{1+\delta^2} F_4(22\tfrac{3}{2}\tfrac{5}{2})\, Q_4 \frac{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|40\rangle}{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|00\rangle} \frac{1-\frac{\langle \frac{5}{2}\frac{3}{2},\frac{5}{2}-\frac{3}{2}|40\rangle}{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|40\rangle}P}{1-\frac{\langle \frac{5}{2}\frac{3}{2},\frac{5}{2}-\frac{3}{2}|00\rangle}{\langle \frac{5}{2}\frac{1}{2},\frac{5}{2}-\frac{1}{2}|00\rangle}P}$$

By introducing the numerical values of the coupling coefficients and of the F_k and Q_k functions, one obtains finally

$$A_2(a=\tfrac{3}{2}) = \frac{1}{1+\delta^2}[1.5492\,\delta - 0.4]\frac{P-1}{P+1}$$

$$A_4(a=\tfrac{3}{2}) \equiv 0$$

$$A_2(a=\tfrac{5}{2}) = \frac{1}{1+\delta^2}[-0.3992 - 2.0240\,\delta + 0.2036\,\delta^2]\frac{1+0.25P}{1+P}$$

$$A_4(a=\tfrac{5}{2}) = \frac{\delta^2}{1+\delta^2}\frac{1-1.5P}{1+P}0.6465.$$

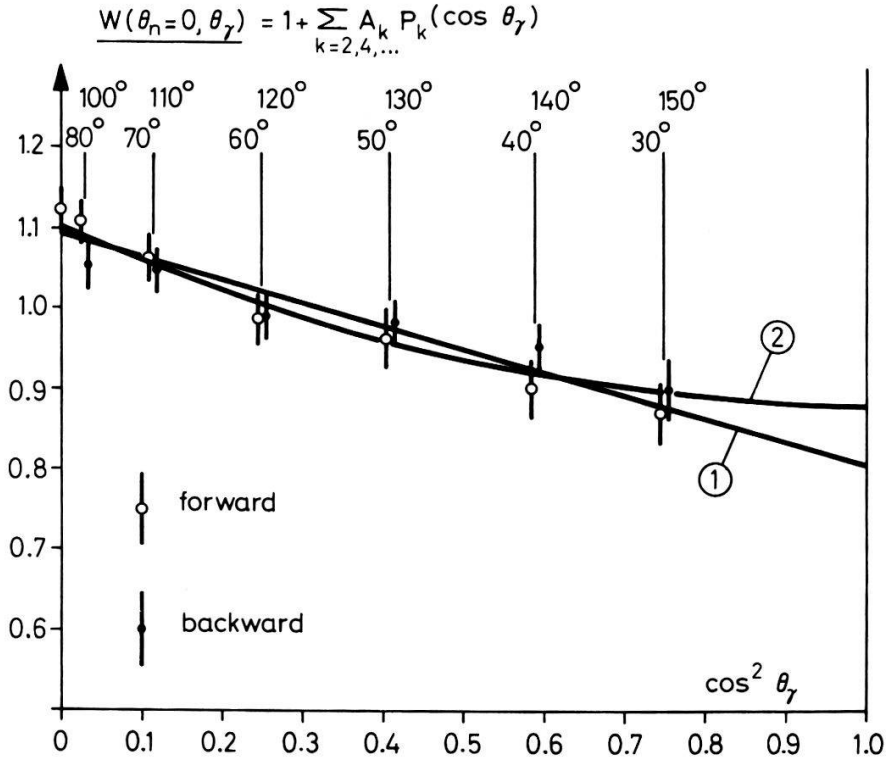

Figure 5
'Colinear' geometry, polynomial Legendre fit to the measured points. (1) $k = 0.2$; (2) $k = 0, 2, 4$.

Figure 5 shows the Legendre Polynomial fit to the measured points. The resulting A_k coefficients and the calculated δ values are given for both spin-assignments in Tables 1 and 2, respectively.

Table 1
A_k- and B_κ-values, resulting from the Legendre Polynomial and cosine fits, respectively

	$k=0$ $\kappa=0$	$k=2$ $\kappa=2$	$k=4$ $\kappa=4$
'Colinear' geometry	$A_k = 1 \pm 0.01$	-0.24 ± 0.03	
	$A_k = 1 \pm 0.01$	-0.20 ± 0.04	0.07 ± 0.05
'Off-axis' geometry	$B_\kappa = 1 \pm 0.01$	-0.14 ± 0.01	
	$B_\kappa = 1 \pm 0.01$	-0.14 ± 0.01	-0.02 ± 0.01

The two solutions δ_3 and δ_4 are not real and therefore not given here. In the $a = \frac{3}{2}$ case a reasonable value of 0.05 was assumed for the relative population parameter P. However it can be seen that δ remains always greater than 0.4, whatever the value of P.

In the 'off-axis' arrangement of the neutron counter the form of the density matrix depends on the populating reaction mechanism and does no longer possess the high symmetry properties. Under the assumption of a pure stripping process, the 'offset' correlation function can nevertheless be expanded in cosine terms, but the coefficients are much more complicated [7]. Figure 6 shows the cosine fit to the measured points and the resulting B_κ-coefficients are given in Table 1. These results are a confirmation of the weakness of the electric quadrupole component.

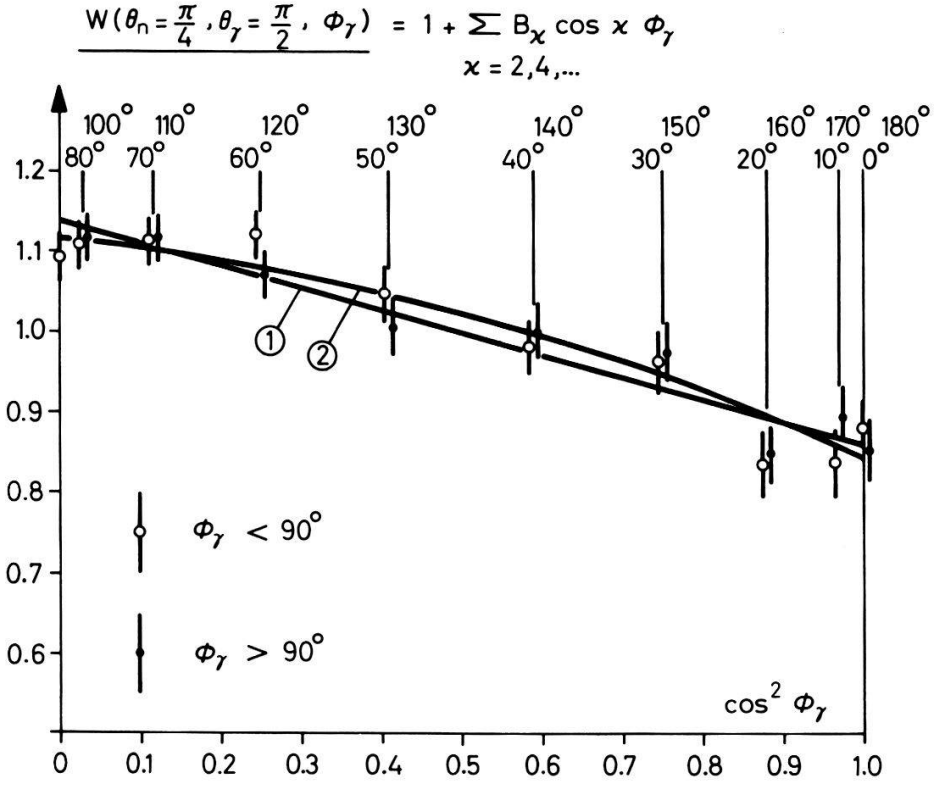

Figure 6
'Off-axis' geometry, cosine fit to the measured points. (1) $\kappa = 0, 2$; (2) $\kappa = 0, 2, 4$.

Table 2
Transition probabilities from the present work and from Pronko et al. [4]

Multipole transition $a \to b$	Present work: $^{20}Ne(d, n\gamma)^{21}Na$				Pronko et al.: $^{24}Mg(p, \alpha\gamma)^{21}Na$			
	$\delta_{1,2}$	$T(E2)$ (WU)	$B(E2)$ (e^2 fm^4)	T(M1) (WU)	$\delta_{1,2}$	$T(E2)$ (WU)	$B(E2)$ (e^2 fm^4)	T(M1) (WU)
$\frac{5}{2} \to \frac{3}{2}$	-0.12 ± 0.02 4.0	39^{+29}_{-17} >3000	170^{+127}_{-73}	$2.5 \cdot 10^{-2}$ $\pm 0.02 \cdot 10^{-2}$	-0.05 ± 0.02	6 ± 4	30 ± 14	$4.3 \cdot 10^{-2}$ $\pm 10^{-2}$
Sodium-21 ($E^* = 330$ keV)								
$\frac{3}{2} \to \frac{3}{2}$	0.4 ± 0.03 5.5	425 ± 60 >3000	1600 ± 200	$2.2 \cdot 10^{-2}$ $\pm 0.02 \cdot 10^{-2}$	>0.46	>400		$<3.6 \cdot 10^{-2}$

4. Spin Assignment and Discussion

The probability of this parity-conservating multipole transition is written as

$$T = T(M1) + T(E2).$$

The probabilities $T(M1)$ and $T(E2)$ of the pure transitions are given in terms of the reduced probabilities $B(M1)$ and $B(E2)$. Remembering that

$$T = \frac{1}{\tau}; \quad \tau = (14 \pm 3)\ \text{ps} = \text{lifetime of the 330 keV level [5]},$$

and that

$$\delta^2 = \frac{|\langle b|L = 2\|a\rangle|^2}{|\langle b|L = 1\|a\rangle|^2} = C^2 \frac{B(E2)}{B(M1)},$$

the expressions to be used for the calculations then become:

$$\frac{1}{\tau} = T(E2)\left[1 + \frac{100}{3}\left(\frac{\hbar c}{E_\gamma}\right)^2 \frac{C^2}{\delta^2}\right],$$

$$\frac{1}{\tau} = T(M1)\left[1 + \frac{3}{100}\left(\frac{E_\gamma}{\hbar c}\right)^2 \frac{\delta^2}{C^2}\right].$$

The constant factor C^2 can be determined with the relation 49 of Moszkowski [11]:

$$C^2 = 0.9 \cdot 10^{19}\ \text{cm}^{-2}.$$

The results are given in Table 2.

It is now clear that the 330 keV level in ^{21}Na must be identified as the spin $= \frac{5}{2}$ level of the ground state rotational band in the Coriolis coupling model. In fact, the result of (39^{+29}_{-17}) Weisskopf units is much more compatible with a collective rotation of a system with 21 nucleons than with a simple-particle excitation in the spherical shell-model. The spin $= \frac{3}{2}$ must be excluded because the corresponding transition probability of (425 ± 60) Weisskopf units is much too large for such a system. Pronko et al. [4] have shown that the energy predicted by the model for this level agrees fairly well with experiment, whereas the simple Nilsson model, which does not take into account band-mixing, is not in agreement with the experimental finding (≈ 1 MeV). The same authors have calculated the theoretical reduced transition probability and give

$$B(E2) = 57\ e^2\ \text{fm}^4.$$

For comparison the experimental results from Pronko et al. [4] are given in Table 2.

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