Low-lying E1 excitation modes: Structure and EM dissociation of ^{9}Be

A. Mengoni[a][b]

[a]ENEA, Applied Physics Division,
Via Don Fiammelli 2 - 40129 Bologna (Italy)

[b]INFN, Bologna Section,
c/o Department of Physics, University of Bologna
Via Irnerio 46 - 40138 Bologna (Italy)

The electric dipole excitation mode leading to low-lying states just above the dissociation threshold is considered. The case of ^{9}Be dissociating into the $^{8}\mathrm{Be}+n$ channel is analyzed in detail. It is shown that the excitation of an s-wave single particle state, located just above threshold, interferes with the direct dissociation process leading to the continuum.

1. Introduction

For most of the known nuclei, the strength of the electric dipole excitation (E1) is concentrated in the Giant Dipole Resonance (GDR). The GDR exhausts 80-90% fraction of the allowed electric dipole sum-rule strength for medium-mass and heavy nuclei. Recently, by studying the electromagnetic excitation/dissociation of some neutron-rich light nuclei, a considerable amount of E1 strength has been experimentally observed at excitation energies much below the GDR centroids. Typical examples were weekly bound nuclei such as ^{11}Li, ^{11}Be, ^{19}C and a few others. These nuclei have shown considerable amount of strength just above the one- or two-neutron dissociation threshold. This strength has been interpreted as a low-lying "soft" dipole mode, or as a single particle-like excitation into the continuum (direct breakup models).

There is, however, an additional possibility to have a concentration of E1 strength at low energies: the presence of a low-lying resonance state. A case which shows this feature is the ^{9}Be nucleus. It possess a $J^{\pi}=1/2^{+}$ state just above the $^{8}\mathrm{Be}+n$ dissociation threshold, located at 1.664 MeV. This state has a strong single-particle configuration and can be excited by an E1 transition originating from the ground $J^{\pi}=3/2^{-}$ state.

In addition, the ^{9}Be dissociation into the $^{8}\mathrm{Be}+n$ is the inverse of the $^{8}\mathrm{Be}(n,\gamma)^{9}\mathrm{Be}$ process, the neutron capture by ^{8}Be, an important reaction for nuclear astrophysics. Recently, it has been proposed that a possible scenario for the r-process nucleosynthesis is a neutrino-heated high-entropy region in the post-collapse phase of a Type II supernovae. In this condition, the so-called α-rich freeze out process can take place, starting from neutrons and α particles. The starting point for the reaction chain

$$\alpha + \alpha \leftrightarrow {}^{8}\mathrm{Be}(n,\gamma){}^{9}\mathrm{Be}(\alpha,n){}^{12}\mathrm{C}\ldots$$

initiating the r-process nucleosynthesis would therefore be precisely the ${}^{8}\mathrm{Be}(n,\gamma){}^{9}\mathrm{Be}$ reaction, which in turn, can be studied by the photo-dissociating ${}^{9}\mathrm{Be}$.

In the following we will show how the E1 excitation mode can lead to a strong E1 peak in the electromagnetic dissociation of ${}^{9}\mathrm{Be}$ and we will show the interplay role of the resonance and of the continuum in this particular case.

2. Electromagnetic excitation of ${}^{9}\mathrm{Be}$

The ${}^{8}\mathrm{Be}(n,\gamma){}^{9}\mathrm{Be}$ and the corresponding ${}^{9}\mathrm{Be}$ excitation processes are schematically shown in Figure 1. The two reaction cross sections are related by detailed balance, which in the present case reads

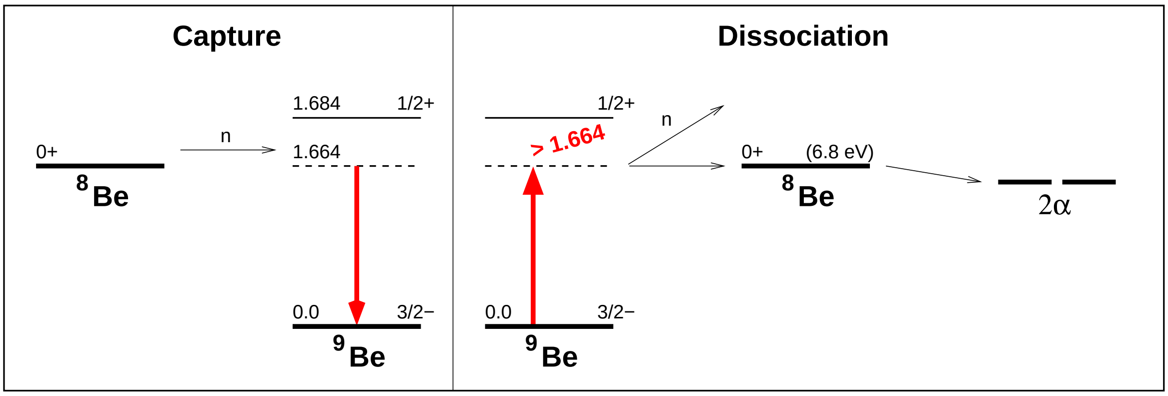

Figure 1. The ${}^{8}\mathrm{Be}(n,\gamma){}^{9}\mathrm{Be}$ and the corresponding ${}^{9}\mathrm{Be}$ dissociation processes.

$$\sigma_{\gamma,n} = \frac{k_n^2}{k_\gamma^2}\frac{1}{4}\sigma_{n,\gamma}$$

where k_n is neutron wave number in the continuum and $k_\gamma \equiv E_\gamma/\hbar c$. The neutron capture cross section is given by

$$\sigma_{n,\gamma} = \frac{16\pi}{9}\frac{k_\gamma^3}{\hbar v}\sum_{l_c j_c} \mid Q^{(\mathrm{E1})}_{c\to b} \mid^2$$

where the matrix elements $Q^{(\mathrm{E1})}_{c\to b} =< \Psi_c \mid\mid \hat{T}^{\mathrm{E1}} \mid\mid \Phi_b >$ can be calculated using some model potential for the continuum, Ψ_c, and for the bound state, Φ_b.

We have used a Woods-Saxon potential model for the calculation of both the single-particle component of the ${}^{9}\mathrm{Be}$ ground state and for the $n + {}^{8}\mathrm{Be}$ scattering state wave functions. The parameters of the potential were $r_0 = 1.25$ fm, $a = 0.65$ fm and a spin-orbit strength of $V_{ls} = 6.5$ MeV. The well-depth of the potential was adjusted as to reproduce the correct binding energy of the ^{9}Be ground state.

In order to have a realistic description of the wave functions, we have performed shell model calculations to obtain the fractional parentage amplitudes (spectroscopic factor) of the ^{9}Be ground state. We have obtained $S \simeq 0.5$ using the so-called MWK interaction and a *psd* model-space [1].

Concerning the $J^\pi = 1/2^+$ state at 1.684 MeV, we have to notice that this has been populated in many reactions and its excitation energy is quite well defined. Shell model calculation with the same interaction and model-space shows that the structure of this state is dominated by the configuration

$$|^8\mathrm{Be}(0^+) \times \nu(2s_{1/2}); 1/2^+ >$$

with a spectroscopic factor of the order of $S \simeq 0.6$.

This set of calculations provided all the necessary ingredients to derive the $^8\mathrm{Be}(n,\gamma)^9\mathrm{Be}$ as well as the ^{9}Be photo-dissociation cross sections.

3. Results

The results of our calculations are shown in Figure 2. There, a comparison is made between the calculated photo-dissociation cross section and the available experimental data. The experimental data was obtained from different sets of measurements. A set was obtained with measurements performed with γ-ray sources [2–4], while a second set of data was obtained with bremsstrahlung radiation (continuum spectrum) [5]. Note that this last set of data may be affected by problems in the determination of the photon absolute flux. The data clearly show a peak above the threshold. This peak is due to a non-trivial combination of a threshold effect and the presence of the $J^\pi = 1/2^+$ state.

The direct breakup contribution (indicated by DRC in the figure) shows in this case a smooth rise with excitation energy, as compared to the peak-like excitation observed in the breakup of weekly bound systems such as ^{11}Be ($S_n \simeq 0.5$ MeV) [6]. In fact here, the binding energy is moderately low ($S_n = 1.664$ MeV) and the bound state is a p-wave state and not the typical $2s_{1/2}$ orbital of halo nuclei. This situation makes the contribution of the direct excitation into the continuum of a much gentle shape.

The calculation of the resonance contribution was made using a single-level Breit-Wigner formula with the parameters; $E_r = 73.4$ KeV, $\Gamma_n = 27$ KeV, and $\Gamma_\gamma = 0.45$ eV. This was assumed to be, of course, an s-wave resonance state. Of particular interest in the present case is the result of the contribution of the interference term. In the presence of a resonant state, the cross section contains a Breit-Wigner term (BW), a direct transition term (DRC), and an interference term

$$\sigma(E) = \sigma_{DRC}(E) + \sigma_{BW}(E) + 2[\sigma_{DRC}(E) + \sigma_{BW}(E)]^{1/2}\cos[\delta_r(E)]$$

where the phase of the interference term is given by

$$\delta_r(E) = \tan^{-1}[\frac{\Gamma(E)}{2(E - E_r)}].$$

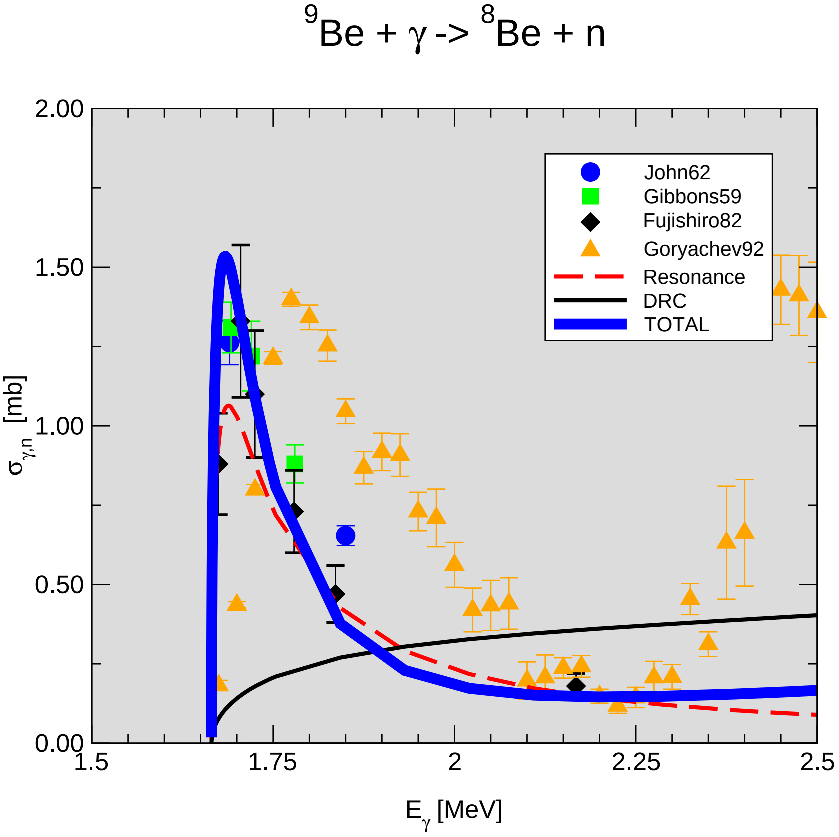

Figure 2. ^{9}Be$(\gamma, n)^8$Be cross section. The experimental data are from Gibbons59 [2], John62 [3], Fujisjiro82 [4], Goryachev92 [5]. The calculated values represents the resonance component (dashed line), the direct dissociation component (thin solid line) and the total (thick solid line), including interference (see text for details).

The interference term seems to be important in particular in the upper energy side of the peak. In fact there, it would not be possible to reproduce the experimental data without a suppression of the DRC contribution. A similar interference effect has been recently found in the case of a p-wave resonance in the ^{16}O$(n, \gamma)^{17}$O reaction, located at 434 KeV [7]. This effect therefore is not peculiar to the vicinity of the threshold, nor to the s-wave character of the state.

4. Conclusion

We have shown that a concentration of E1 strength above the dissociation threshold can be due to the presence of a resonance state, in addition to the recently proposed soft-dipole and/or direct transition modes. This situation holds in the special case of the ^{9}Be excitation/dissociation. In this case, the presence of a $J^\pi = 1/2^+$ resonance state is well established and its location allows for a fine tuning of the excitation mechanisms. We have shown that the presence of the resonance state, in addition to the unavoidable direct excitation mode, gives rise to interference which is necessary to reproduce the available experimental data. The implications of the present results in the reaction network for r-process nucleosynthesis are under study at the moment.

Acknowledgements

This work has been partially supported by the European Union (contract 983090) with a research grant for a stage spent at the University of Tokyo. I would like to express my sincere gratitude to Prof. T. Otsuka and to the Department of Physics of the University for the hospitality offered.

REFERENCES

1. B. A. Brown, A. Etchegoyen, and W. D. M. Rae, MSUCL Report **524** (1988).
2. J. H. Gibbons, R. L. Macklin, J. B. Marion, and H. W. Schmidt, Phys. Rev. **114** (1959), 1319.
3. W. John, and J. M. Prosser, Phys. Rev. **127** (1962), 231.
4. M. Fujishiro, T. Tabata, K. Okamoto, and T. Tsujimoto, Canad. J. Phys. **60** (1982), 1672.
5. A. M. Goryachev, G. N. Zalesny, and I. V. Pozdnev, Izv. Rossiiskoi Akademii Nauk, Ser.Fiz. **56** (1992), 159.
6. T. Nakamura *et al.*, Phys. Lett. B **331**, (1994), 296
7. Y. Nagai, private communication. See also A. Mengoni, and T. Otsuka, Proceeding of the 10th International Conference on Capture Gamma-Ray Spectroscopy and Related Topics, Santa Fe, New Mexico (USA), September 1999. In press (2000).