BB

ISSN 1343-2230
CNS-REP-47
ISSN 1346-244X
RIKEN-AF-NP-435
September, 2002

CNS Report

Isomeric 0^+ state in ^{12}Be

S. Shimoura, A. Saito, T. Minemura, Y.U. Matsuyama,
H. Baba, H. Akiyoshi, N. Aoi, T. Gomi, Y. Higurashi, K. Ieki,
N. Imai, N. Iwasa, H. Iwasaki, S. Kanno, S. Kubono,
M. Kunibu, S. Michimasa, T. Motobayashi, T. Nakamura,
H. Sakurai, M. Serata, E. Takeshita, S. Takauchi, T. Teranishi,
K. Ue, K. Yamada, Y. Yanagisawa, M. Ishihara, N. Itagaki

submitted to Physics Letters B

Center for Nuclear Study (CNS)

Graduate School of Science, the University of Tokyo
Wako Branch at RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Correspondence: cnsoffice@cns.s.u-tokyo.ac.jp

Isomeric 0^+ State in ^{12}Be

S. Shimoura [a,*] A. Saito [b] T. Minemura [c] Y. U. Matsuyama [b]

H. Baba [b] H. Akiyoshi [c] N. Aoi [d] T. Gomi [b] Y. Higurashi [b] K. Ieki [b]

N. Imai [d] N. Iwasa [e] H. Iwasaki [a] S. Kanno [b] S. Kubono [a]

M. Kunibu [b] S. Michimasa [a] T. Motobayashi [b] T. Nakamura [f]

H. Sakurai [d] M. Serata [b] E. Takeshita [b] S. Takeuchi [b] T. Teranishi [a]

K. Ue [a] K. Yamada [b] Y. Yanagisawa [c] M. Ishihara [c] N. Itagaki [d]

[a] *Center for Nuclear Study, University of Tokyo, Saitama 351-0198, Japan*

[b] *Department of Physics, Rikkyo University, Tokyo 171-8501, Japan*

[c] *Institute for Physical and Chemical Research (RIKEN), Saitama 351-0198, Japan*

[d] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

[e] *Department of Physics, Tohoku University, Miyagi 980-8578, Japan*

[f] *Department of Applied Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan*

Preprint submitted to Physics Letters B *11 September 2002*

Abstract

An isomeric 0^+ state in ^{12}Be was found at E_x=2.24 MeV. The isomer was identified by measuring coincident two γ rays from in-flight ^{12}Be nuclei, $^{12m}\mathrm{Be} \rightarrow {}^{12}\mathrm{Be}^* (2_1^+) \rightarrow {}^{12}\mathrm{Be}_{\mathrm{g.s.}}$, produced by the projectile fragmentation of ^{18}O at 100*A* MeV on a beryllium target. Its spin was determined to be 0^+ by the angular correlation of the two γ-rays. The low excitation energy of the 0^+ state is a strong evidence of the break of the $N = 8$ shell closure in the ^{12}Be nucleus.

Key words: Isomeric state, γ-γ correlation, Radioactive beam experiment

PACS: 27.20.+n, 23.20.En

* Corresponding author.
Email address: `shimoura@cns.s.u-tokyo.ac.jp` (S. Shimoura).

The neutron-rich nucleus ^{12}Be has attracted much attention, since it is suggested that the $N = 8$ shell closure may be broken in the neutron-rich Be isotopes. It is well known that ^{11}Be has the ground state of $1/2^+$ 320 keV below the normal $1/2^-$ state, indicating that the gap between p- and sd-shells is strongly quenched and the $p_{1/2}$ and $s_{1/2}$ orbitals almost degenerate. The spectroscopic factor of the n+^{11}Be($1/2^+$) for the ground state of ^{12}Be has been extracted to be about 50 % in a study of the neutron knockout reaction ^{9}Be(^{12}Be,^{11}Be+γ)X[1, 2]. A large deformation of ^{12}Be has been found in an experiment of the ^{12}Be(p,p$'$)^{12}Be*(2^+) reaction[3]. These facts indicate that a break of the $N = 8$ shell closure is seen in ^{12}Be as well as in ^{11}Be. The recent finding of a low-lying intruder 1^- state at $E_x = 2.7$ MeV populated by a Coulomb excitation[4] also supports the picture that the p- and sd-shells almost degenerate in ^{12}Be.

Another consequence of the degeneracy might be the existence of the second 0^+ state at a low excitation energy. A possibility of the low-lying 0_2^+ states in the $T = 2$ multiplets of $A = 12$ nuclei was discussed already in 1976 by Barker[5] based on the picture of degeneracy of p- and sd-shells in ^{11}Be. The 0_2^+ excitation energy for ^{12}Be was predicted to be 2.35 MeV. Many recent theoretical studies[6–12] also predict a low-lying 0_2^+ state. Experimentally, the 2.7-MeV state found in the ^{10}Be(t,p) reaction was a candidate of the 0_2^+ state[13]. However, the recent assignment of 1^- [4] to the 2.7-MeV state stimulates an experimental attempt to search for the undiscovered 0_2^+ state.

In an earlier experiment on the (p,t) and (p,^{3}He) reactions on ^{14}C, two $T = 2$ states were found both for ^{12}C and ^{12}B [14]. In the presently adopted assignment, the lower states are of 0^+ which form the isospin multiplet with the ground state of ^{12}Be, while the spins of the higher ones are uncertain[15]. Although the energy differences between the two states are almost equal (about 2.1 MeV) to the excitation energy of the 2_1^+ of the ^{12}Be, the angular distributions of the (p,t) and (p,^{3}He) reactions favor $l = 0$ transitions[14]. These facts suggest a possibility that both the 2_1^+ and 0_2^+ states are closely located at around E_x=2.1 MeV for the $T = 2$ isospin multiplets of $A = 12$ nuclei.

If we assume that the 0_2^+ state in ^{12}Be locates just above the 2^+ state (2.1 MeV), the 0_2^+ state is expected to decay through γ emission to the 2^+ state, which is to be followed by a cascade γ decay to the ground state. In addition a direct decay to the ground state by emission of e^+e^- pair is possible. In both cases, the decay energies are so small that the lifetime of the 0_2^+ state can be as long as several tens of ns, and hence the state could appear as an isomer.

In order to produce ^{12}Be in the isomeric 0_2^+ state, we used a projectile fragmentation reaction of ^{18}O ions. The reaction is expected to populate various low-lying states of fragment nuclei as demonstrated in several experiments of in-beam γ-spectroscopy[16, 17] and in studies on isomeric ratios in the projectile fragmentation[18, 19]. In the present study, the isomeric state was identified by detecting the cascade γ rays in coincidence, which were to appear in its de-excitation (isomer $\rightarrow 2^+ \rightarrow 0^+$). These γ rays were measured in coincidence with the fragment which was confirmed to be ^{12}Be both before and after the decay. This method enabled one to reduce background γ-rays due to nuclear reactions induced by the beam particles in stopping materials.

The experiment was performed at RIKEN Accelerator Research Facility. A primary beam of ^{18}O projectiles at 100 A MeV bombarded a 2-g/cm^2 thick Be target. The $^{12(m)}$Be nuclide at 60 A MeV was selected through the RIKEN Projectile Fragment Separator (RIPS)[20]. The intensity and purity of the ^{12}Be beam were typically 2×10^4 pps and 85 %, respectively. Two plastic scintillators at the second (F2) and the third (F3) focal points of the RIPS were used for event-by-event identification of ^{12}Be fragments with the time-of-flight (TOF) between the two scintillators and the energy losses in the scintillators. Gamma rays were detected by an array of 68 NaI(Tl) scintillators (DALI) positioned at 70 cm downstream of the F3 scintillator. Each NaI(Tl) had an active volume of $12 \times 6 \times 6$ cm^3, and was set with its longer axis along the horizontal direction vertical to the beam axis. The array was divided into 6 vertical layers. They respectively consisted of 8, 12, 14, 14, 12, and 8 scintillators and were placed with their centers aligned to the beam line. The energy threshold for each detector was set to be lower than 50 keV. Timing signals were used to distinguish between the true and accidental coincidence events. They were also used to determine the vertex point at which the γ-ray was emitted. This information on the vertex point was used for the Doppler-shift correction. Time resolution of each NaI(Tl) was better than 1 ns (1σ) for 1-MeV photons. The ^{12}Be nucleus after the isomeric decay was detected by a plastic scintillator hodoscope with a 1×1 m^2 active area located 4 m downstream of DALI. The hodoscope consisted of a 5-mm thick ΔE plane and a 60-mm thick E plane[21]. Particle identification was performed by using ΔE-TOF and E-TOF information.

Figure 1(a) shows a two dimensional histogram of $E_{\rm high}$ vs $E_{\rm low}$ for those events in which two of the NaI(Tl) scintillators recorded signals from an in-flight ^{12}Be particle. Here $E_{\rm high}$ and $E_{\rm low}$ denote the higher and lower pulse heights from the two detectors, respectively. As shown in the figure, there is a broad peak around $E_{\rm high}$ = 2 MeV and $E_{\rm low}$ = 0.15 MeV. This peak becomes sharp after the Doppler correction as shown in Fig. 1(b), where $E^{\rm c}_{\rm high}$ and $E^{\rm c}_{\rm low}$ denote the corrected energies for $E_{\rm high}$ and $E_{\rm low}$, respectively. Since the peak energy of $E^{\rm c}_{\rm high}$ = 2.10 MeV corresponds to the excitation energy of the first excited 2^+ state, the coincident low-energy γ ray may be ascribed to the preceding transition from a new isomeric state, which is located at around 0.15 MeV above the 2^+ state.

In order to precisely determine the excitation energy of the new state, the projected $E^{c}_{\rm low}$ spectrum with a gate of $1.8 < E^{c}_{\rm high} < 2.4$ MeV (Fig. 2) has been analyzed with a Monte Carlo simulation (GEANT[22]). We assume that two photons, one of which is with the energy of 2.1 MeV, are simultaneously emitted from an in-flight fragment. The geometry of the experimental setup, the finite energy resolutions and thresholds of the NaI(Tl) detectors are taken into account. The best fit has been obtained for $E^{c}_{\rm low} = 0.14 \pm 0.01$ MeV. This result indicates that the excitation energy of the new state is $E_{\rm x} = 2.24 \pm 0.01$ MeV. We note that a small peak appeared at $E_{\rm x} = 2.24$ MeV in the spectrum of the ^{10}Be(t,p) reaction[13]. It is probable that the peak corresponds to the present isomeric state.

In order to make spin assignment to the new state, an angular correlation of the two cascade γ rays was obtained. In Fig. 3, the coincidence yield is plotted as a function of the difference between the azimuthal angles for the two γ rays, which were measured with respect to the direction of the ^{12}Be momentum. We have taken the azimuthal-angle correlation rather than other usual angular correlations since the best angular resolution can be obtained. The azimuthal angle can be directly obtained from the geometrical position of the γ-detector, and hence was determined with a good accuracy, irrespective of the position of the γ-emitter along the beam line. For comparison, theoretical predictions on the angular correlations are shown for different spin values of the isomer, where the experimental efficiencies and angular resolutions are taking into account. Three cases of cascade transitions are illustrated, respectively representing the isomer spin values of 0, 3 and 4; $0 \rightarrow 2 \rightarrow 0^+_1$ (solid curve), $3 \rightarrow 2 \rightarrow 0$ (dashed curve) and $4 \rightarrow 2 \rightarrow 0$ (dot-dashed curve), where only the lowest allowed multipolarity is considered for the γ transition. The isomer spins of 1 and 2 were not considered because the relevant lifetime should be too short for the isomer to survive through a pass of about 30 m before reaching the detector position. The excellent fit seen in the figure confirms the spin value of 0. Among possible spin-0 states at low excitation energies possible 0^- states are theoretically expected only to appear above the 1^- state at 2.7 MeV. Thus the observed isomeric state is most likely to be the second 0^+ state in ^{12}Be.

The decay probabilities of the isomer can be obtained by comparing the γ-ray yields to the number of isomeric fragments existing in the range of the γ-ray detection. Here the latter is calculated from the observed ^{12}Be flux and by the isomer ratio at F3 (R_{F3}). As mentioned before, the 0_2^+ state decays either by emission of the cascade γ rays or by emission of an e^+e^- pair leading to the ground 0^+ state. The partial decay probability for the cascade γ emission was obtained directly from their coincidence yield as $W_{2\gamma} = (1.5 \pm 0.1) \times 10^4 / R_{F3}$ [sec^{-1}]. On the other hand the probability for the e^+e^- pair emission was obtained from the yield of correlated 0.511-MeV γ ray pairs, which were associated with positron annihilation by materials such as in a beam pipe near the γ detectors. Assuming that all the observed annihilation γ rays originate from the isomeric state, the e^+e^- decay probability was estimated as $W_{e^+e^-} = (7.5 \pm 0.5) \times 10^4 / R_{F3}$ [sec^{-1}] $= 5.0 \pm 0.5\ W_{2\gamma}$. These results lead to branching ratios of 17±2 and 83±2 % for the E2 and E0 decays, respectively. In extracting the probabilities, a Monte-Carlo simulation was performed to estimate the spatial distributions of the pair-decay and annihilation processes and the detection efficiencies of these events. It included all the geometries of the experimental setup. The quoted errors are mainly due to uncertainties in the γ ray detection efficiency. By incorporating these probabilities with the traveling time (260 ns) between the target and F3, we deduced the lower and upper limits of the total decay rate to be 9.0×10^4 and 2.0×10^7 [sec^{-1}], respectively, which correspond to the limitation of 50 ns $< \tau <$ 11 μs on the meanlife τ of the 0_2^+ state.

The present finding of the 0_2^+ state at 2.24 MeV is in good harmony with the earlier discussion by Barker[5] mentioned before, which predicts the state at 2.35 MeV. The degeneracy of the $1/2^-$ and $1/2^+$ states in ^{11}Be leads to a picture for the neighboring nucleus ^{12}Be that the last two valence neutrons occupy almost equally these two orbits and hence two 0^+ states close in energy should appear. Indeed a recent shell model calculation considering the N/Z dependence of the single-particle energies[23] indicates that the ground and first excited 0^+ states are mainly composed of mixtures of the $(p_{1/2})^2$ and $(s_{1/2})^2$ configurations and they are separated from each other by about 1.8 MeV[12]. Another theoretical approach may be made based on clustering structures in Be isotopes as typically manifested in ^{8}Be. According to the α+α+4n model by Itagaki et al.[9], two non-perturbative 0^+ states with the $(3/2^-)^2(1/2^-)^2$ and $(3/2^-)^2(1/2^+)^2$ configurations for the four valence neutrons degenerate. By using the residual interactions used in ref. [9], the energy spacing between the two 0^+ states is calculated to be 1.7 MeV. Thus the observed 0_2^+ state is roughly understood as a result of the quenching of the p-sd shell gap that leads to almost degenerating orbitals of $p_{1/2}$ and $s_{1/2}$. The remaining difference in the observed and predicted excitation energies requires refinement of the models. For example, the single particle energies and the pairing interactions adopted in the models should be carefully examined.

In summary we have found an isomeric 0^+ state in ^{12}Be produced by the fragmentation of ^{18}O. The excitation energy is deduced to be 2.24 $\pm$ 0.01 MeV and the decay branches of the E2 transition to the first 2^+ state and the E0 (pair) decay to the ground 0^+ state are 17$\pm$2 and 83$\pm$2 %, respectively. The lower and upper limits of the meanlife are 50 ns and 11 μs, respectively. Further lifetime measurements with a better precision are anticipated for more detailed understanding on the nuclear structure of the neutron-rich Be isotopes.

We would like to thank the RIKEN Ring Cyclotron staff members for their operation during the experiment. We acknowledge valuable discussions on shell-model calculations with T. Otsuka. The present work was partially supported by the Grant-in-Aid for Scientific Research (No. 11440081) by the Ministry of Education, Culture, Sports, Science and Technology.

References

[1] A. Navin, et al., Phys. Rev. Lett. 85 (2000) 266.

[2] F. Nunes, et al., Nucl. Phys. A609 (1996) 43.

[3] H. Iwasaki, et al., Phys. Lett. B481 (2000) 7.

[4] H. Iwasaki, et al., Phys. Lett. B491 (2000) 8.

[5] F. Barker, J. Phys. G2 (1976) L45.

[6] A. Walters, et al., Phys. Rev. C42 (1990) 2062.

[7] N. Mau, J. Pacheco, Nucl. Phys. A607 (1996) 163.

[8] R. Sherr, H. Fortune, Phys. Rev. C60 (1999) 064323.

[9] N. Itagaki, et al., Phys. Rev. C62 (2000) 034301.

[10] F. Nunes, et al., Nucl. Phys. A703 (2002) 593.

[11] Y. Kanata-En'yo, Nucl. Phys. A687 (2001) 146c.

[12] T. Suzuki, R. Fujimoto, T. Otsuka, to be submitted to Phys. Rev. C .

[13] H. Fortune, et al., Phys. Rev. C50 (1994) 1355.

[14] D. Ashery, et al., Phys. Rev. C13 (1976) 1345.

[15] F. Ajzenberg-Selove, Nucl. Phys. A506 (1990) 1.

[16] K. Yoneda, et al., Phys. Lett. 499B (2001) 233.

[17] M. Belleguic, et al., Nucl. Phys. 682 (2001) 136c.

[18] B. Young, et al., Phys. Lett. 311B (1993) 22.

[19] J. Daugas, et al., Phys. Lett. 476B (2000) 213.

[20] T. Kubo, et al., Nucl. Instr. Meth. B70 (1992) 309.

[21] I. Hisanaga, et al., RIKEN Accel. Prog. Rep. 31 (1998) 162.

[22] Program code GEANT, CERN program library.

[23] T. Otsuka, et al., Phys. Rev. Lett. 87 (2001) 082502.

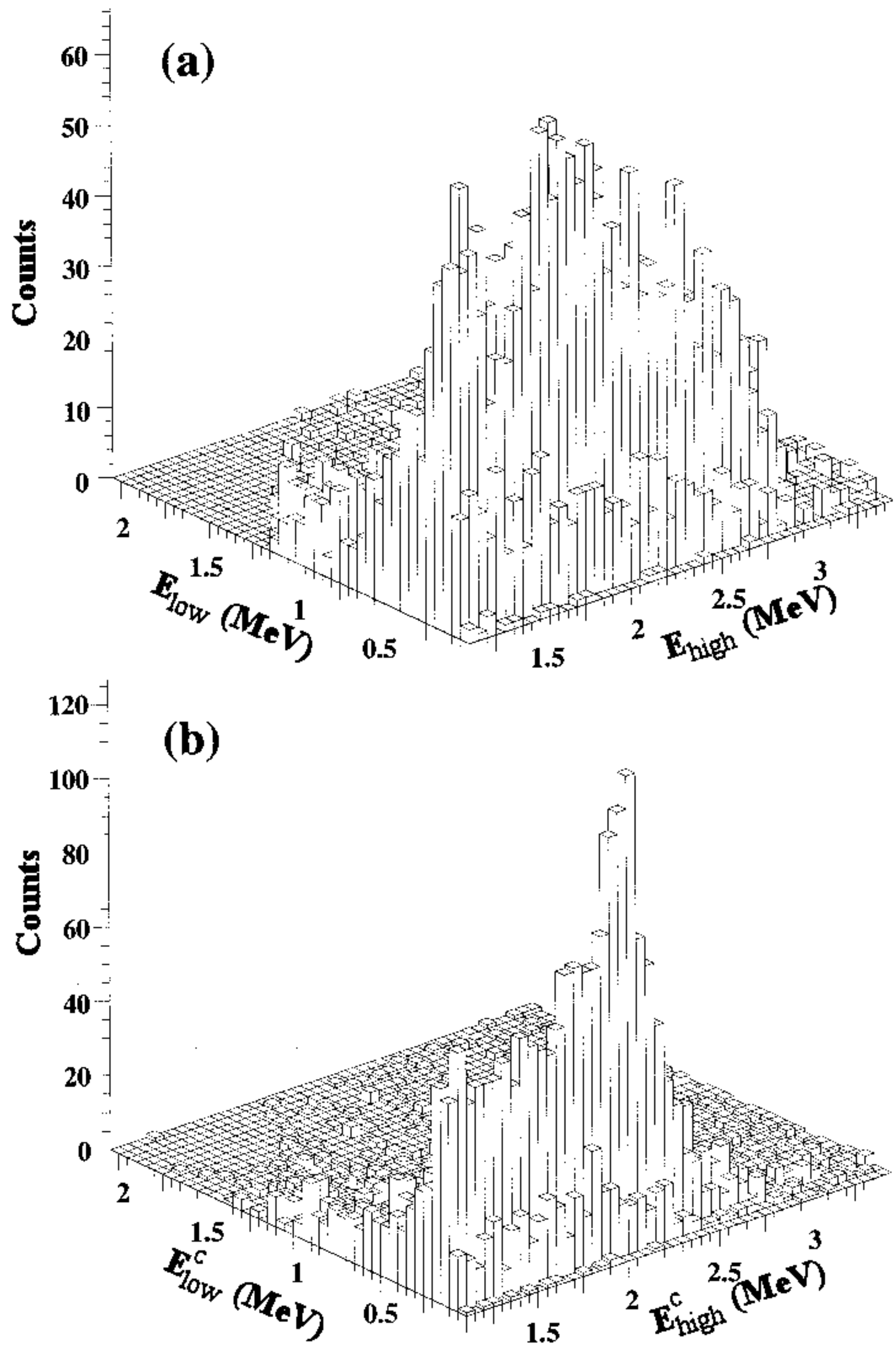

Fig. 1. Two dimensional histograms as functions of (a) $E_{\rm high}$ and $E_{\rm low}$ for two-hit events in DALI and (b) their Doppler-shift corrected energies, $E^{\rm c}_{\rm high}$ and $E^{\rm c}_{\rm low}$.

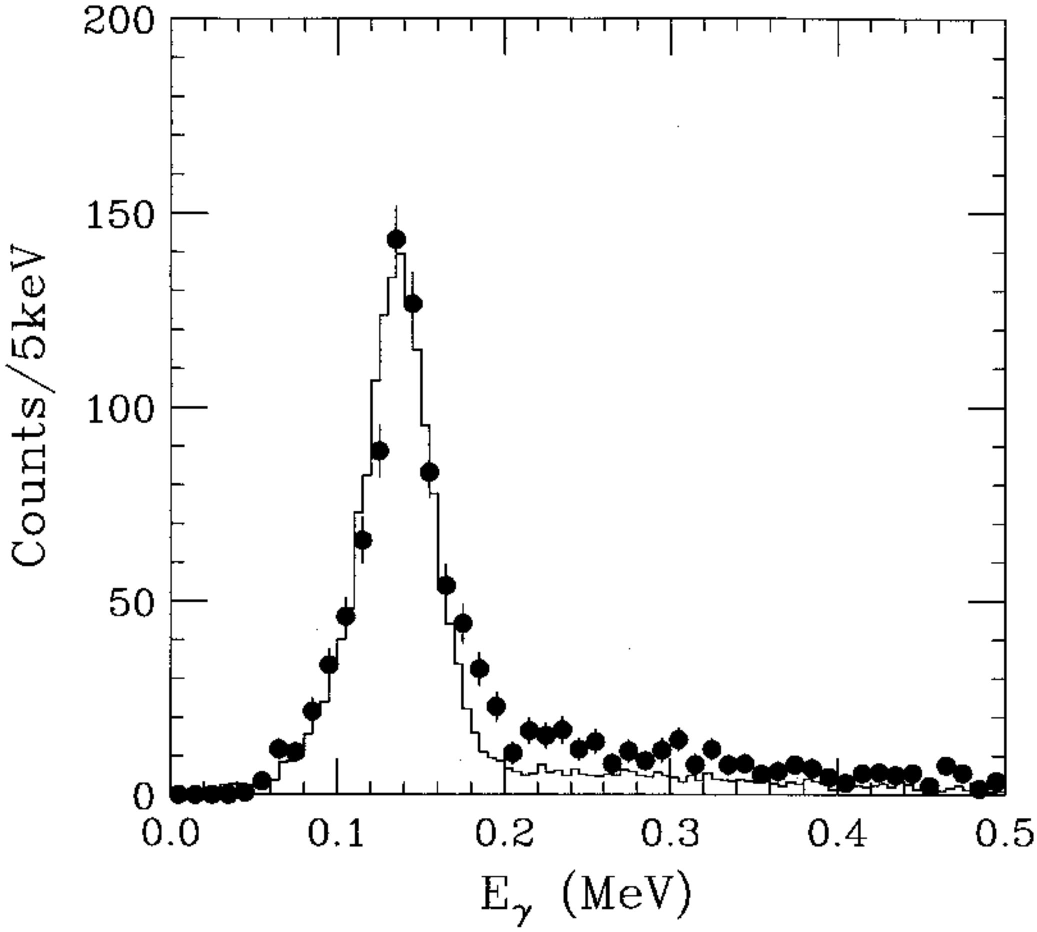

Fig. 2. Doppler-shift corrected γ ray spectrum coincident with a $2_1^+ \rightarrow 0_1^+$ (2.1 MeV) γ. Histogram denotes the prediction of a Monte Carlo simulation assuming an in-flight cascade decay emitting 0.14 and 2.1 MeV γ's.

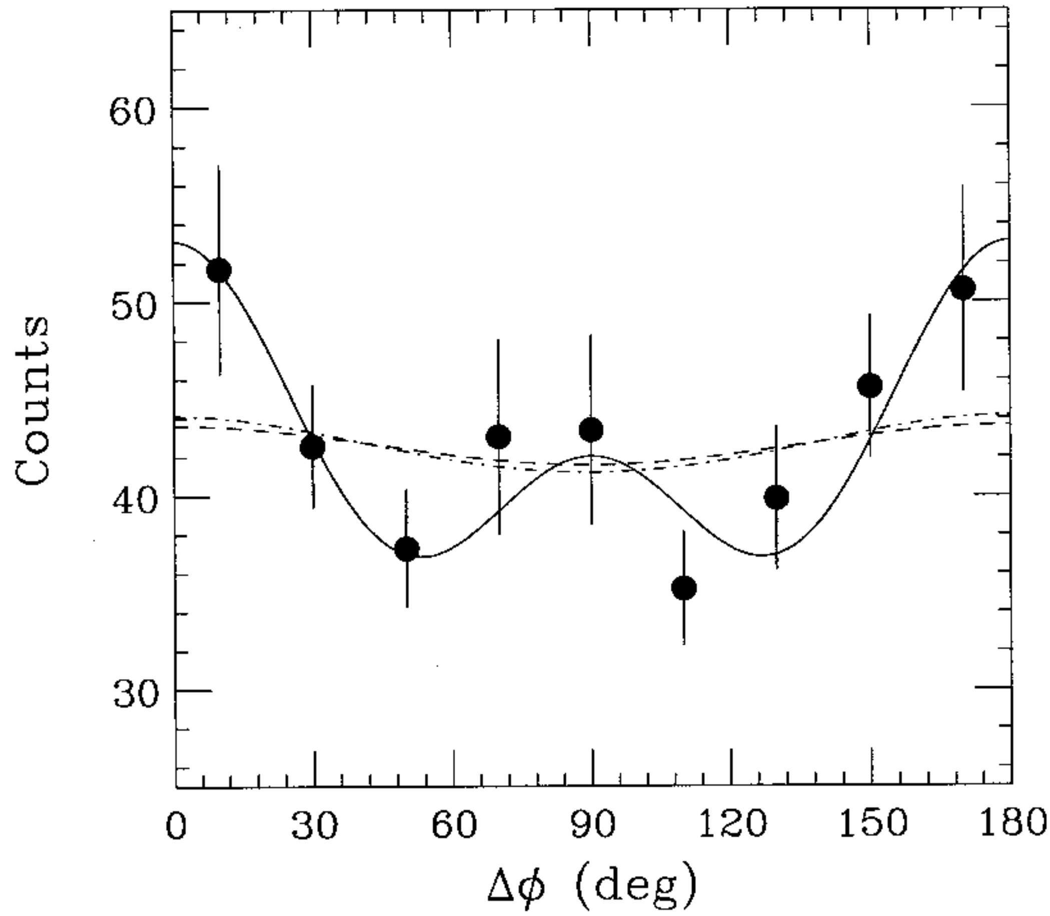

Fig. 3. Azimuthal angular correlation for 2.1-MeV and 0.14-MeV γ rays. Solid, dashed, and dot-dashed curves show the theoretical predictions assuming the $0 \to 2 \to 0$, $3 \to 2 \to 0$ and the $4 \to 2 \to 0$ transitions, respectively.